Probabilistic Optimization of Polarized Magnetic Actuators by Coupling of Network and Finite Element Models

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Outline

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- **Probabilistic Simulation and Optimization**
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Objective

- Designing a bistable magnetic actuator for a pneumatic microvalve of an integrated pressure sensor in LTCC Multi Layer Technology
- Finding a fast acting bipolar magnetic system that features pre-defined holding forces by algorithmic design optimization
- Including the effects of geometrical and material properties tolerances on the system behavior into optimization
- Computing the distributions of the system function variables

Pressure sensor in LTCC Technology without valves, Fraunhofer IKTS, ADZ Nagano GmbH 2007
Concept of Probabilistic Design

**Design Optimization with Regard to the Tolerances**

- **Distributed input parameters:**
  - Dimensional tolerances
  - Scattering of material properties
  - Shifting of ambient conditions
  - Wear and tear
  - Human influence

- **Simulation model:**
  - Analytic model
  - Lumped element model
  - FE-model

- Calculation of distributed output parameters (function)
Concept of Probabilistic Design

**Computation of Output Distributions**

- Monte Carlo sampling
  - Random sample
  - Bad convergence properties
  - Exponential increase of the computational effort with the number of DOF's
  - Weak demands on the model

- Moment Method (implemented in OptiY)
  - Analytical approximation for the distribution functions by second order analysis
  - Good convergence properties
  - Quadratic increase of the computational effort with the number of DOF's
  - Deterministic model required
Polarized Magnetic Actuators

**Working Principle**

- **Components:**
  - Armature with permanent magnet
  - Linear bearing
  - Air-core coil
  - Upper and lower yoke
  - Back iron

- **Function:**
  - Bistable in both end positions
  - Controlled by +/- current pulses
Polarized Magnetic Actuators

Modeling approach

- Simulation of the dynamic behavior by a network model that includes look-up tables of magnetic flux linkage $i(\Psi, x)$ and magnetic force $F_m(i, x)$
- Computation of the look-up tables by a FEA model
- Arrange the network model for design optimization and probabilistic simulation (OptiY)

\[ u = i R + \Psi(i, x) \]

Kirchhoff’s voltage law

\[ m \ddot{x} = F_m(i, x) \]

Equation of motion
Polarized Magnetic Actuators

**Finite Element Analysis Model**

- Magnetostatic axi-symmetric 2D model
- Magnetic vector potential approach
- Implemented in FEMM 4.2
- Computation of look-up tables of flux linkage $\Psi(i,x)$ and magnetic force $F_m(i,x)$
- Reversing the flux linkage look-up table $\Psi(i,x) \rightarrow i(\Psi,x)$ by a Matlab routine
Polarized Magnetic Actuators

Model Coupling for Probabilistic Simulation and Optimization

- Arranging the data flow by the OptiY 3.0 tool
- Computation of the look-up tables on each iteration step of the optimization
- Allows the design to be changed and to be optimized
- Starting with a preliminary design (analytic approach, network model)
Probabilistic Simulation and Optimization

Steps in Tolerance Analysis and Optimization

- Nominal Optimization → Set of design parameters for an optimal function
- Sensitivity Analysis → Importance of the tolerances to the function
- Design for Minimal Rejections → Set of design parameters for an optimal function with regard to the tolerances
Probabilistic Simulation and Optimization

**Nominal Optimization**

- **Input Parameters for optimization:**
  - Width of the upper yoke $W_{UY}$
  - Width of the lower yoke $W_{LY}$
  - Height of the armature $H_{UA}$

- **Output Parameters for Optimization:**
  - Upper holding force $F_{op}$  → constrained [2 N; 5 N]
  - Lower holding force $F_{cl}$  → constrained [-10 N; -5 N]
  - Switching time for opening $t_{op}$  → find minimum
  - Switching time for closing $t_{cl}$  → find minimum
Probabilistic Simulation and Optimization

Nominal Optimization

- Design variables iteration process
- Function variables iteration process
Probabilistic Simulation and Optimization

System Failure Analysis

- Design variables tolerances:
  - $W_{LY}$, $W_{UY}$ +/- 0.1mm ($6\sigma$)
  - Voltage +/- 0.25V ($6\sigma$)
  - Normally distributed

- Function variables distributions:

![Graph showing distributions](image)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Skewness</th>
<th>Kurtosis</th>
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</thead>
<tbody>
<tr>
<td>$F_{cl}$</td>
<td>-5.00034</td>
<td>-0.0183586</td>
<td>2.99959</td>
</tr>
<tr>
<td>$F_{op}$</td>
<td>3.38539</td>
<td>0.0484834</td>
<td>2.99114</td>
</tr>
</tbody>
</table>

- Normally distributed

$W_{LY}$, $W_{UY}$
Probabilistic Simulation and Optimization

System Failure Analysis

- Pareto Charts:
Probabilistic Simulation and Optimization

**Design for Minimum Rejections**

![Diagram of probabilistic simulation and optimization with function variables Y1 and Y2, showing optimal design point, feasible (safe) region, and infeasible (failed) region, with constraint boundary and initial design point.]
Probabilistic Simulation and Optimization

**Probabilistic Design**

- Minimizing the failure probability and the scattering of the function
- Optimization includes computing the distributions of the functional parameters on each iteration step
- Result is a design optimized for a set of functional requirements and design tolerances with a negligible failure probability

<table>
<thead>
<tr>
<th>Constr.</th>
<th>Initial Value</th>
<th>Optim. Value</th>
<th>Robust Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{op}$</td>
<td>$[2N;5N]$</td>
<td>4.7N</td>
<td>3.4N</td>
</tr>
<tr>
<td>$F_{cl}$</td>
<td>$[-10N;-5N]$</td>
<td>-5.6N</td>
<td>-5.0N</td>
</tr>
<tr>
<td>$t_{op}$</td>
<td>Find Min.</td>
<td>4.1ms</td>
<td>3.6ms</td>
</tr>
<tr>
<td>$t_{cl}$</td>
<td>Find Min.</td>
<td>4.9ms</td>
<td>4.0ms</td>
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</table>
Conclusions

- By means of a bipolar magnetic actuator of a micro valve it was 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.
- The optimization algorithm can also handle design variables that are given in form of distribution functions, e.g. for finding a robust optimum.
- Also other dynamic properties can be included in the optimization, e.g. the velocity of the armature at certain points of the working stroke.
- In further models the eddy currents should have to be involved for more accurate results.
- The effort to merge the different simulation systems inside of the optimization tool OptiY is low.
- All computations were done on a quad core PC running windows.