A Magnetic Library for Modelica

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Abstract

A Modelica library for modeling of electro-magneto-mechanical actuators and drives is presented in this paper. The model components in this library are suited for actuator design itself as well as for dynamic simulation of complete drive systems. For modeling of the magnetic subsystem of actuators and drives, the concept of magnetic flux tubes is used in this library, leading to a network model of the actuators magnetic subsystem. Both the method of magnetic flux tubes and the developed library will be presented below. As an example, modeling of an industrial solenoid actuator will be explained.

Keywords: Magnetic library; Magnetic flux tube; Magnetic network; Solenoid Actuator

1 Introduction

Electromagnetic motors and actuators convert electrical energy via a magnetic field into mechanical work (or vice versa for generators). Different physical effects are utilized for this energy conversion, depending on the structure of the electromagnetic device. It is necessary to arrange the interactions in the electro-magneto-mechanical energy conversion process carefully during actuator design in order to achieve an optimal solution. Also, not only the actuator itself but also the environment of the system to be developed must be considered during design, too. For example, the efficiency of electromagnetic actuators and drives can be significantly increased by means of electronic circuits for excitation and control. The complexity of the above design task requires utilization of computer-based modeling and simulation techniques for both:

- design of the distribution of the magnetic field inside the actuator, and
- dynamic simulation of the complete drive system.

Latter task can be accomplished e. g. with the multi-domain model description language *Modelica* and accompanying simulation environments, where the system to be simulated is described with a set of differential and algebraic equations (DAE).

The problem for the design of magnetic actuators is, however, that the distribution of the magnetic field is described by partial differential equations (*Maxwell*'s equations). Calculation and optimization of such field distributions and resulting integral quantities such as magnetic forces is necessary during actuator design. Finite Element Analysis (FEA) is a valuable tool for this task. However, the high computational effort of FEA restricts its use in most cases to stationary field calculations. Dynamic simulation of a complete system incorporating a detailed model of the actuators magnetic field and detailed models of the feeding electronics and the mechanical load to be moved is not possible with reasonable effort using FEA.

To overcome the difficulties described above, the method of magnetic flux tubes can be used for actuator and system design [1]-[4]. This method allows a simplified description of the magnetic field inside a magnetic device so that the field distribution can be described with a set of algebraic equations rather than with the precise partial differential equations. With this approach, the field distribution in a magnetic actuator can be simulated together with neighboring subsystems in one DAE system with little computational effort. The accuracy is reasonable for coarse design of actuators and for system simulation.

2 Magnetic Flux Tubes

A magnetic flux tube is a defined volume inside a magnetic field with homogenous distribution of the magnetic field strength **H** and the magnetic flux density **B** within this region (Fig. 1).

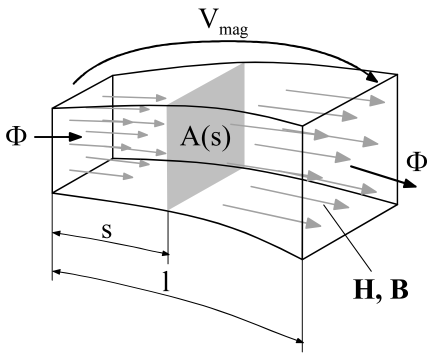

Fig. 1 Magnetic flux tube

Presuming that the principal distribution of the magnetic field inside a magnetic device is known, the magnetic field in the complete device can be divided into a network of flux tubes. For each flux tube element, a magnetic potential difference V_{mag} is defined as an across variable:

$$V_{mag} = \int_s \mathbf{H} ds = H l \quad (1).$$

The magnetic flux Φ through each cross sectional area A of a flux tube is calculated as follows:

$$\Phi = \int_A \mathbf{B} dA \quad (2)$$

With the above across variable V_{mag} and the flow variable Φ, a magnetic reluctance R_{mag} can be defined analogue to resistive network elements in other physical domains:

$$R_{mag} = \frac{V_{mag}}{\Phi} = \frac{\int_s \mathbf{H} ds}{\int_A \mathbf{B} dA} \quad (3).$$

Homogenous distribution of **B** and **H** through each cross section inside a flux tube is one of the assumptions of the flux tube approach. Hence, equation (2) simplifies to

$$\Phi = B(s) A(s) \quad (4).$$

Maxwell's constitutive equation

$$\mathbf{B} = \mu_o \mu_r \mathbf{H} \quad (5)$$

describes the material properties (μ_0 - permeability of vacuum, μ_r - relative permeability, see section 3.2). With the equations (3)-(5), the general formula for a magnetic reluctance of any shape can be given:

$$R_{mag} = \frac{V_{mag}}{\Phi} = \int_s \frac{ds}{\mu_0 \mu_r(s) A(s)} \quad (6).$$

For a prismatic or a cylindrical volume of length l and cross sectional area A with the magnetic flux entering and leaving the region through its end planes, equation (6) simplifies to

$$R_{mag} = \frac{l}{\mu_0 \mu_r(B) A} \quad (7).$$

As for the above example, equations for the magnetic reluctance of other common geometries can be found.

Similar lumped elements with the same magnetic flow and across variables can be defined for sources of a magnetic potential difference V_{mag} (see section 3.3) or for sources of a magnetic flux Φ, if needed. For a magnetic network consisting of at least one source and one reluctance element, the field distribution in a magnetic device can be calculated with little computational effort according to *Kirchhoff*'s laws.

3 Structure of the Magnetic Library

Based on the concept of magnetic flux tubes, a Modelica library for modeling of magnetic components and devices has been developed. The structure of this library is shown in Fig. 2. Its sublibraries and model components are described only in short in this section; a more detailed description of selected model components can be found in section 4, where usage of the library elements is explained with an example.

3.1 Interfaces Sublibrary

A domain specific magnetic connector was defined:

```
connector MagneticPort
  Modelica.SIunits.MagneticPotentialDifference V_mag
    "Magnetic potential at the port";
  flow Modelica.SIunits.MagneticFlux Phi
    "Magnetic flux flowing into the port";
end MagneticPort;
```

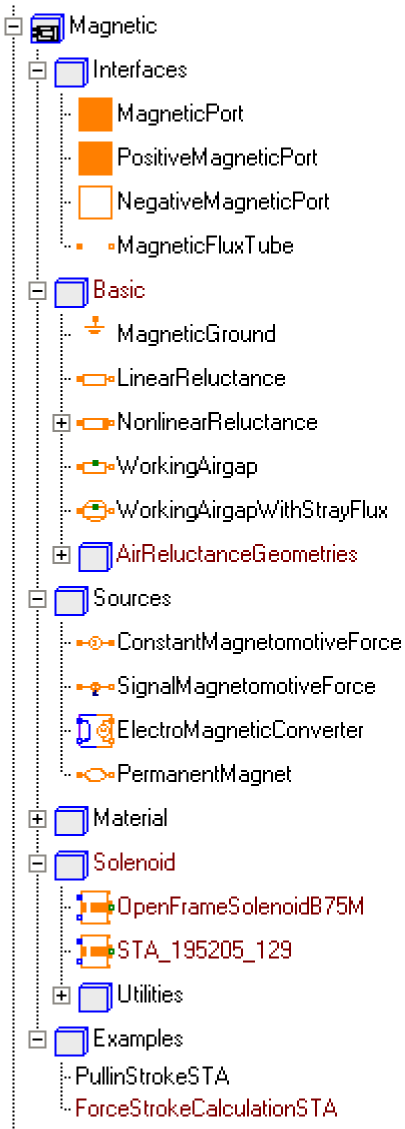

Fig. 2 Structure and sublibraries of the Modelica Magnetic library

Based on the connector definition above, a base model for all reluctance elements and selected source elements is used throughout the library:

```
partial model MagneticFluxTube
    "Component with two magnetic ports p and n and
     magnetic flux Phi from p to n"
  PositiveMagneticPort p "Positive magnetic port";
  NegativeMagneticPort n "Negative magnetic port";
  Modelica.SIunits.MagneticPotentialDifference V_mag
    "Magnetic potential difference between the two ports";
  Modelica.SIunits.MagneticFlux Phi
    "Magnetic flux flowing from pin p to pin n";
equation
  V_mag = p.V_mag - n.V_mag;
  0 = p.Phi + n.Phi;
  Phi = p.Phi;
end MagneticFluxTube;
```

3.2 Basic Sublibrary

Most magnetic devices contain ferromagnetic components that carry the magnetic flux imposed by one or more coils or permanent magnets to a working air gap where the desired magnetic force (or torque for rotating machines) is generated. This is because of the high relative permeability of ferromagnetic material compared to that of vacuum or air ($\mu_r = 1$). However, the relative permeability for each point of a ferromagnetic material is not constant but depends on the actual magnetic field strength H respectively the actual magnetic flux density B of this point [2], [4]. The so called commutation curve $B(H)$ of a steel commonly used in magnetic devices is shown in Fig. 3 as an example. According to equation (5) this results in the characteristic shape $\mu_r(H)$ of Fig. 3. Proper modeling of this nonlinear relationship is crucial for the accuracy of flux calculations and hence for the resulting magnetic forces. In engineering practice, the relationship $\mu_r(B)$ is often used instead of $\mu_r(H)$.

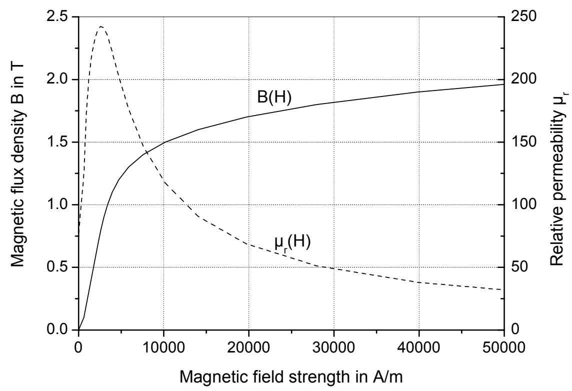

Fig. 3 Magnetic flux density B vs. magnetic field strength H and corresponding relative permeability μ_r for steel 1.0715 (9SMn28)

For the nonlinear reluctance elements in the Basic sublibrary, the relationship $\mu_r(B)$ is approximated with a function [4]. The Material sublibrary contains the coefficients of this function for different ferromagnetic materials. It is planned to implement additional possibilities to describe the relationship $\mu_r(B)$, e. g. spline interpolation.

3.3 Sources Sublibrary

The source elements *ConstantMagnetomotiveForce* and *SignalMagnetomotiveForce* both are ideal sources of a magnetic potential difference V_{mag}. They are intended for use in stationary flux calculations where no coupling between the feeding electrical and the magnetic subsystem is needed and where dynamic effects of this coupling need not to be considered.

The source element *ElectroMagneticConverter* couples the electrical subsystem of a electromagnetic drive system with the magnetic subsystem, i. e. with the network of magnetic flux tubes. Two equations are needed to describe this coupling [4]: *Faraday*'s law

$$u_{ind} = -w \frac{d\Phi}{dt} \tag{8}$$

and

$$V_{mag} = i \cdot w \tag{9}$$

Equation (8) describes the voltage u_{ind} induced in a coil due to a change of the flux linkage $w\Phi$ inside this coil with respect to time (w – number of coil windings). In most electromagnetic devices, the coil flux Φ is a nonlinear function of both the coil current i (due to saturation effects in ferromagnetic components) and the position x respectively φ of the device's moving component: $\Phi = f(i, x)$ for translational actuators and $\Phi = f(i, \varphi)$ for rotating electrical machines. The dependencies of the coil flux Φ on both current and position are intrinsically accounted for in actuator models according to the flux tube approach as will be obvious from the example in section 4.

Equation (9) describes the magnetic potential difference V_{mag} fed into a network of flux tubes due to the coil current. This equation is derived from *Ampere*'s law.

The Sources sublibrary is completed by a model of a permanent magnet. It is made up of a series connection of an ideal source of a magnetic potential difference V_{mag} and the linear ($\mu_r = const.$) reluctance of the permanent magnet [2], [3].

4 A Solenoid Actuator as an Example

Solenoid actuators offer a very robust and simple structure, a good force to mass ratio with respect to dynamic behavior and stroke and a low price. For that reasons they are widely used as drive element in a huge diversity of applications, e.g. in locking mechanisms throughout automation and automotive engineering, in fluidic valves or in relays and switchgear.

The principal structure of an electromagnetic actuator is shown in Fig. 4. Depicted is an industrial DC solenoid for applications throughout automation. The cross-sectional view above shows a solenoid of the Saia-Burgess STA series that will be used as modeling example [5]. In contrast to the depicted actuator with a conical pole shape, the modeled solenoid STA 195205-129 has a plane pole face as shown in the schematic view below.

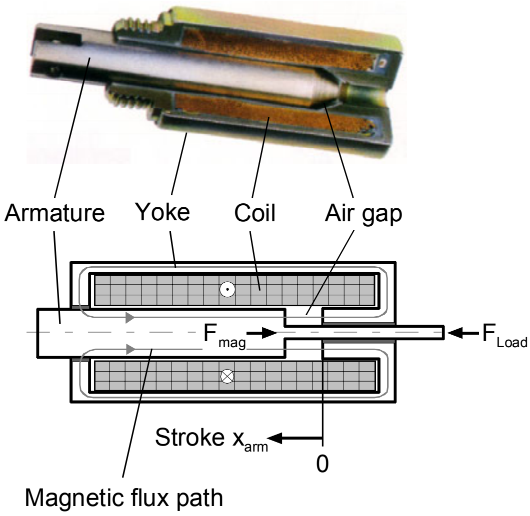

Fig. 4 Cross-sectional view and principal structure of a typical solenoid actuator [5]

The working principle of solenoid actuators is based on reluctance forces [2], [4]: The magnetic flux Φ generated by a current in the coil goes through a working air gap where a magnetic force is developed due to the gradient in relative permeability μ_r on the boundaries between the ferromagnetic parts with $\mu_r >> 1$ and the air with $\mu_r = 1$.

The force-stroke characteristics of electromagnetic actuators can be widely influenced and shaped according to applications needs by variation of the geometry of pole and armature. Typically however for most electromagnetic actuators is a highly nonlinear force-stroke characteristic $F_{mag}(x_{arm})$ with a minimum force at the armature rest position (maximum air gap length) and a strong increase in magnetic force towards minimum air gap length [2].

4.1 Model of the Solenoid

The graphical representation of the Modelica model of the actuator is shown in Fig. 5. It consists of the electrical subsystem (coil) on the left side with the electro-magnetic converter, the magnetic network based on the method of flux tubes in the middle, and the mechanical subsystem that models the armature dynamics on the right side. At the right flange connector, additional models from the Translational library of the Modelica Standard library can be attached, e.g. a mass to be moved, a return spring or process forces.

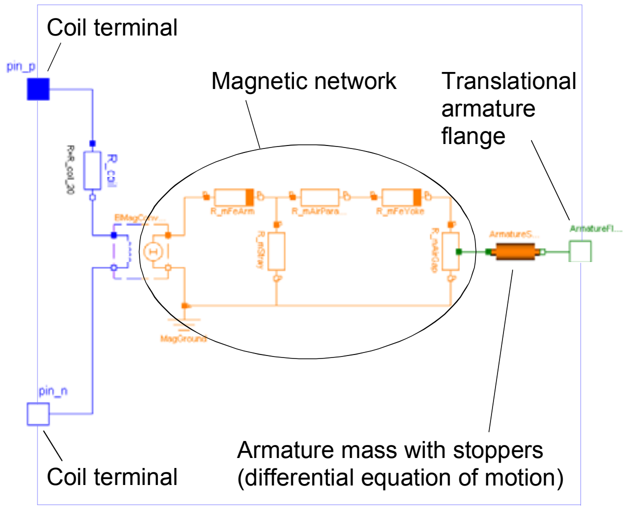

Fig. 5 Graphical representation of the Modelica model of the solenoid

The electrical subsystem with the current i, the voltage across the coil terminals v_{coil}, the magnetic flux Φ enclosed by each of the w windings, and the winding resistance R_{coil} is described with the following equation (see also equation (8)):

$$v_{coil} = iR_{coil} + w\frac{d\Phi}{dt} \quad (10).$$

For voltage controlled operation of the solenoid, v_{coil} is the voltage of the driving voltage source.

The magnetic network of Fig. 5 is intentionally kept simple in this example. In Fig. 6 the network is shown over a field plot of the actuators magnetic field obtained from FEA.

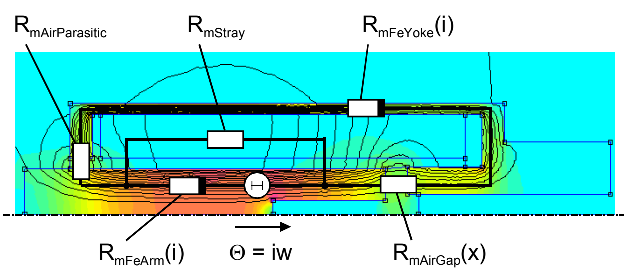

Fig. 6 Magnetic network over a FEA field plot of the sample actuator (line of symmetry at the bottom)

The magnetomotive force Θ is fed into the network by the electro-magnetic converter. It is an ideal source of a magnetic potential difference V_{mag} according to equation (9). The two ferromagnetic reluctance elements $R_{mFeArm}(i)$ and $R_{mFeYoke}(i)$ represent the ferromagnetic components of the actuator. They are calculated from the actuators main dimensions with equation (7). Due to the nonlinear $B(H)$-relationship of ferromagnetic materials, they depend on the solenoid current i. The steel 1.0715 with the $B(H)$-characteristic of Fig. 3 is used in both reluctance elements. An approximated function $\mu_r(B)$ derived from that material data is used for calculation of both reluctance values with equation (7).

Three reluctance elements through air are present in this magnetic network model: R_{mStray} is a simple but yet effective description of the stray flux of the solenoid. Despite the simple structure of the actuators magnetic network it should not be omitted in the model. This is because of the large ratio of total actuator length to outer diameter of the sample actuator. Typical for solenoids with such a geometry is that part of the magnetic field lines close without going through the working air gap $R_{mAirGap}$.

The reluctance of the working air gap is calculated with equation (7), where air gap length l is identical with the armature position x_{arm}. The magnetic or reluctance force F_{mag} that is generated at the boundaries between the ferromagnetic armature respectively the pole and the air is calculated with *Maxwell*'s formula [2], [4]:

$$F_{mag} = \frac{\Phi^2}{2\mu_0 A} \quad (11),$$

where A is the cross sectional area of the air gap respectively the area of the pole face. The developed force F_{mag} is fed as driving force for the armature mass into the mechanical subsystem of the actuator model, where acceleration, velocity and armature position x_{arm} are calculated from the differential equation of motion.

The magnetic network is completed with the reluctance $R_{mAirParasitic}$. This element describes the parasitic air gap in the non-ferromagnetic slide guiding for the armature.

4.2 Force-Stroke Characteristics

An important criterion that characterises an actuator is its force-stroke characteristics. For the solenoid model, this characteristic $F_{mag}(x_{arm})$ was calculated with a quasi-static enforced movement of the armature (Fig. 7). This is in accordance to real force-stroke measurements on actuators.

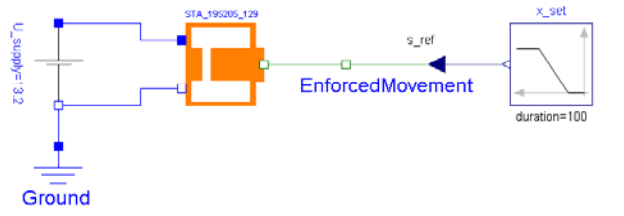

Fig. 7 Quasi-static enforced armature movement for calculation of the force-stroke characteristics

Simulated and measured curves for the sample actuator are compared in Fig. 8. Simulation was done with the magnetic network model of Fig. 5. Measured data was taken from the catalogue of the manufacturer. For comparison, the force-stroke characteristic obtained from FEA at different armature positions is included in this diagram, too.

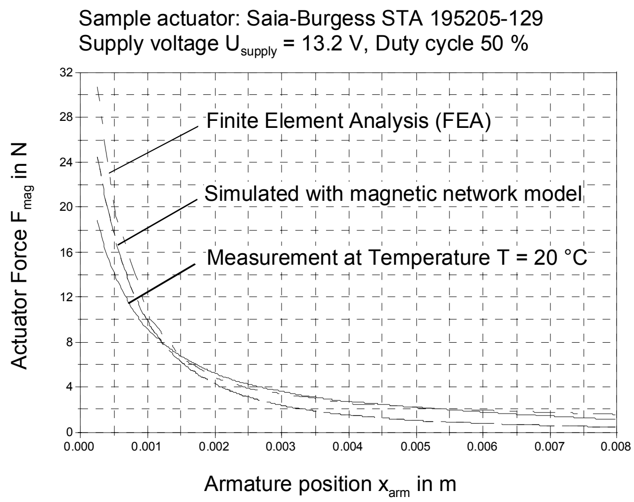

Fig. 8 Comparison of measured and simulated force-stroke characteristics of the sample actuator

Reasons for the differences between the three curves are:

- limited accuracy of the force-stroke measurement especially at small air gaps due to deflection of the load cell and the mounting rack,
- simple structure of the magnetic flux tube model in this example (e. g. no additional stray reluctance around the working air gap),
- neglect of additional parasitic air gaps especially in the FEA model, e. g. between yoke lid and yoke,
- differences between the simulated and the real material characteristics $\mu_r(B)$ for the ferromagnetic yoke and the armature.

Despite the differences between measurement and simulation with the magnetic network model, the flux tube approach is well suited for coarse design of magnetic devices and estimation of force-stroke characteristics respectively torque-angle characteristics for rotational devices prior to further design steps.

4.3 Simulation of a Pull-in Movement

The main advantage of a modeling approach based on magnetic flux tubes compared to a design approach using FEA is the little computational effort of flux tube models that allows for extensive dynamic simulations during both actuator and system design. To illustrate the capabilities of magnetic network models for dynamic simulation, a pull-in stroke of the armature was simulated with the network model of the sample solenoid of Fig. 5. In Fig. 9, simulated coil current i and armature position x_{arm} are shown together with measured data after a voltage step from 0 to 13.2 *VDC* at time $t = 0$ was applied. The armature was in horizontal position, no additional mechanical load was attached to it.

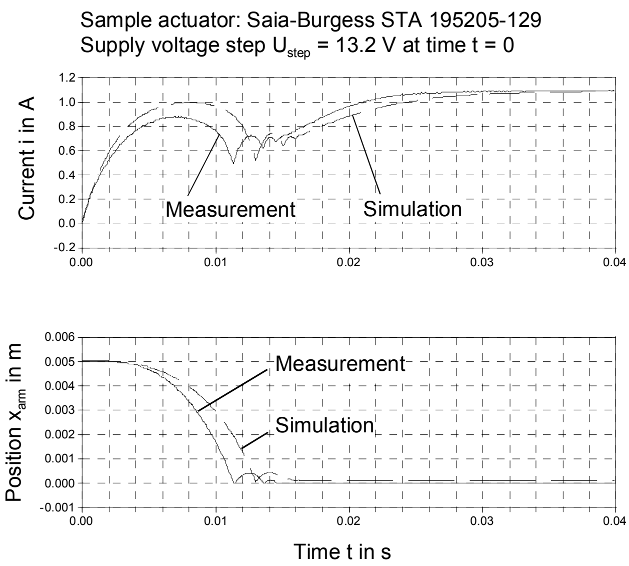

Fig. 9 Comparison of simulated and measured solenoid current i and armature position x_{arm} after a voltage step at time $t = 0$

The characteristic current drop during the pull-in stroke of the armature results from the increase of the solenoids inductance as the armature moves into the solenoid. This is due to the decrease of the air gap reluctance and the increase of the total magnetic flux during the movement.

Differences between the measured and the simulated curves can be explained with the simple structure of the network model. Higher accuracy of the solenoid model can be achieved with a more detailed magnetic network, if needed.

5 Conclusions

Basic magnetic network elements in Modelica were already presented in [6]. The model elements described in this paper are intended for modeling of rotating electrical machines. The magnetic elements (e.g. linear magnetic resistance, electro-magnetic converter) are described in terms of integral machine parameters. Differently from the approach in [6], the model components of the newly developed Magnetic library are defined in terms of their geometric dimensions and their material properties. They are hence suited for modeling of the geometry of magnetic components during actuator design, but for system simulation of the actuator together with its neighboring subsystems, too.

A dynamic model of a general purpose solenoid was presented to illustrate the concept of magnetic flux tubes as well as usage of the library. Modeling of the dynamic properties of solenoids during actuator design is of vital importance in many sectors. For example, electromagnetic injection valves in automotive applications must actuate in as little as 1 *ms*, and proportional solenoids that drive valves in fluidic applications operate at frequencies above 100 *Hz*.

Future work on the Magnetic library will focus on the following issues:

- refinement of implementation details, e. g. the description of material properties with tables and spline interpolation,
- estimation of eddy current losses for flux tube elements with electrical conductivity,
- implementation of additional models for magnetic devices, e.g. for solenoids with different pole shapes, electrodynamic drives or small rotating motors.

Preferably, the latter models shall be scalable, so that device manufacturers can easily build models for each product within a product family with different sizes. On the other hand, system engineers can use these models for simulation of complex mechatronic systems, e.g. in automation industry or in automotive applications.

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