

The method of finite elements in the design process of valve solenoids

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ABSTRACT

The method of finite elements (FEM) is a suitable tool for the simulation of electromagnetic valve actuators and hence the determination of their stationary as well as dynamic properties. In the past was shown their application to calculate stationary forces and transient shifting times for both proportional and switching solenoids. This paper demonstrates the determination of cut-off frequencies of different proportional electromagnetic actuators in FE simulation under the consideration of eddy currents. The dynamic limits of different concepts thus can be compared in simulation already before the sampling process is started.

NOMENCLATURE

B	magnetic flux density	Vs/m ²
f	Frequency	1/s
t	time	s
v	speed	m/s
x	stroke	m
δ	intrusion deepness	mm
μ	magnetic permeability	Vs/Am
ρ	specific electric resistance	Ωm

1 INTRODUCTION

Many actuators in proportional as well as on/off valves are based on electromagnetic field effects between soft iron, permanent magnets and temporary field sources like copper wire coils. The coherences in the electromagnetic field described by Maxwell's equations are too complex to be solved analytically. The method of finite elements (FEM) is widely used in the design process of rotatory electric drives to calculate their stationary as well as transient behaviour [Kr01]. Despite their generally more complex geometries, rotatory machines simulation-wise show the advantage of constant radial air gaps. FEM can be used with some adaptations to calculate linear electromagnetic actuators as well, in order to speed up their development and time to market (Figure 1).

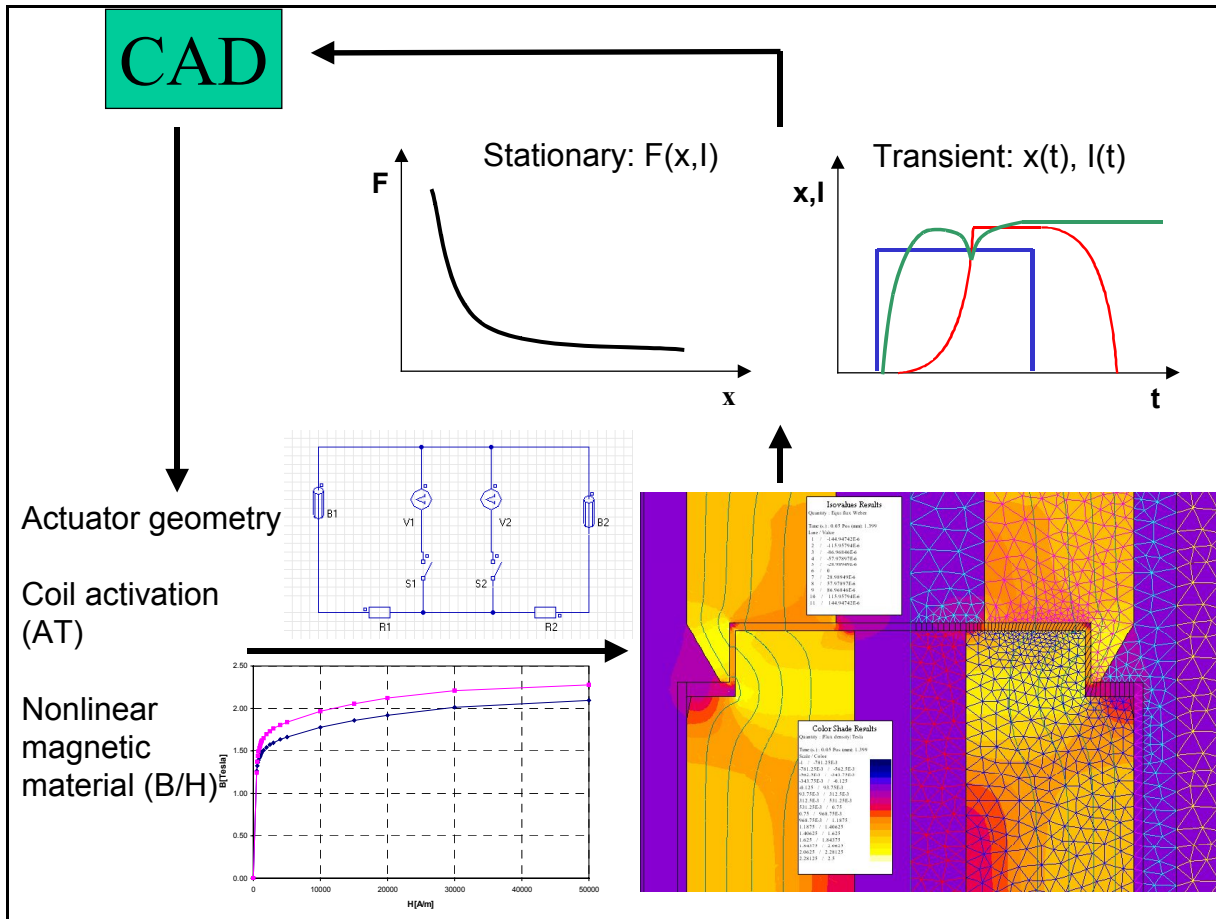


Figure 1: FEM in the design process of valve solenoids

The axial air gaps have to be meshed such that the automatic adaption of the mesh is possible during the linear movement, especially for transient calculations. The non-linear

magnetic material behaviour has to be taken into account. The effects of counter-induction and eddy currents have to be considered in transient simulation.

2 PROPORTIONAL VALVE ACTUATORS

There are different physical concepts to actuate proportional valves in hydraulics and pneumatics /Sh02/. The choice between the electro-dynamic principle (voice coils, torque motors..), the electromagnetic principle (linear motors as known in fluid power, solenoids..) and new principles like piezo actuators depends on various requirements like force density, dynamics, durability and costs. Solenoids have their technical advantages in their robustness and the generated force per volume at the price of limited dynamics due to strong eddy currents induced into the full iron circuit and the operation against a reverse element, typically a spring. Switching solenoids can be used for continuous operation as well /Ta99/.

This paper shows an approach to the improvement in dynamics of a proportional solenoid (**Figure 2**).

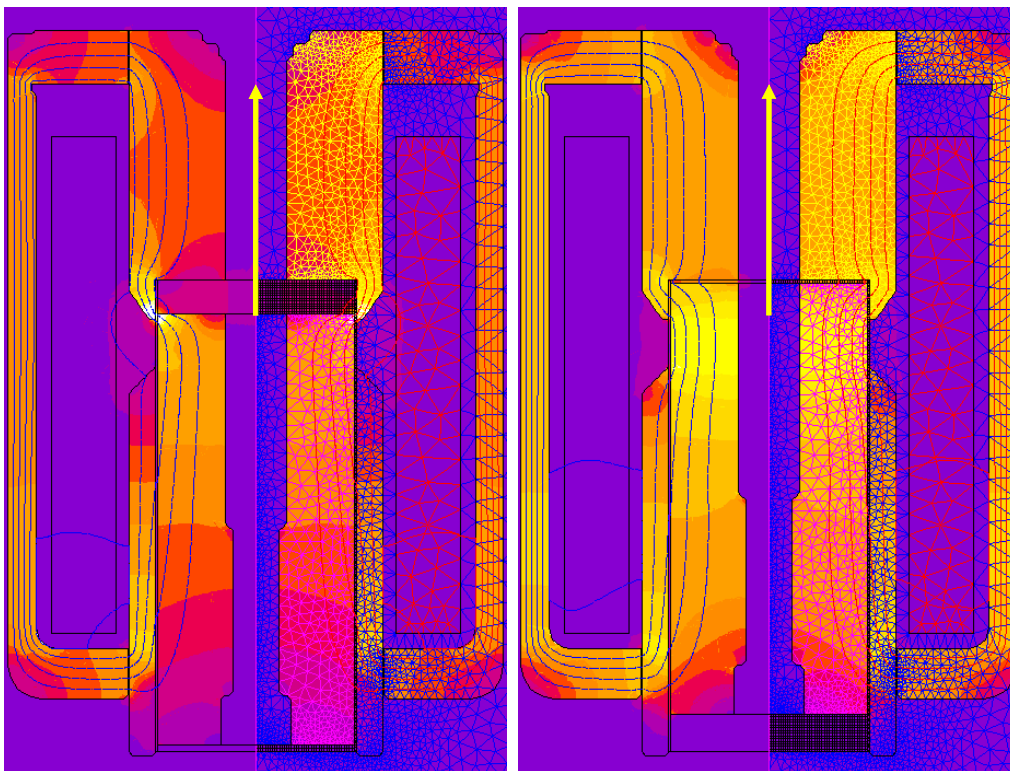


Figure 2: FE plot with field lines & saturation of the single-acting proportional solenoid

The standard design is compared with a double-acting design with two coils and a permanent magnet ring to pre-magnetise the iron circuit and to latch the armature at both end stops (**Figure 3**).

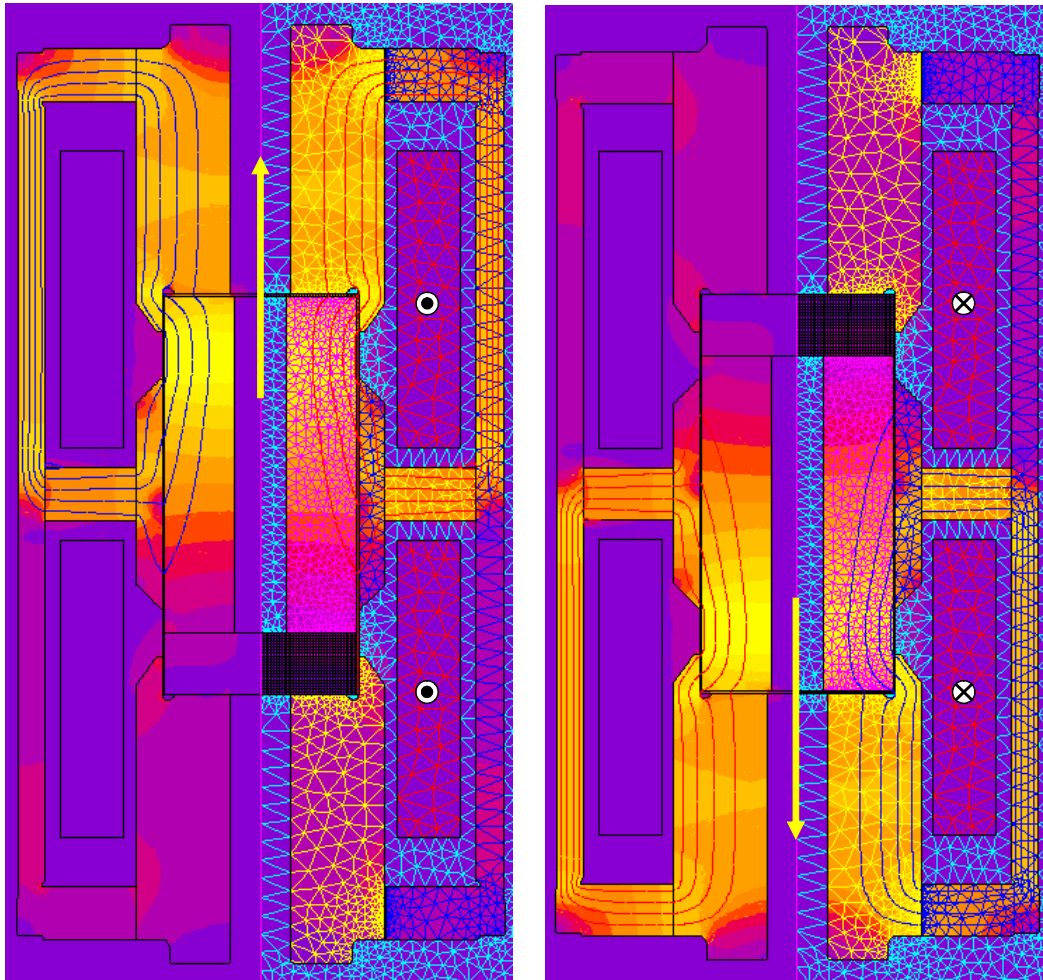


Figure 3: FE plot with field lines & saturation of the double-acting proportional solenoid

Transient FE simulation allows to determine the dynamic limits of both designs. The simulation results are compared with measured frequency responses.

3 SIMULATION AND TESTING

3.1 Stationary behaviour

In a first step the stationary force versus stroke is calculated. The force of the single-acting solenoid is well met by the simulation results (lower dotted line vs. hysteresis

curve in **Figure 4**). The standard proportional generates approximately 45 N at 532 ampère-turns. The stationary force of the designed double-acting geometry lies above this force level along the entire stroke according to FEM (upper dotted line in Figure 4). It does not show a horizontal course though, which demands an adaption of the solenoid's cone to later applications.

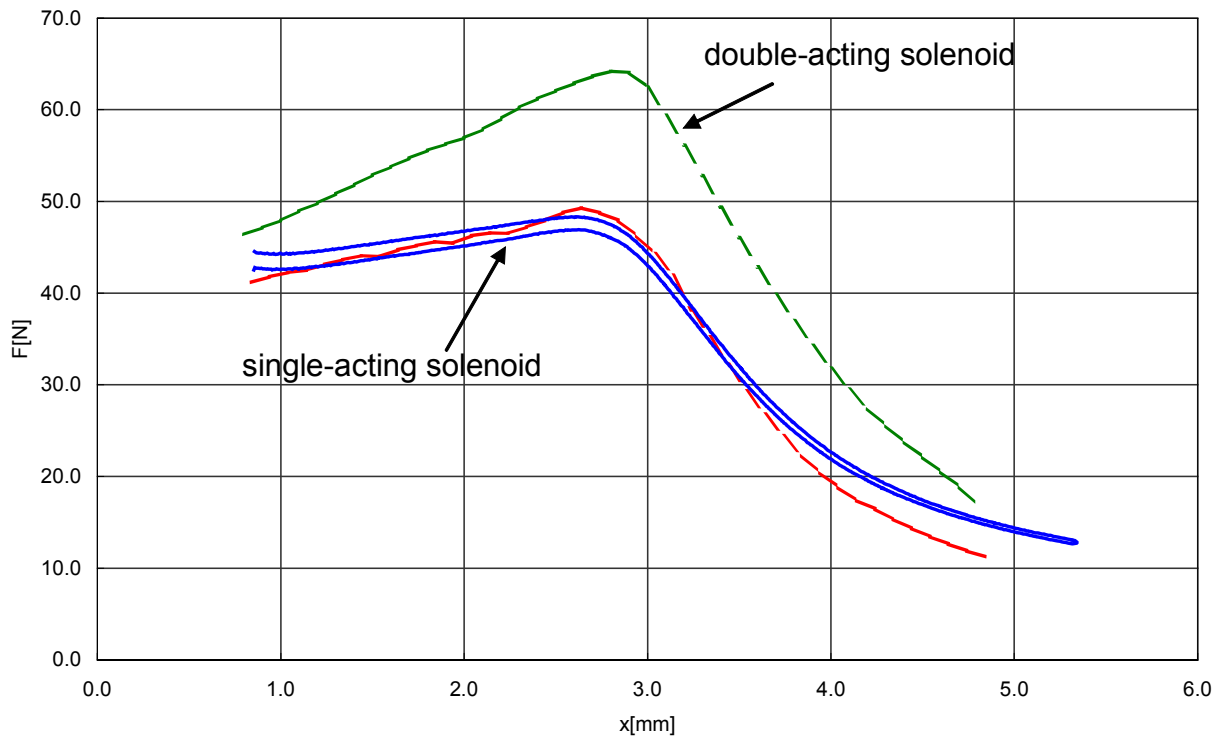


Figure 4: Stationary force vs. stroke at 532 ampère-turns

The higher force density is partly due to the permanent magnet ring in the double-acting geometry that shows responsible for a constant magnetic pre-tension.

3.2 Dynamic comparison

The transient FEM allows to determine the oscillation amplitudes and phase lags of the solenoid armature for different current frequencies in the coil under consideration of eddy currents (see **3.3**). A “discrete frequency response” thus can be simulated and compared to dynamic measurements on a test bench with optical displacement sensor (**Figure 5**).

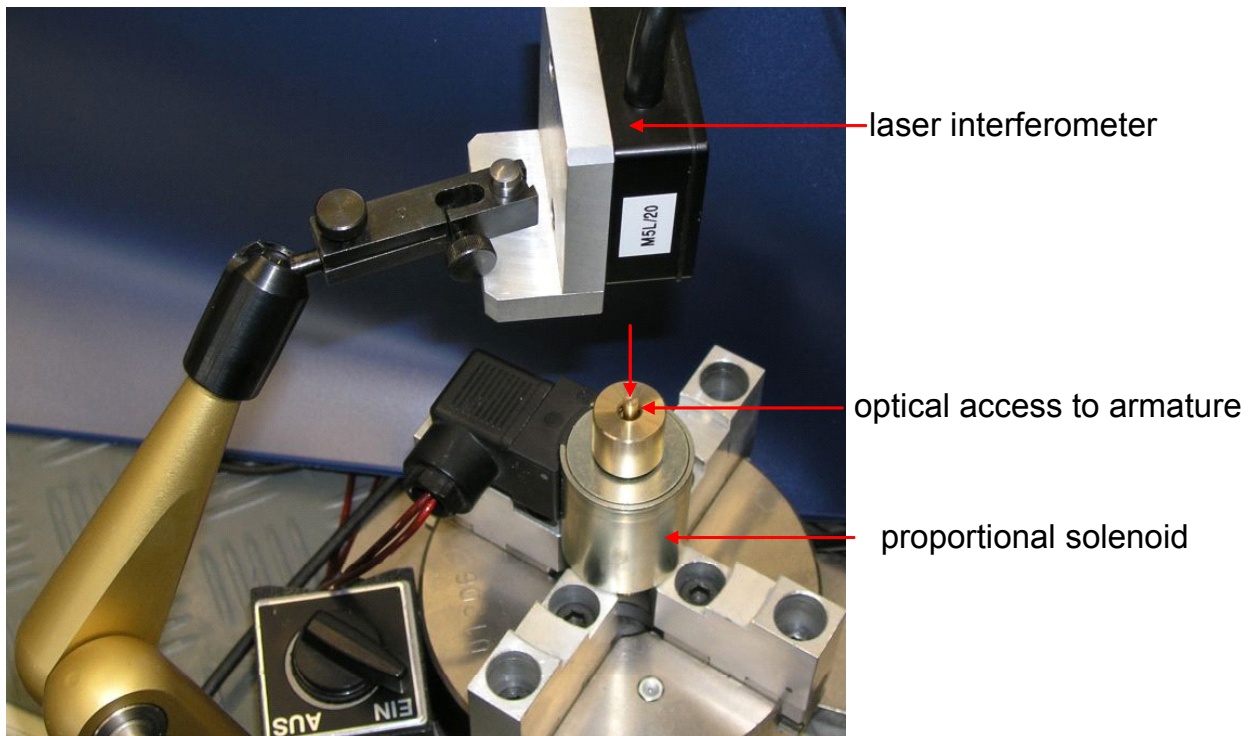


Figure 5: *Dynamic solenoid test bench*

Figure 6 shows the current in the coil and the armature stroke of the proportional solenoid at 100 Hz. A special controller assures a sinusoidal course of the input current against the coils' inductance and the counter induction caused by the armature movement. Former publications have shown their effects on dynamic step responses /S105, 205/. In simulation a strictly sinusoidal excitation can be assumed as well.

The armature oscillates with 0.85 mm at 100 Hz (Figure 6 solid line), the simulation predicts 0.91 mm (Figure 6 dotted line). This corresponds to 47 % (-6.6 dB) resp. 50 % (-6 dB) with 1.8 mm maximum amplitude. The rising slope is slightly lower, the falling slope slightly higher in simulation than in measurement, which indicates further potential for optimisation in the spring- and friction model. The phase lag of approximately 180 degrees between input signal and armature stroke factually disables large signal operation at 100 Hz in closed loop control. Simulation and measurement were done and compared for several frequencies so that the amplitude gain along the relevant frequency band could be plotted (**Figure 7**).

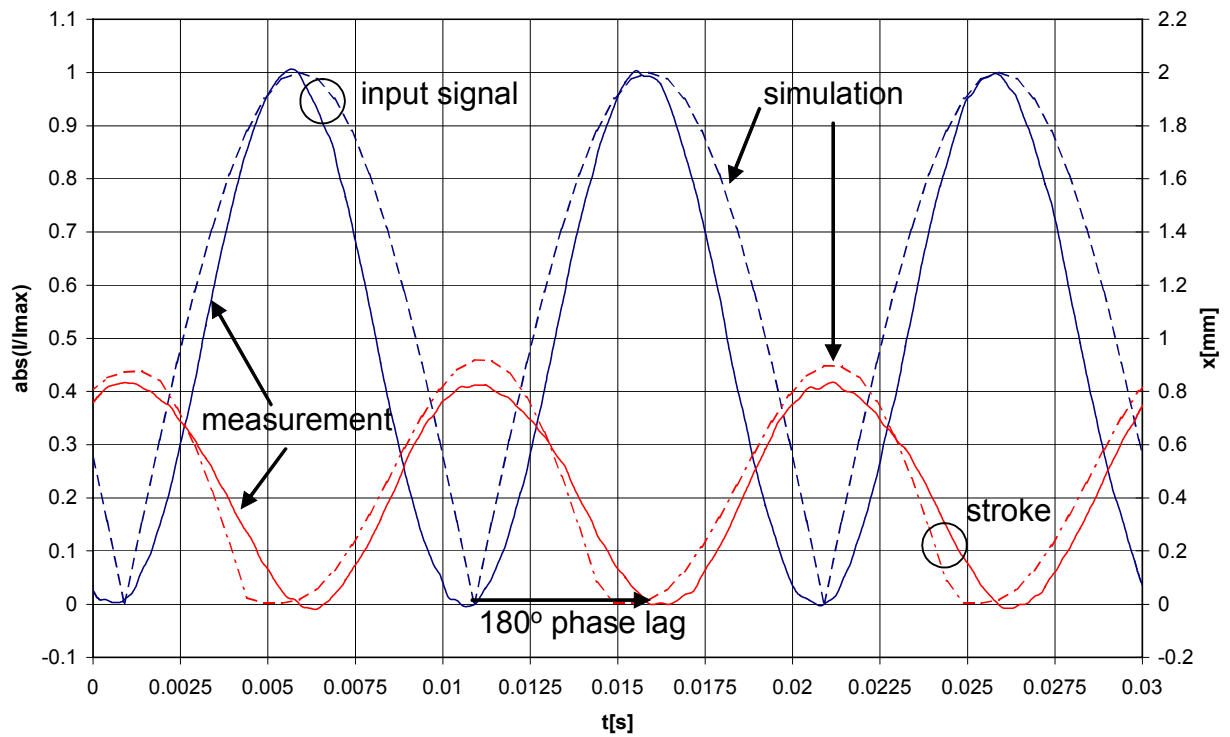


Figure 6: Simulation vs. measurement at 100 Hz

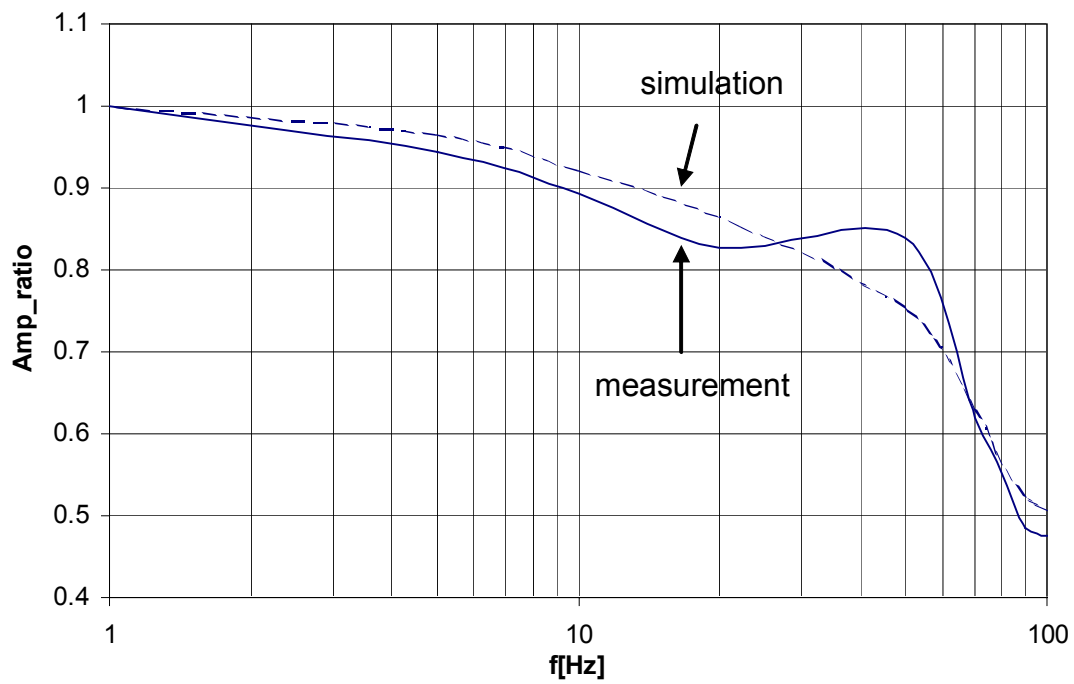


Figure 7: Amplitude gain vs. frequency in simulation and measurement

The testing of samples showed a resonance at 40 to 50 Hz that could not be rebuilt in simulation. The -3 dB frequency lies slightly above 60 Hz for large signal operation in both measurement and FEM. The simulation shows good reproduction of the real behaviour apart from the resonance.

The results of the solenoid's dynamics in large signal operation cannot directly be compared to the cut-off frequencies of hydraulic valves, typically given for small signal operation (e.g. at 5 % input signal).

The transient simulation of the double-acting device shows a total armature stroke of 3.3 mm at 100 Hz with approximately 90 degrees phase lag (**Figure 8**). At 125 Hz the full amplitude in armature stroke is not achieved any more and the phase lag comes close to 180 degrees as well. This rather optimistic simulation result promises stable large signal operation with full amplitude at 100 Hz and has to be verified in samples. It indicates the dynamic potential of the double-acting device with a permanent magnet ring and bi-directional operation without strong mechanical reverse elements.

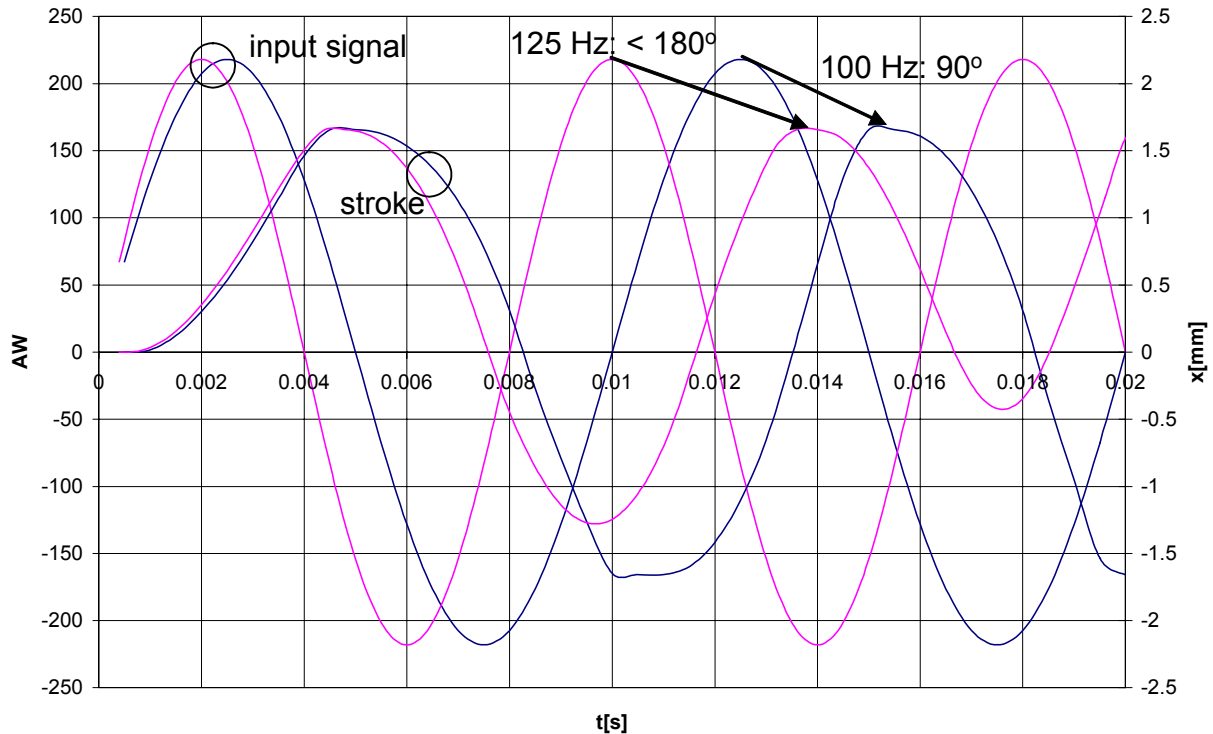


Figure 8: Amp-turns and stroke of the double-acting solenoid at 100 and 125 Hz

3.3 Eddy currents

The transient magnetic field induces a current into the electrically conducting iron material (specific electric resistance $\rho_{\text{Copper}} = 1.7\text{E-}8 \text{ }\Omega\text{m}$, $\rho_{\text{Iron}} = 1\text{E-}7 \text{ }\Omega\text{m}$) during the shifting process of the solenoid. These so called eddy currents are swirling around the primary magnetic field and create a secondary magnetic field themselves that counteract the original field and its intrusion into the material following the rule of Lenz. The intrusion velocity v depends on the specific electric resistance ρ of the material and its magnetic permeability μ (1).

$$\frac{\partial^2 B}{\partial x^2} = \frac{\rho}{\mu} \frac{\partial B}{\partial t} \Rightarrow v^2 \sim \frac{\rho}{\mu} \quad (1)$$

With higher electric resistance lower eddy currents are induced with less counteraction against the original field and vice versa. The simulation allows to “switch off” the electric conductivity. The influence of eddy currents at high frequencies thus can be quantified. The transient force of the double-acting solenoid at fixed middle position of the armature is reduced by about 8 % at 100 Hz through the influence of eddy currents in simulation (Figure 9).

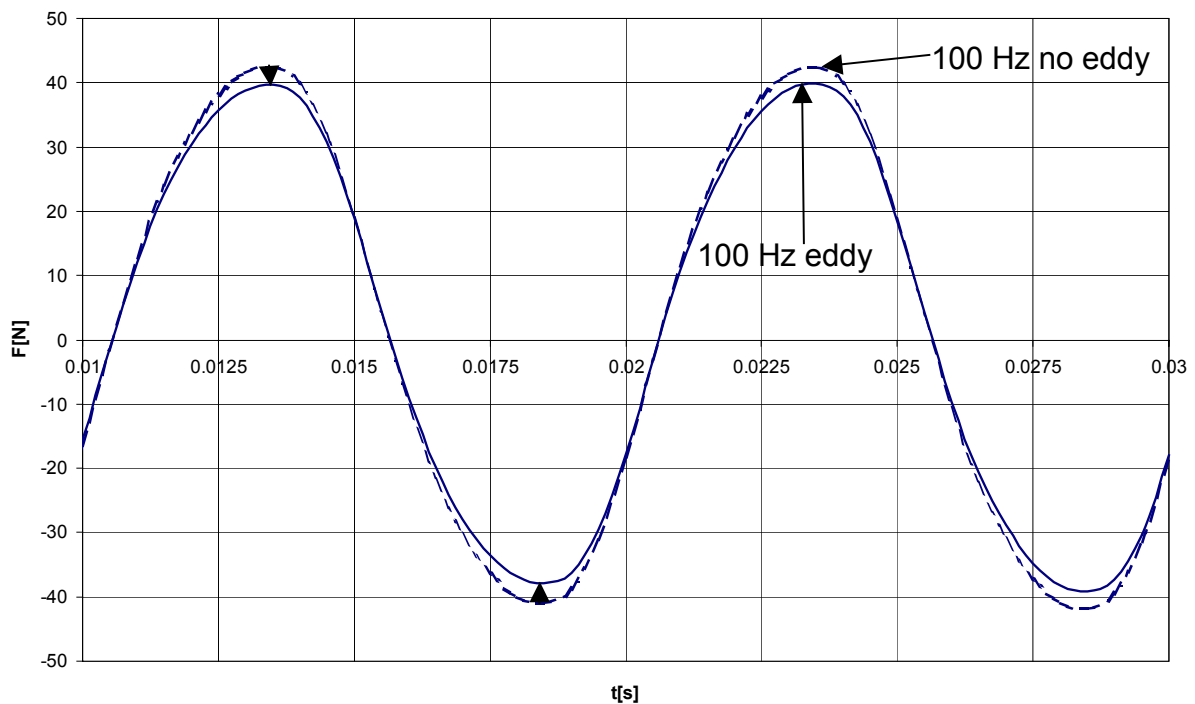


Figure 9: Simulated oscillating force with and without eddy currents at 100 Hz

The effect of eddy currents on the primary electromagnetic field also can be visualised in simulation. **Figure 10** shows the field propagation into the armature at 100 Hz with (left) and without electric conductivity (right). It can be seen that the field at 100 Hz intrudes the armature only about half due to eddy currents, whereas in the (unreal) case without conductivity, it would go all the way through to the concentric drilling. The field intrudes to a deepness δ that is proportional to the inverse square root of the excitation frequency f (2).

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad (2)$$

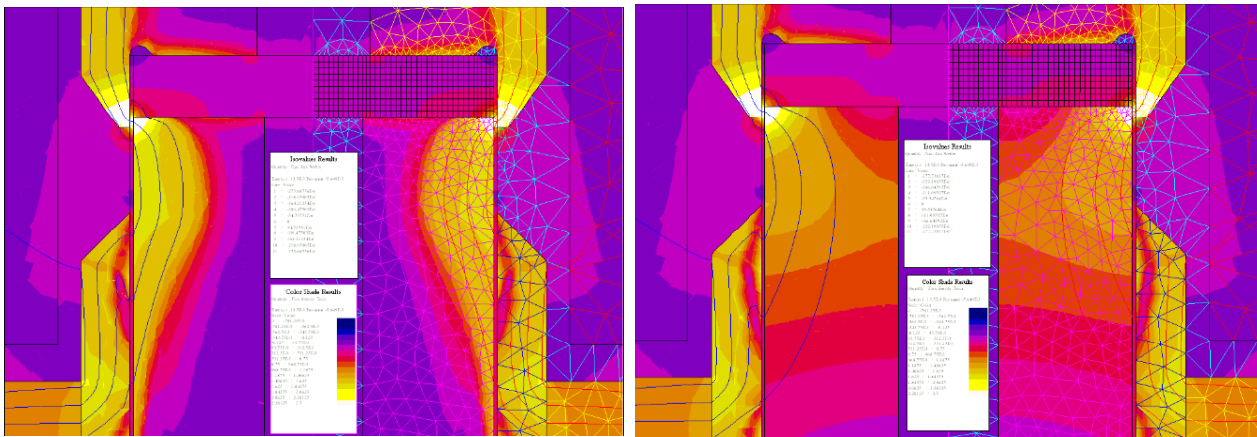


Figure 10: Field propagation into the armature at 100 Hz with and without eddy currents

CONCLUSION AND OUTLOOK

Apart from the calculation of stationary forces and transient shifting times under the consideration of counter-induction, FE simulation also allows to determine the cut-off frequencies of electromagnetic valve actuators. It was calculated for a standard proportional solenoid and compared to optical measurements with good correlation. The layout as double-acting device with two coils and a permanent magnet ring promised improvements in the stationary force level as well as the dynamic limits. These improvements will have to be verified in the testing of samples.

The influence of eddy currents at high frequencies can be quantified and visualised in FE simulation, material changes with different electric conductivities thus can be evaluated.

Hence the method of finite elements allows to determine and compare all functional properties of electromagnetic valve actuators. Future works could add the physical simulation of temperature and abrasion aspects in order to enable predictions about their robustness, endurance and reliability.

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