Excerpt from the Proceedings of the COMSOL Conference 2008 Hannover

Optimization of an Electromagnetic Actuator with COMSOL Multiphysics

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Abstract

This paper describes the automatic optimization of an electromagnetic actuator using a genetic algorithm.
The actuator modeled here is dedicated for charge changing valve actuation in internal combustion engines. In the first step of the simulation, several operating points are calculated using the script language of COMSOL Multiphysics. In order to reduce computation time, only one segment of the circular construction is simulated. The force of the actuator and the flux linkage to the coils, both depending on ampere turns and displacement, are computed. With respect to the dynamic requirements of the application, the voltage equation of the actuator delivers terminal current and voltage, and therefore, the necessary electrical power to achieve the demanded displacement. Measurement data is used to verify the simulated behavior.
Based on the computed terminal quantities a quality function is formulated. A genetic algorithm is being used to find a set of geometric parameters maximizing the actuators quality function. The optimization results for intake and exhaust valves are shown and discussed.

Keywords: electromagnetic actuator, genetic algorithm, permanent magnet, electric characteristics

1. Introduction

Modern actuators often are complex. Their characteristics are difficult to figure out. In many cases the optimization of a single aspect leads to a degradation of several others. Therefore, an analysis of the complete problem is to be preferred. The electrical operating parameters are the most important information during the development of electromagnetic actuators. A maximal efficiency and a minimal effort in construction and operation are required. The designed actuator has to meet the specified electric and kinematic demands and has to operate within the limitations of the application. A simulation of the actuator promises an optimization of the conceived construction. With the method of finite elements a powerful tool for actuator behavior calculation is available. In complex geometries a comparison of simulation and measurements in existing configurations is essential to justify the model. Often the simulation of static operating points is easier to realize than a dynamic simulation. The implementation in software is more directly and less susceptible to errors.

The following sections describe a procedure that computes a static operating map of an electromagnetic actuator as a basis for the calculation of the electrical parameters. The dynamic requirements for intake charge changing valve actuation in internal combustion engines are taken as reference (see [Tab99]). An automated adaption of the actuators geometry to the needs of the application is described. Finally, the results of a genetic optimization are shown.

2. Automated optimization using genetic algorithms

An automated optimization is used to find a minimum or a maximum of a problem that is formulated as a mathematical quality function. This objective criterion is calculated from a set of parameters. The goal is to find the set of parameters leading to the best solution.

A genetic optimization algorithm mimics the concept of evolution. At first, an initial population is built. This is often done using random values. The individuals are evaluated, and the best of them are used to compute the first generation. The individuals generated during this process – the children – are analyzed again; the best of them form the basis of the next generation. The whole process is repeated until a solution is found.

There are several ways to compute new individuals from their parents. The problem can be seen as the combination of several sets of parameters, leading to several new individuals with, hopefully, better attributes. One example is a linear combination of two sets of parameters, or randomized parameter combinations.

The mayor advantages of genetic optimization are:

- Good convergence, even with many parameters
- A good initial population improves calculation time, but a bad one does not lead to wrong results
- Old optimization results can be used as a new initial population – even when the quality function has been changed

For the results in this publication a free MATLAB implementation was utilized [Hou98].

3. The analyzed geometry

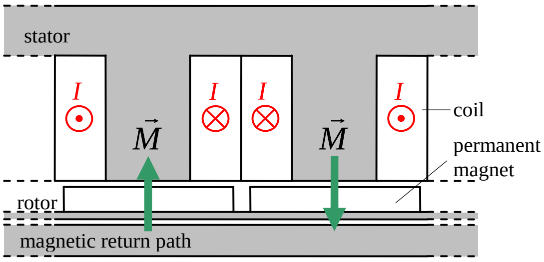

Figure 1: Schematic diagram of the construction in an unwinded view

The actuator under investigation is composed of several segments. An unwinded segment is shown in figure 1. The construction is circular, but not axially symmetric. The working angle of the rotor is about the angle between two permanent magnets. The coils are driven by the same amount of current I, with directions as shown in figure 1. The rotor consists of permanent magnets with alternating magnetization mounted to a sheet steel.

In the simulation, the magnetic nonlinear parts are implemented as interpolating functions. The magnetization curve of the magnets is nearly linear, so it is modeled by their remanent flux density B_r and their relative permeability μ_r.

The actuators depth is big compared to the other dimensions, so a two dimensional simulation is adequate.

4. Calculating the operating maps

The operating map of an electromagnetic actuator is an assignment of mechanic and electric values. Without loss of generality a rotary principle is considered in this publication, so the appropriate mechanical variables for this purpose are torque and angle.

With the simulation tool used here, COMSOL Multiphysics, the easiest operating map to compute is the torque M that is produced at a certain displacement angle α with a certain current I flowing in the coils.

The operating map consists of a multitude of discrete points, each computed automatically by nested loops. The implemented model is a completely parametrically MATLAB script. The geometry is built just once, the rotation of the rotor and the setting of the current is done separately.

5. Calculating the electric parameters

The time dependent electric parameters can be calculated from the operating maps and the desired kinematical profile.

The torque M depends on angle α and current I. With a maximum current, a torque operating area can be defined. It is to be mentioned, that, if the edges of two magnets are beneath one tooth of the stator, nearly no torque is produced.

Therefore, the actuator can not follow every kinematical demand. A control algorithm is needed to compute the actual time dependent angle α_{act} (see figure 5). The input variables are α_{des} and $\ddot{\alpha}_{\text{des}}$, describing the desired kinematical profile.

The torque needed to move the armature depends on the moment of inertia, which is calculated from the desired acceleration, and the gas forces, if an outtake valve is moved.

The actuator itself is a rotating construction coupled to the valve which moves in a translative way. Therefore, the effective moment of inertia is composed of a translatory and a rotary part. The gas forces decrease when the valve is opened; a linear function is being used here. An

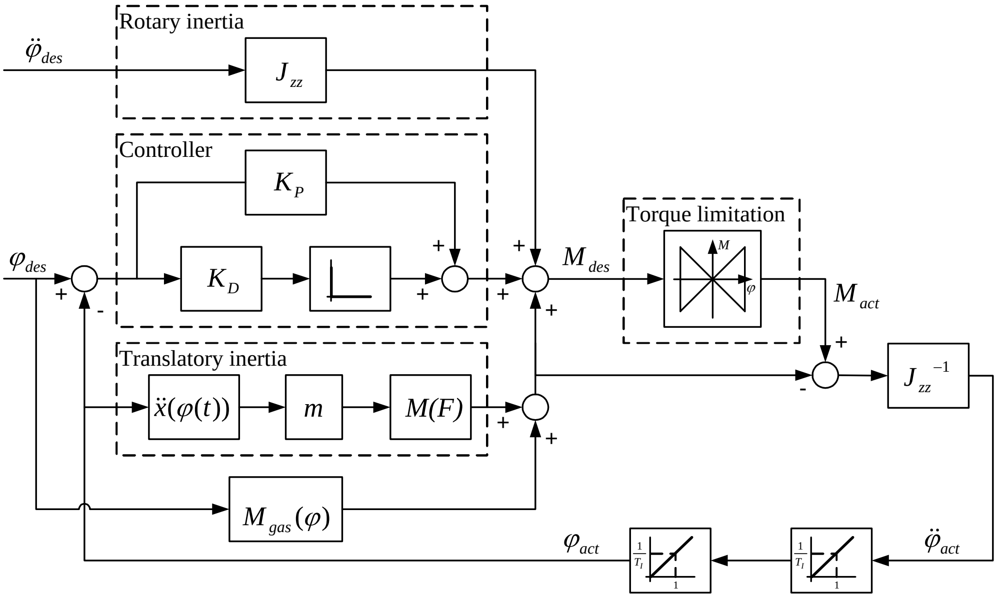

Figure 5: Control structure for angle correction, needed due to torque limitations

additional torque is added to control the system. Then the summarized torque is limited to keep the current needed to control the rotor within the selected interval. The rotatory part of the limited torque divided by the rotational inertia factor J_{zz} results in the acceleration of the rotor. The actual angle can easily be computed by integrating the acceleration twice. Due to the integrating feedback path in the control loop a PD control algorithm is implemented, providing a stable control system.

For small angles even small torques will result in high currents, without any contribution to the dynamic behavior. Therefore the torque M_{act} for angles below ~6°[1] can be set to the torque of the currentless actuator, without producing significant control errors.

The whole process is implemented as a MATLAB script, with equally time spaced vectors as time dependent variables.

To compute the current *I*, the simulated static operating map *M(α,I)* is inverted to *I(α,M)* by interpolation. From the actual displacement angle α_{act} and the actual torque M_{act} calculated above now follows the time dependent current $I(t)=I(\alpha_{act}(t), M_{act}(t))$ (see figure 6).

The flux linked to the coils $\Psi(\alpha_{act}(t),I(t))$ is already known (see figure 7).

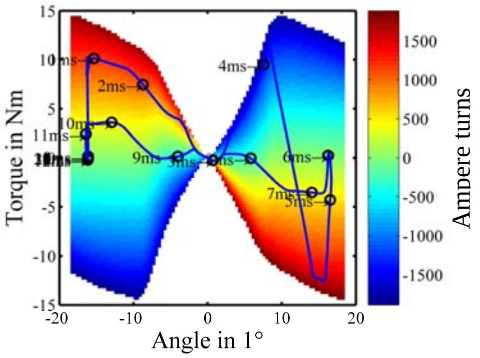

Figure 6: Current depending on torque and angle. The movement of the actuator is also shown.

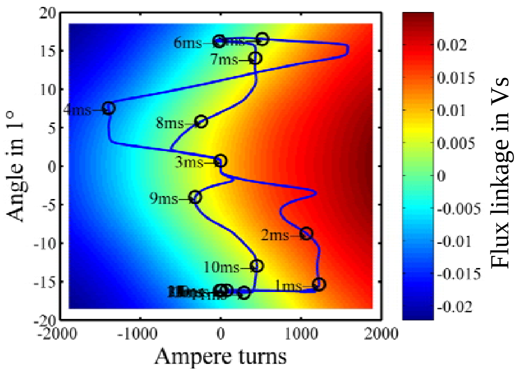

Figure 7: Flux linkage depending on current and angle.

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[1] Outtake valve actuator optimization

The voltage $u_i(t)$ induced in the coils follows from the derivative of $\Psi(t)$ with respect to the time t. The resistive part of the voltage equation

$$u(t) = u_R(t) + u_i(t)$$

is calculated from the homogeneous power density in the coils:

$$\frac{\mathrm{d}P_{\mathrm{SP}}}{\mathrm{d}V} = \frac{S^2}{\kappa} \Rightarrow P_{\mathrm{SP}} = \frac{S^2 V}{\kappa} = \frac{S^2 lA}{\kappa}$$

$$\Rightarrow u_R(t) = \frac{P_{\mathrm{SP}}}{i(t)}$$

Here P_{SP} is the power dissipated in the coil volume (lA) and κ is the specific conductivity of the material.

With respect to the coil wiring, the electrical quantities needed to achieve the demanded kinematical behavior are known. Power and energy as functions of time are easily calculated.

To ensure a correct simulation, the work consumed and produced was analyzed (see figure 9).

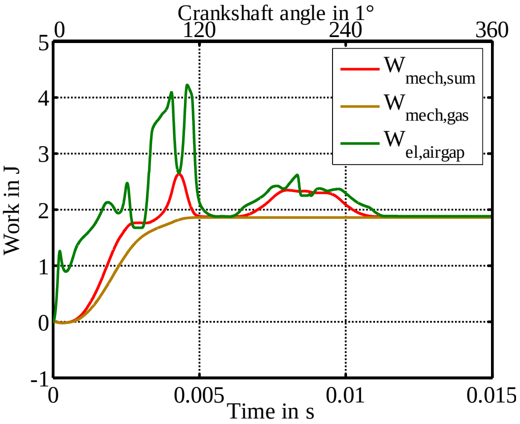

Figure 9: Mechanical and electrical work.

For t=6 ms and for t>12 ms the electrical work, the summarized mechanical work and the work against gas forces are equal. The differences between the plots result from the energy stored in the magnetic field, which is zero at the times mentioned above. This justifies the simulation.

6. Implementing a genetic optimization algorithm

The most important part of the optimization implementation is the quality function. The actuator should fulfill the dynamic and the electric demands of the application, so both of them have to be considered.

The quality function used here evaluates the mean value of the resistive losses $\overline{P_{\mathrm{SP}}}$, the maximal current $I_{\max}$ and the sum of the squared control deviation $\Sigma(\Delta\alpha)^2$. Note, that all time dependent functions are implemented as vectors with equally spaced time steps. The three parameters are divided by the values describing the original construction, and weighted as follows:

$$Q = 2 - (0.5\frac{\overline{P_{\mathrm{SP}}}}{\overline{P_{\mathrm{SP,orig}}}} + 0.2\frac{I_{\max}}{I_{\max,\mathrm{orig}}} + 0.3\frac{\Sigma(\Delta\alpha)^2}{\Sigma(\Delta\alpha_{\mathrm{orig}})^2})$$

The quality of the original construction is Q = 1, better constructions according to the function shown above will result in greater values.

On a modern computer approx. 1 hour is needed to compute and evaluate the data of a single individual. However, the main part of the calculation time is spent for the FEM simulation due to the large number of data points needed for the operating maps. In less complex constructions a much faster computation can be estimated.

7. Results

As an example an optimization of an outtake valve actuator at 4000 rpm (crankshaft) is performed. The optimization process converges after approximately 80 iterations (see figure 8).

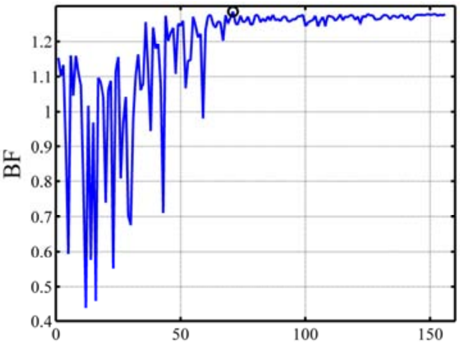

Figure 8: The quality function converges after approx. 80 iterations

The characteristics of the best individual are shown in table 1. The result strongly depends on the quality function. Even small changes can lead to different favorites, so as few parameters as possible should be used to keep the whole process under control.

The dimensions of the permanent magnets (thickness and angle along the rotor) and the tooth geometry were optimized. The outer diameter of the construction and the angle between two teeth were kept unchanged.

The optimized magnets are radial stretched and moved towards the outer diameter. The angle along the rotor was reduced by 10%. This leads to a higher moment of inertia, and to smaller currents needed for the desired movement.

In the optimized structure there is more magnetic material in the air gap, increasing the generated torque. More magnetic material in the air gap will be useless due to short circuit effects below the poles.

	$\overline{P_{\mathrm{SP}}}$	$I_{\max}$	$\Sigma(\Delta\alpha)^2$
original	63.62W	234.4A	0.464
favorite	50.29W	219.8A	0.206

Table 1: Characteristics of the actuator before and after the optimization

The electrical power consumption of the optimized structure is reduced by 13.3 W.

8. Summary

With the proposed simulation a practical numeric simulation of an electromagnetic actuator is available. Calculated operating maps, verified by measurements, provide the electrical quantities needed to perform a desired kinematical profile. A genetic optimization strategy was successfully used to find a favorite. Both exhaust and intake valves can be optimized.

9. Literature

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