Optimization of Bipolar Magnetic Actuators for Microvalves with Regard to the Tolerances

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Abstract:
Starting from a preliminary design, optimization for finding a fast acting bipolar magnetic system is performed based on a network model that refers to static look-up tables calculated with an axiosymmetric FEA-model. The effects of the geometrical and material properties tolerances on the system behavior are included into optimization, input in form of distribution functions. Computing the distributions of the system output variables is by approximation through second order analysis.

Keywords: magnetic actuators, probabilistic design optimization, micro valve, tolerance analysis

Introduction

Design and optimization of magnetic actuators is a challenging matter because of the bidirectional cause-effect relations between electric and magnetic field, nonlinear magnetic material behavior, and the fact that often both the static and the dynamic behavior of the actuator have to be considered. Our study deals with the optimization of the static and the dynamic behavior of a bipolar magnetic actuator designed for a pneumatic microvalve. We performed the optimization with regard to the unavoidable scattering of the design parameters and material properties, the so-called tolerances. Background is an LTCC pressure sensor the microvalves are used for. Important requirements set on the actuator are predefined power-off holding forces at the upper and the lower end position, minimum overall size dimensions, and minimum power consumption because of the battery based power supply of the application. Also, a fast acting is desirable. This set of requirements suggests that a bipolar magnetic principle be applied for the actuator, where a permanent magnet and a coil work together.

Working Principle of the Actuator

Bipolar magnetic systems for actuators are based on different structures and working principles [1]. A minimum of the electric work for switching a bistable design is achieved when the magnetic flux the permanent magnet produces can commutate between a working and a shunt air gap [1, 2]. We concretized this working principle to a preliminary design that contains one fixed coil and one permanent magnet moving with the armature. It is shown in Figure 1. For moving the armature up or down the current is applied to the coil with alternating sign. Schematics of the magnetic field at both end positions are given in Figure 2.

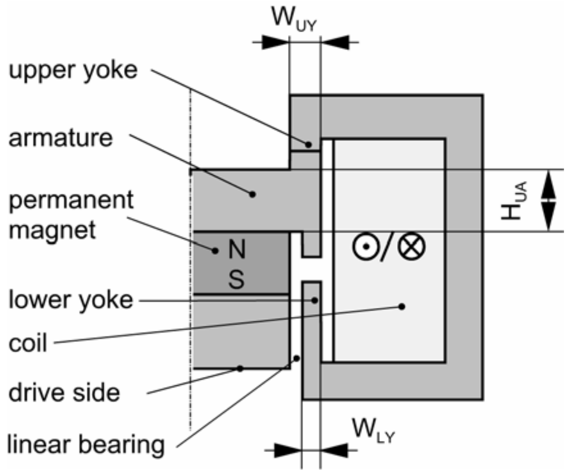

Fig. 1: *Preliminary design of the bipolar magnetic actuator, upper position of the armature*

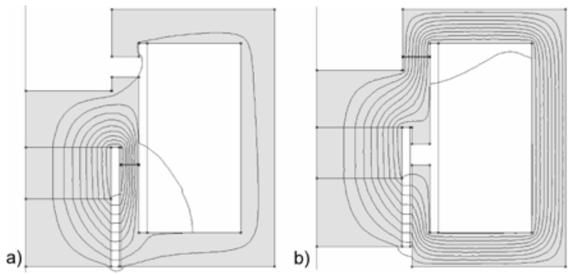

Fig. 2: *Static magnetic field in lower (a) and upper (b) position of the armature, FEA-model at power-off.*

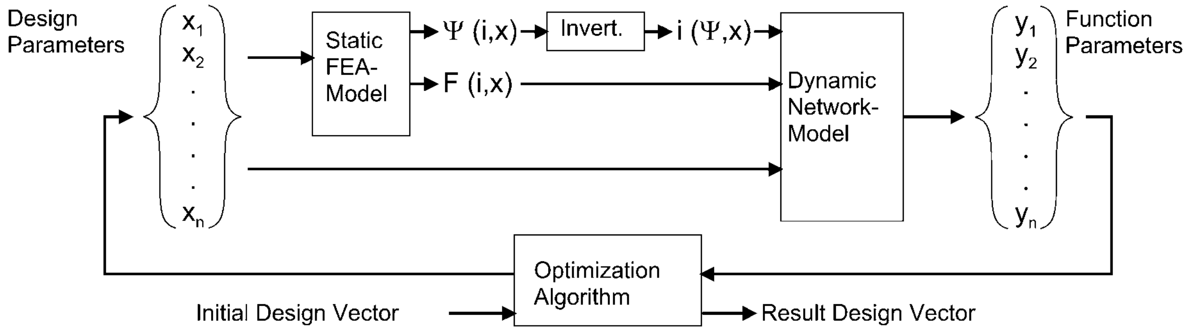

Fig. 3: *Data Flow for the Optimization of the Bipolar Magnetic Actuator.*

Modeling Approach

State of the art in simulation of the dynamic behavior of magnetic actuators are network models that include look-up tables computed from FEA models [3, 4]. This approach is more accurate than network models that use concentrated network elements in place of the look-up tables, especially if large air gaps or complex geometries have to be modeled. Because the look-up tables are valid only for the geometry they are computed for, no design optimization based on such a network model can be performed. Further, FEA models have been published that include the ordinary differential equation of the motion of the armature for simulating the dynamic behavior without previous computation of static look-up tables, e.g. with moving meshes [5]. This allows the eddy currents to be included in the simulation. However, this approach restricts itself to simple geometries because the description of the mesh movement is required, and with respect for the computing time.

To carry out design optimization we improved the first of these two modeling approaches. To this end we computed the look-up tables on each iteration step of the optimization. This allows the design to be changed and to be optimized with regard to the static and the dynamic behavior. For building up the network and the FEA models we used *SimulationX* and *FEMM* [6, 7]. For arranging the data flow we used the *OptiY* tool as we did before in other optimization problems with network or FEA models alone [8, 9, 10]. Further, we involved a Matlab routine for reversing one of the look-up tables computed from the FEA model [11]. Figure 3 gives a schematic of the data flow controlled by *OptiY*.

The design optimization comprises three steps. In the first design optimization step we used the models for finding an optimized design meeting our requirements. In the second step, we made a tolerance analysis, that calculates the probability distributions of functional variables from the probability distributions of the design parameters. This enables the probability of a system failure to be deduced. In the final step, a design of the actuator was calculated that minimizes the system failure propability.

Nominal Optimization

The first step is a nominal optimization for finding a fast acting system that fulfill our static and dynamic requirements, inclusive of supply voltage. Therefore, three design parameters are set as input variables for the optimization process (Figure 1):

- Width W_{UY} of the upper yoke,
- Width W_{LY} the lower yoke,
- Heigth H_{UA} of the upper armature.

Initial point of the optimization is the preliminary design of the bipolar magnetic system that determines the working principle of the magnetic actuator. After about 175 runs of the models inside of the Hooke-Jeeves-algorithm the optimization converges. This is shown for the iterative development of the input variables in Figure 4, and the static forces at the end positions and the switching times in Figure 5.

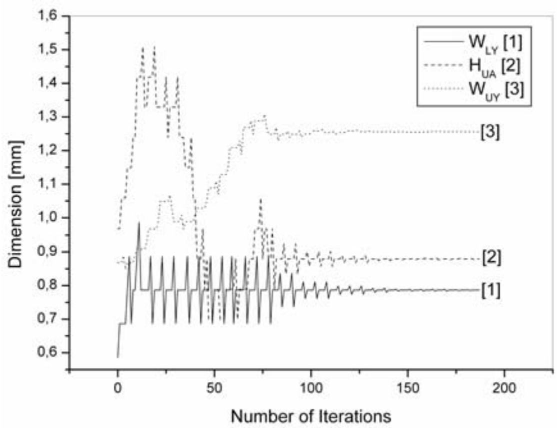

Fig. 4: *Optimization input variables W_{UY}, H_{FL} and W_{LY} over the number of iteration steps.*

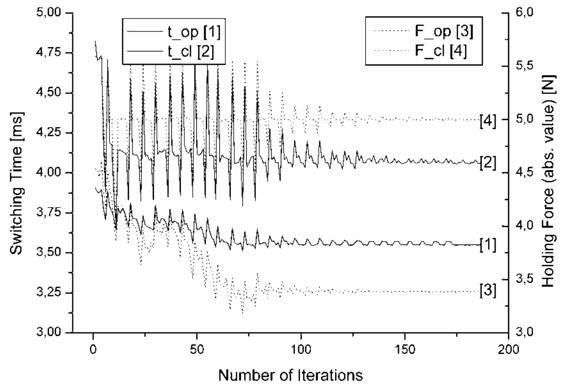

Fig. 5: *Static forces at both end positions F_{op}, F_{cl} and switching times for opening t_{op} and closing t_{cl} over the number of iteration steps.*

As a result we get the set of design parameters that fulfill the restrictions and functional demands at optimum, given in Table 1.

Tolerance Simulation

The second step is a tolerance simulation at the optimum design point found in the nominal optimization. By way of example, the effects of the tolerances of the width of the yokes W_{UY} and W_{LY} and of the supply voltage on the actuator's behavior are calculated. The tolerances are input in the form of distribution functions with any user-defined form allowed. Here we assumed normally distributed tolerances with a range (6σ) of 0.1mm for W_{UY} and W_{LY}, and 0.25V for the voltage. Computing the distributions of the system output variables applies an approximation through second order analysis. Compared with Monte Carlo methods, this is substantially faster. The constraint boundary violations of the output variables due to tolerances are shown in Figure 6. The ratio of inoperable solutions to all scattering solutions is called failure probability. For the design found by the nominal optimization the failure probability is about 50% because the optimum is located on a boundary of the interval allowed for the lower holding force F_{cl}.

Pareto charts allow to see the importance of the design tolerances included in the calculations of the functional parameters and how the tolerances interact. Figure 7 gives the charts for the influence of the tolerances on F_{cl} and t_{cl} as an example. If the total effect of one influence almost completely originates from its main effect the terms resulting from the pairwise combination of the tolerances in the second order analysis can be neglected. Therefore, a reduced second order analysis with a solely linear dependence of the computational effort on the number of the variables is sufficient for further calculations.

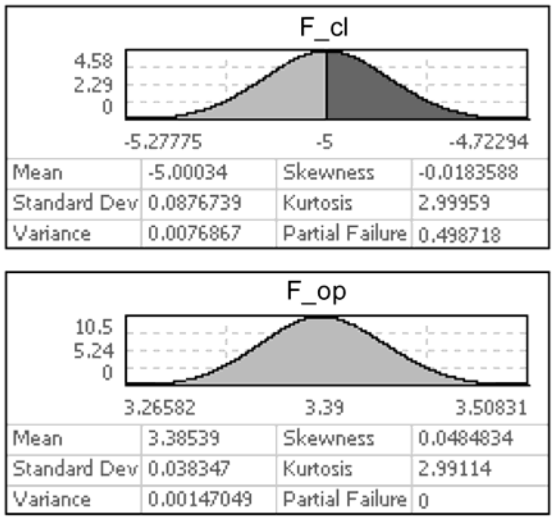

Fig. 6: *Distributions of the static forces F_{cl}, F_{op} due to tolerances. A dark area stands for a behavior outside the acceptable range.*

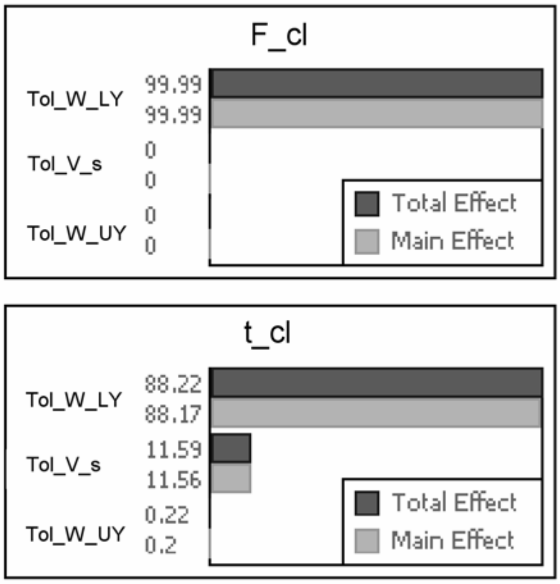

Fig. 7: *Pareto charts of the influence of the tolerances of W_{UY} and W_{LY} on the force F_{cl} and the switching times t_{cl}.*

Robust Design Optimization

In the third step, we minimized the scattering of the functional variables as well as the failure probability of the design. To this end an optimization is performed that includes computing the distributions of the functional parameters on each iteration step. The principle is shown in Figure 8. As a result we obtained a design optimized for a set of functional requirements and design tolerances (s. Table 1) with a negligible failure probability as shown in Figure 9.

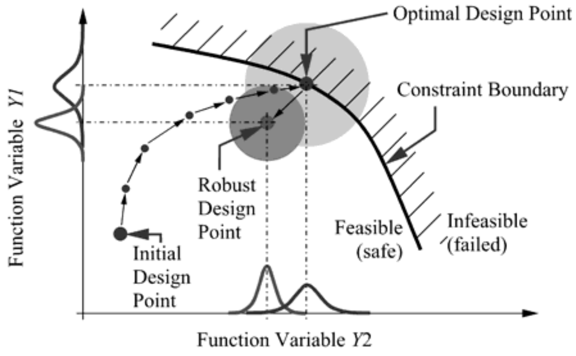

Fig. 8: Principle of robust optimization.

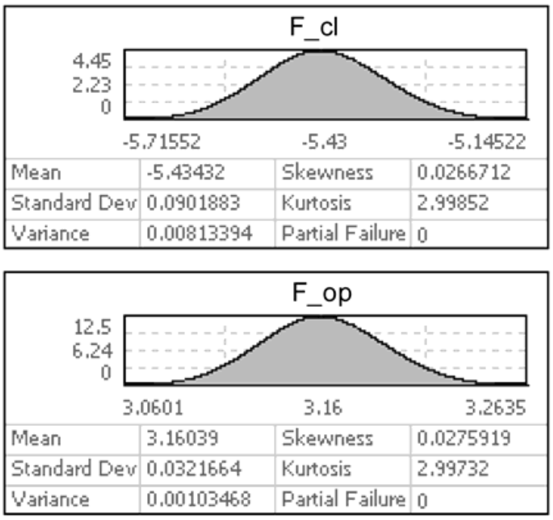

Fig. 9: *Distributions of the static forces F_{cl}, F_{op} after robust optimization.*

***Tab. 1**. System Behavior of the bipolar magnetic actuator at different design stages*

	Constr.	Initial Value	Optim. Value	Robust Value
F_{op}	[2N;5N]	4.7N	3.4N	3.2N
F_{cl}	[-10N;-5N]	-5.6N	-5.0N	-5.4N
t_{op}	Find Min.	4.1ms	3.6ms	3.5ms
t_{cl}	Find Min.	4.9ms	4.0ms	4.3ms

Conclusions

By means of a bistable, bipolar magnetic actuator of a micro valve it was exemplarily shown that algorithmic design optimization can be performed based on a dynamic network model that includes look-up tables computed from a static FEA model. The look-up tables were computed on each iteration step of the optimization according to the change in the design. The static holding forces were introduced as constraints, the switching times as optimization criteria to be minimized into the optimization process. Starting from a preliminary design we obtained an optimum design for a defined set of requirements. The optimization algorithm can also handle design variables that are given in form of distribution functions. That makes possible to find the robust optimum with regard to the tolerances of the design parameters as well as the nominal optimum. Not only the switching time, but also other dynamic properties of the actuator can be included in the optimization as constraints or criteria, such as the velocity of the armature at certain points of the work stroke. However, in further models the eddy currents should have to be involved for more accurate results. Low effort is needed to merge the different simulation systems inside of the optimization tool. All computations were done on a quad core PC running windows.

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