Robust Design Optimization of Electromagnetic Actuator Systems Using Heterogeneous Models

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Outline

1. Introduction
2. System Models
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1. Introduction

**Electromagnetic Actuators**

- Fast actuation, medium forces and strokes
- High energy density
- Design varies in a very wide range
Electromagnetic Actuator Systems

- Reluctances forces
- Electrodynamical forces
- Solid state actuators
2. Models

**Electrical Circuit**
- Kirchhoffian network models
- Network equations, element relations

**Electromagnetic transducer**
- Maxwell’s and material equations
- Generalized Kirchhoffian network models
- Static (and dynamic) finite-element-models

**Gear and load**
- Kinematic and dynamic models, rigid body mechanics
- Equation of motion, element relations
System model characteristics of electromagnetic actuators

- **Multiphysics models** including electrical, magnetic, mechanical, thermal and other domains
- **Non-linear effects** in all subsystems, e.g. electronic components behavior, magnetic hysteresis, mechanical material behavior
- **Time-dependent models** with rather different time constants of the subsystems, e.g. of the electrical and thermal
- **Heterogeneous system models** which couple subsystems from different simulation tools, e.g. network simulators and finite-element-solvers
3. Examples

- Electromechanical clock
- Tripping unit of a circuit breaker with a Magnetic Shape Memory alloy
- Electromagnetic Braille printer
Electromechanical clock
System Dynamics Model

- Rigid bodies with point-mass
- Elasticities, stoppers
- Friction, damping
- Implemented in *SimulationX*

Actuator System

- Lavet step motor
- Electrical control unit
- Six gears
- Manual correcting actuator with an additional gear
- Friction clutches
- Second hand, minute hand, short hand
Dynamic System Model

- Objective → Minimizing power consumption
Tripping unit of a circuit breaker with a MSM alloy

- Used to break overloads and short circuits in power grid systems
- Tripping unit with solenoid and thermostatic bimetal
- Solenoid works as a sensor and actuator as well

*Bindl et al. 2011*
Magnetic Shape Memory (MSM) alloy

- Innovative principle based on so-called magnetic shape memory alloys, e.g. NiMnGa alloy system
- External magnetic field controls the crystal orientation and shape
- Effect is reversible with a remarkable hysteresis

Stroke of a MSM alloy by moving twin boundaries under external magnetic fields

Bindl et al. 2011
MSM hysteresis behavior

Bindl et al. 2011
Tripping Unit Principle and Dynamic System Model

1 Electrical conductor
2 Iron core
3 MSM element
4 Latch mechanism

Bindl et al. 2011
**Design Optimization**

- Based on the system model
- Objective $\rightarrow$ Tripping time and overall volume to be minimized

![Graph showing displacement, flux density, and time](image)

*Initial solution – 34 mm high*

*Optimized design – 22 mm high*
Electromagnetic Braille Printer

- Based on a design with a minimum of elements
- Function:
  - A needle embosses paper sheets
  - Paper as a nonlinear elasto-plastic counterforce load
  - Dynamic forces of the masses
  - Nonlinear magnetic material behavior
Actuator System Design

- **First stage** bases on a rough analytical static model
  \[ A_{Cu}, A_{Fe}, N = f(F_{mag}, s_{max}, V_0, P_{Cu}, B_m) \]

- **Second stage** uses a dynamic network model
  - Kirchhoff’s network laws
  - Ampère’s circuitical law
  - Maxwell’s law of induction
  - Maxwell’s eq. for the magnetic force
  - ODE of motion
Actuator System Design

- *Third stage* applies a dynamic network model with characteristic diagrams of the magnetic force and the magnetic flux linkage computed from a static finite-element model.
Simulated dynamic behavior

- Embossing cycle
- Objective of the design optimization → cycle time to be minimized
Simplified network model

- Magnetic transducer as time dependent force depending on geometry parameters
- Implemented in *SimulationX 3.4*
- Starting point for testing the interface *OptiSlang – SimulationX*
4. Challenges for design optimization

- System simulations are time-consuming due to
  - Multiphysics models
  - Heterogeneous models (e.g. network and finite element)
  - Non-linear behavior
  - Dynamic simulations (time range)
- Design space dimensions in the range of 5 ... 100 typically
- Only small subspaces contain valid designs
- Constraint and objective functions often have a complicated shape