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F. Schiedeck / W. Littmann

Mechatronic Analogy: An Advanced Approach of Multi-domain Modeling Applied to Maglev Systems

Introduction

Magnetic levitation (maglev) systems like magnetic monorail trains consist of electric, magnetic, and mechanic subsystems. Those three physical domains in such mechatronic systems interact with each other by the meaning of energy transformation in both forward and backward direction. By applying state-of-the-art approaches for modeling of magnetic systems it is not possible to create a consistent model of the maglev system combining all subsystems. For this reason, a novel multi-domain modeling approach is required to derive an integrated equivalent circuit incorporating all three domains.

Reluctance as "magentic resistance"

Fig. 1 shows the equivalent circuit diagram of an electromagnetic transducer. The representation of reluctance as "magnetic resistance" in traditional modeling is a key problem. Generally, ohmic resistance correlates with a dissipative element. In fact, magnetic reluctance has the character of an energy storage [1] and should not be modeled as resistance.

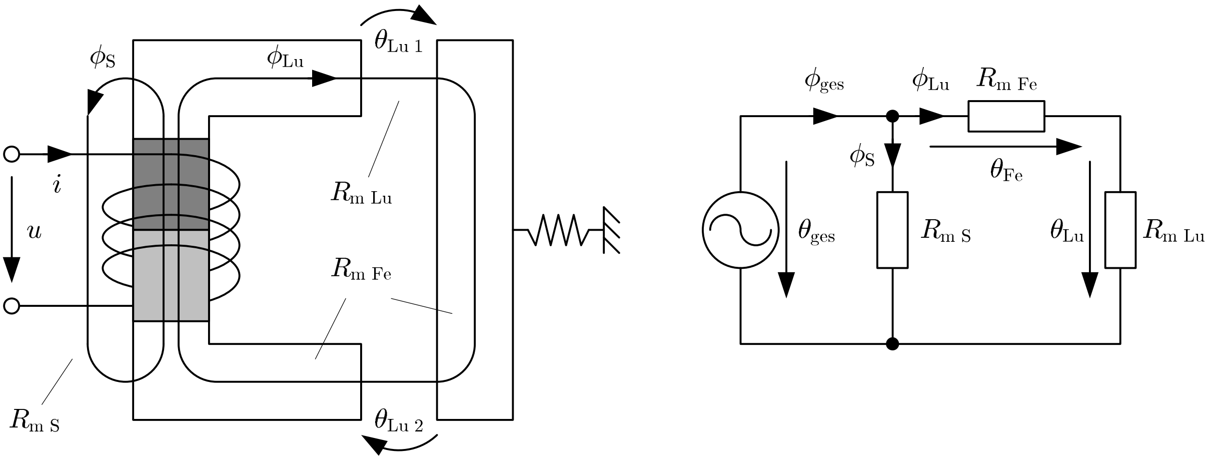

Fig. 1: Electromagnetic transducer and corresponding equivalent circuit diagram of the magnetic circuit with traditional representations [1,2]

Analogy of reluctance, spring, and capacitance

The energy stored in reluctance (not the dissipated power!) can be calculated by

$$W = R_{\mathrm{m}} \phi^2 \, .$$

This equation is comparable to the calculation of the energy in a capacitor or spring:

$$W = \frac{1}{C} Q^2 \text{ and } W = c x^2$$

Therefore, this contribution proposes an alternative analogy for magnetic reluctance which considers the reluctance as magnetic energy storage element, like capacitance or spring (Fig. 2). This approach provides a methodology to build lumped models integrating electric, magnetic, and mechanic constitutive laws in one single equivalent circuit model. According to the electromechanical analogy introduced by Lenk [2] for electromechanical systems this approach is called "mechatronic analogy".

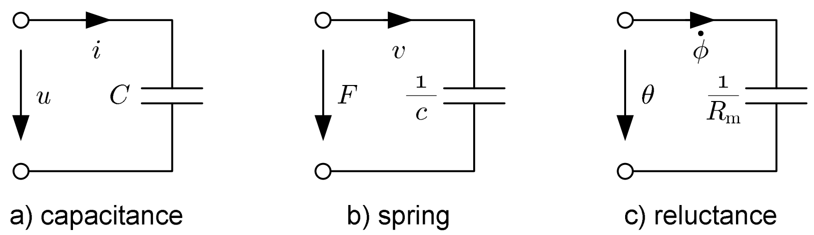

Fig. 2: Equivalent circuits using "mechatronic analogy"

Representation of equations by equivalent circuit diagrams

The spring-mass-system shown as mechanic equivalent diagram in fig. 3 is described by the differential equation

$$m\ddot{x} + cx = F \, .$$

The equation can also be represented by an electric equivalent diagram, interpreting the equation as a sum of currents (1. Kirchhoff's law) or voltages (2. Kirchhoff's law). In the former case the analogies force-current and velocity-voltage are used, in the latter case force-voltage and velocity-current. Hence, both circuits are equivalent and transferable into each other by changing from series to parallel connection and vice versa.

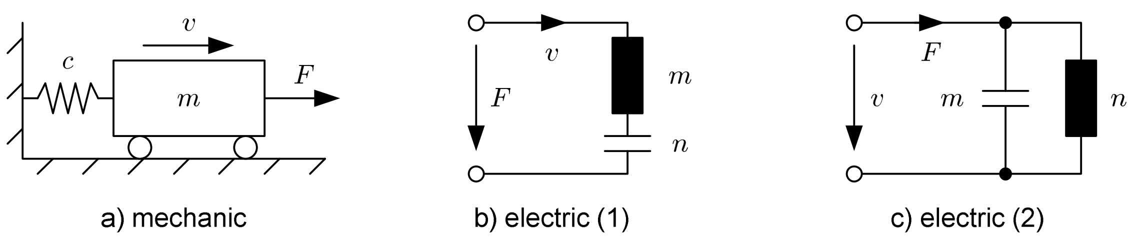

Fig. 3: Mechanic and electric equivalent diagrams of a spring-mass-system

Modelling of magnetic levitation systems

The practicability of the “mechatronic analogy” is exemplarily shown by applying this approach on vertical dynamics of magnetically levitated systems (Fig. 2). Fig. 3 shows the modeling of the equivalent circuit diagram starting with the combination of the electric, magnetic, and mechanic circuit and using the following transfer matrices for the linearized electromagnetic and magnetomechanical transformation [2]:

$$\begin{bmatrix} i \\ u \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{w} \\ \frac{1}{w} & 0 \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{1}{w} & 0 \\ 0 & \frac{1}{w} \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\phi} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \dot{\phi} - \dot{\phi}_{\mathrm{L}} \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{l_0}{B_0 A} & 0 \\ 0 & \frac{l_0}{B_0 A} \end{bmatrix} \begin{bmatrix} v \\ F \end{bmatrix}$$

Even leaking flux can be taken into account. Gravity is modeled by a prestressed weak spring with an elasticity $n = 1/c$. After that, the circuit is transformed in a way to obtain a circuit with two ideal transformers. The model can be easily adapted to similar maglev systems like magnetic bearings or trains.

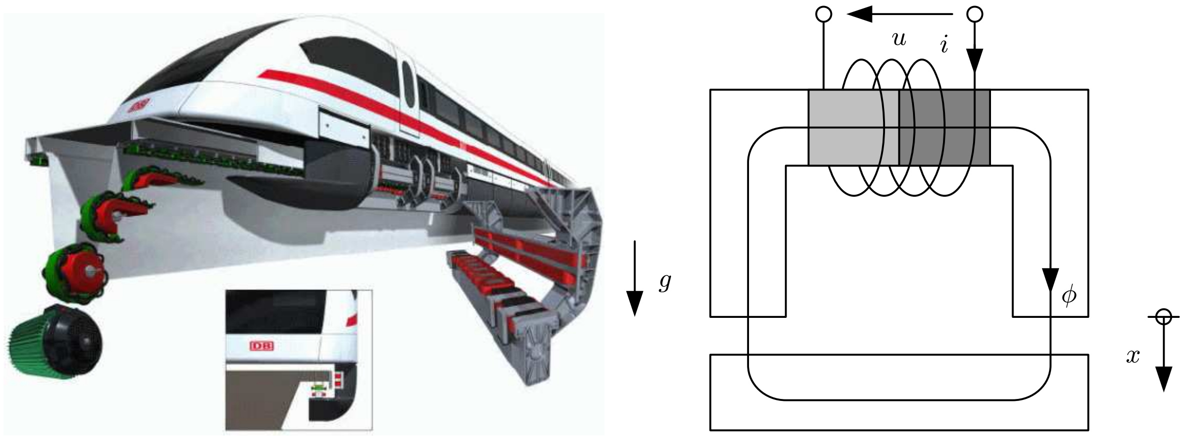

Fig. 2: Magnetic levitated train (www.tri.de) as a sample for maglev systems

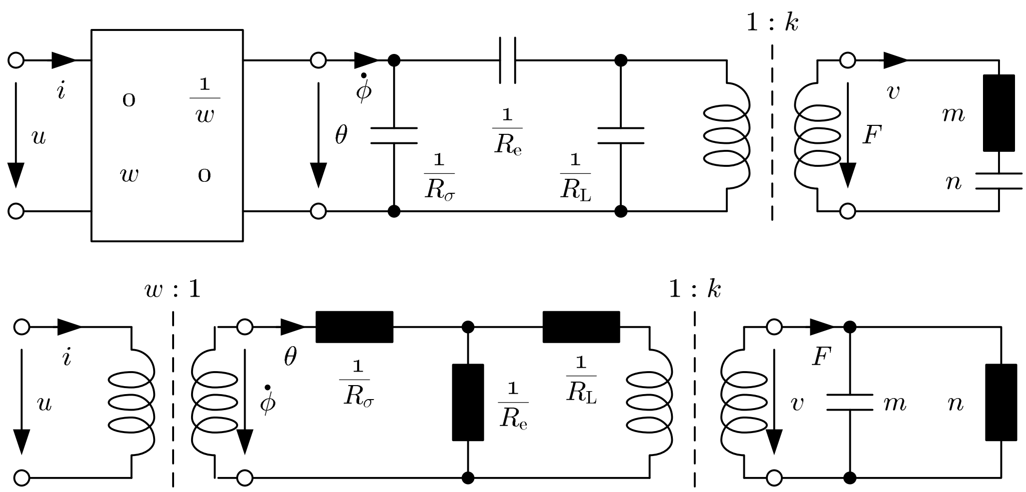

Fig. 3: Mechatronic equivalent circuit of a maglev system

Conclusion and Remark

Based on energy considerations, representation of reluctance as capacitance is proposed. Starting from analogies between electric, magnetic, and mechanic state variables, universal representations of the parameters of all three domains can be defined for equivalent circuits. Using these representations, an integrated description of electromagnetic (e.g. transformators) and electromagnetomechanical systems (e.g. magnetic bearings) is possible. Electromagnetic and magnetomechanical interactions can be represented by ideal transformers. The derivation of the mechatronic analogy is described in detail by the authors in [3].

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[1] Kallenbach, E. et al.: Elektromagnete. 2., überarb. und erg. Aufl. Wiesbaden : B. G. Teubner Verlag, 2003
[2] Lenk, A.: Elektromechanische Systeme. Bd. 1: Systeme mit konzentrierten Parametern. Berlin : Verlag Technik, 1971
[3] Littmann, W.; Schiedeck, F.: Neue mechatronische Analogien in der Magnetik zur Modellierung elektromatgnetomechanischer Systeme. In: Forschung im Ingenieurwesen (Vol. 72, No. 2), June 2008

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