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**NONLINEAR ANALYSIS OF ELECTROMAGNETS CONTAINING PERMANENT
MAGNETS**

PHD DISSERTATION
THESIS BOOKLET

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Miskolc
2026

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1. INTRODUCTION

The electromagnet is a widely used electrical device, the basics of which were discovered by Faraday in 1831. He moved a permanent magnet near an electric conductor and, using a galvanometer, observed that an electric current appeared in the conductor, but when the magnet stopped moving, the current ceased. This phenomenon is called electromagnetic induction.

Over the past 200 years, there has been a great deal of technical progress, because of which electromagnets have been widely used in engineering applications. Including relays and magnetic switches, automotive starters, hydraulic and pneumatic valves, and safety systems, such as door and magnetic locks or emergency stop mechanisms.

Electromagnets occur in both alternating current and direct current systems. The term coil refers to an air-core version, while it is called a solenoid if it also contains an iron core. The iron core in the retractor is capable of movement, therefore it is also used as an actuator in electromechanical systems. In one application area of retractors, the iron core can be locked mechanically (with a spring) or by using a permanent magnet. The latter is called a “latching solenoid” in international literature and catalogs.

A fundamental requirement in engineering work is that during the design of a mechatronic system, simulation programs are available that correctly simulate the operation of the solenoids intended for installation. There are several options for the modeling process, e.g., the application of analytical relationships found in technical books, the use of approximate numerical methods, such as the Finite Element Method (FEM), the Finite Volume Method (FVM), and the Boundary Element Method (BEM). Energy-based methods are also available for describing concentrated parameter electromechanical systems.

The dissertation aims to model a latching solenoid containing a permanent magnet, the use of which has increased in energy-efficient solutions since the 2000s. Modeling such solenoids is challenging because it not only ensures the locking of the iron core, but also affects the dynamics of the system, the saturation of the iron core and thus the nonlinear behavior of the solenoid. The energy-based approach is advantageous for modeling lumped-parameter mechatronic systems, as it treats both electrical and mechanical phenomena in a unified way. Its theory is based on the extended Hamilton principle and the Lagrange equations of the second kind derived from it. The modeling of a solenoid containing a permanent magnet can be implemented using purely theoretical methods or measurement-based methods. The method used in this dissertation is fundamentally based on static force measurements and dynamic tests. The former is necessary for generating the complex magnetic co-energy of the solenoid, while

the latter is necessary for generating the permanent magnet flux and damping factor that determines the motion induction characteristic of the dynamic behavior. After establishing a system of requirements for performing the measurements, it is essential to develop a modular, unique measuring device that is suitable for performing different types of tests. Measurements are necessary not only for model creation, but also for validating the simulation results.

During the literature review, [1] – [59] publications were processed. Regarding the energy-based approach, textbooks and scientific articles were grouped based on the methods used. There are those that use analytical descriptions during model creation and perform calculations based on known physical relationships and formulae. The second group includes distributed parameter model creation, which mostly uses finite element software. The concentrated parameter description method was less typical, but solutions can also be found in this area. During the literature review, special emphasis was placed on modeling electromechanical systems that also include permanent magnets, thus reducing the number of relevant results even further.

Among the reviewed publications, there were only two [13], [14] in which the DC latching solenoid had a permanent magnet. In these, finite element software (FEM) was used to investigate how the placement of the permanent magnet affects the magnitude of the pulling force acting on the iron core. One of their designs was similar to the RS177-0138 type latching solenoid examined in the dissertation (see Figure 1.1).

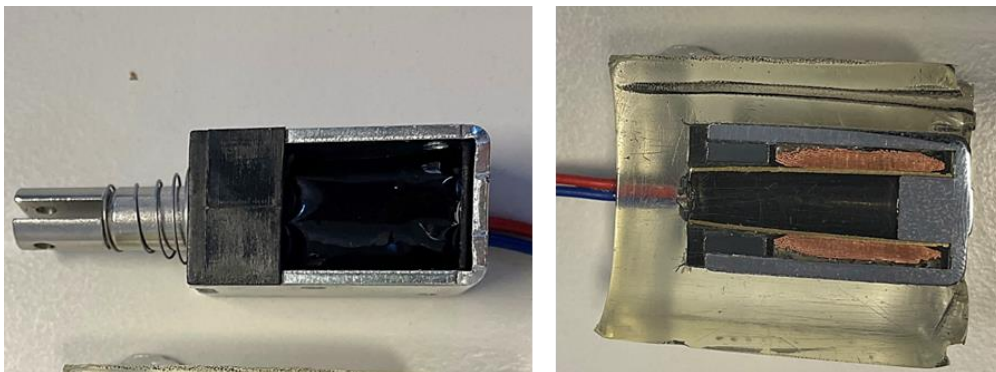


Figure 1.1. RS177-0138 type solenoid

After the literature review, the following most important conclusions can be made:

- research on solenoids has also yielded new results in recent years;
- the electrical equations of the electromechanical system are generated analytically based on the Faraday-Lenz laws, with field equations, with Kirchhoff laws for lumped parameter descriptions, and with an energy-based approach;

- the mechanical equations of the electromechanical system are derived from the momentum theorem and the Lagrange equation;
- both linear and nonlinear relationships occur with respect to the material laws;
- the examination of systems containing permanent magnets is mostly handled using finite element software.

Only one author has dealt with the modeling of the solenoid containing a permanent magnet to be examined in the dissertation using a theoretical approach to finite element static simulation.

The following points include the main goals of the doctoral research work, which serve as scientific results:

- energy-based modeling should be carried out, which produces the electrical and mechanical equations in a unified approach, which is used in the literature [3], [4], [16];
- the magnetic co-energy and the flux of the permanent magnet should be implemented based on force measurements as a function of the iron core position and the coil current;
- the modeling should be done with nonlinear constitutive equations;
- to determine the magnetic co-energy components of the complex system;
- to determine the flux of the permanent magnet as a function of the iron core position;
- to examine the effect of the permanent magnet on the coefficients of the electromechanical equations;
- to develop a modular system, which is suitable for performing static force measurements as a function of the iron core position and the coil current, and for simultaneous measurement of displacement and current during dynamic behavior;
- develop a simulation program to solve the electromechanical system of equations, the results of which can be compared with the measurement data.
- develop a parameter identification procedure for unknown damping and flux parameters arising during modeling.

2. SOLVING THE RESEARCH TASK

The modeling of electromagnets containing permanent magnets have been performed using an energy-based approach, where the magnetic co-energy, kinetic co-energy and potential energy were given an important role by using the extended Hamiltonian principle [4]. The Lagrange equations of the second kind were written with the charge q and displacement x variables.

Figure 2.1 a) shows the simplified electromechanical model, while part b) shows the magnetic co-energy components: the permanent magnet $W_{mp}^*(x)$ and the excited coil $W_{me}^*(x, \dot{q})$. On the saturation curve of the iron core, at zero coil current, a flux $\lambda_p(x)$ is valid due to the presence of the permanent magnet, which varies with the position of the iron core.

Figure 2.1 a) shows the electromagnet excited by a DC voltage source U_0 , a current \dot{q} is started in the coil with resistance R ohms, which acts on the iron core. The iron core is suspended by force $F_s(x)$ of a spring with nonlinear stiffness and internal damping r . Moreover x denotes the initial position of the iron core's base point, and x_h is the initial position, while m denotes its mass. The coil is bounded by a horseshoe-shaped curved plate, which reduces the scattering of the flux lines and allows the coil to be fixed at the application site, the permanent magnets are indicated by N, S poles.

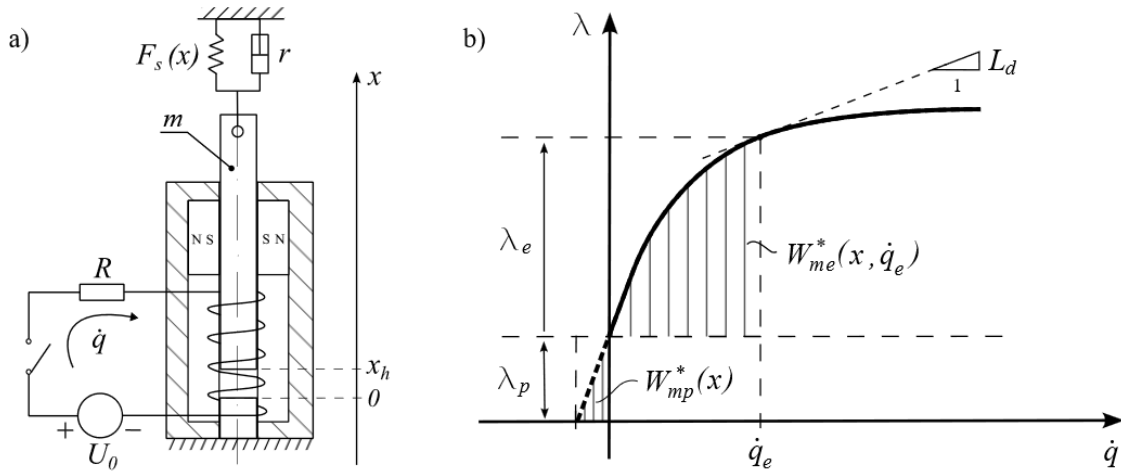


Figure 2.1. a) Electromechanical system, b) Magnetic co-energy

The magnetic co-energy of the latching solenoid can be interpreted as the sum of the two components as illustrated in Figure 2.1 b)

$$W_{m\Sigma}^*(x, \dot{q}) = W_{mp}^*(x) + W_{me}^*(x, \dot{q}). \quad (2.1)$$

According to [3], [4], the Lagrangian of the system contains in addition to the magnetic co-energy $W_{m\Sigma}^*(x, \dot{q})$, the kinetic co-energy of the iron core $T^*(\dot{x})$ and the potential energy $V_p^c(x)$

$$\mathcal{L} = T^*(\dot{x}) + W_{m\Sigma}^*(x, \dot{q}) - V_p^c(x), \quad (2.2)$$

where $V_p^c(x)$ contains the spring deformation energy, the iron core potential energy with the gravitational acceleration g and the penalty function valid at the time of impact.

According to [3], [4], the virtual work of the non-conservative elements of the system U_0 , R , r also contains the voltage $\lambda'_p(x)\dot{x}$ resulting from the motion induction and the counterforce $\lambda'_p(x)\dot{q}_{ind}$ occurring according to Lenz's law

$$\overline{\delta W}_{nc}^c = (U_0 - \lambda'_p(x)\dot{x} - R\dot{q})\delta q + (\lambda'_p(x)\dot{q}_{ind} - r\dot{x} + F_{cont}^d)\delta x, \quad (2.3)$$

where F_{cont}^d is the contact force assumed to be perfectly inelastic at the impact

$$F_{cont}^d = -m \frac{\dot{x}(t_n)}{\Delta t}, \quad (2.4)$$

Δt is the time step of the numerical integration, (2.4) is supplemented with a penalty term

$$F_{cont} = -\frac{m\dot{x}(t_n)}{\Delta t} - \alpha\bar{g}(x), \quad \text{ahol } x < 0 \text{ és } \dot{x}(t_n) < 0. \quad (2.5)$$

During motion induction, a gyrator principle applies [4], its power P is zero

$$P = F_{ind}\dot{x} - U_{ind}\dot{q}_{ind} = 0. \quad (2.6)$$

In the case where the circuit is open, only the permanent magnet provides magnetic flux, then the induced voltage can be written as the time derivative of the flux of the permanent magnet

$$U_{ind} = \frac{\lambda_p(x)}{dt} = \frac{\lambda_p(x)}{dx} \frac{dx}{dt} = \lambda'_p(x)\dot{x}. \quad (2.7)$$

Substituting the resulting expression into equation (2.6) and simplifying with the velocity, the counterforce F_{ind} acting on the iron core can be obtained

$$F_{ind} = \lambda'_p(x)\dot{q}_{ind}. \quad (2.8)$$

Substituting expressions (2.2) and (2.3) into the Lagrange equations based on [4]

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{q}} \right) - \frac{\partial \mathcal{L}}{\partial q} = U_0 - \lambda'_p(x)\dot{x} - R\dot{q}, \quad (2.9)$$

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{x}} \right) - \frac{\partial \mathcal{L}}{\partial x} = \lambda'_p(x)\dot{q}_{ind} - r\dot{x} + F_{cont}^d, \quad (2.10)$$

the differential equations (2.11) and (2.13) are obtained, which are complemented by equation (2.12) determining the induced current \dot{q}_{ind} resulting from the motion induction

$$\frac{\partial^2 W_{m\Sigma}^*(x, \dot{q})}{\partial \dot{q}^2} \frac{d\dot{q}}{dt} + \frac{\partial^2 W_{m\Sigma}^*(x, \dot{q})}{\partial x \partial \dot{q}} \frac{dx}{dt} + R\dot{q} = U_0 - \lambda'_p(x)\dot{x}, \quad (2.11)$$

$$\frac{\partial^2 W_{m\Sigma}^*(x, \dot{q})}{\partial \dot{q}^2} \frac{d\dot{q}_{ind}}{dt} + R\dot{q}_{ind} = -\lambda'_p(x)\dot{x}, \quad (2.12)$$

$$m\ddot{x} + r\dot{x} + F_s(x) = \frac{\partial W_{m\Sigma}^*(x, \dot{q})}{\partial x} + \lambda'_p(x)\dot{q}_{ind} - mg + F_{cont}. \quad (2.13)$$

3. MEASUREMENTS AND EXPERIMENTS

The magnetic co-energy $W_{m\Sigma}^*(x, \dot{q})$ in the system of differential equations (2.11) – (2.13), the flux $\lambda_p(x)$, and the spring force $F_s(x)$ can be determined by measurements and parameter identification.

The requirements for the measurement system are presented in detail in the dissertation. It enables three types of measurements: firstly, force measurements in static core positions, secondly, it measures displacement and induced voltage during drop tests, and finally, it can record current and iron core displacement during operation.

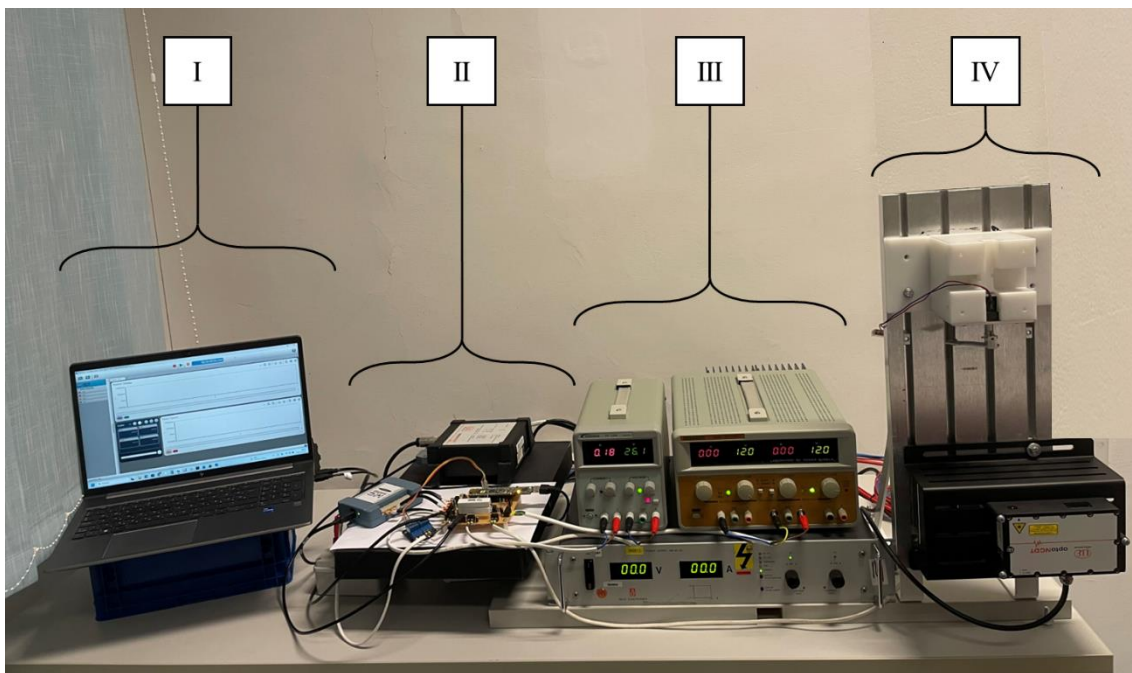


Figure 3.1. Measurement system

The general structure of the measuring device is shown in Figure 3.1, which contains four main parts. Unit I is a personal computer on which the voltage control can be programmed, the measurement data acquisition card can be configured, and the measured data series can be saved in .csv file format. Unit II is a special purpose circuit, which also contains a measurement data acquisition card. Unit III contains the laboratory power supplies that supply sensors, the operational amplifiers, and programmable voltage sources. Unit IV is the modular mechanical part of the device, the basis of which is a T-slot aluminum mounting plate, which is arranged vertically. The distance sensor, the part holding the pull-in coil and the positioning unit can be mounted on this plate, their arrangement varies depending on the type of measurement.

Figure 3.2 shows the structure of the mechanical unit designed and constructed for static force measurements. This allows the magnitude of the force acting on the iron core to be measured at fixed iron core positions and for different current strengths.

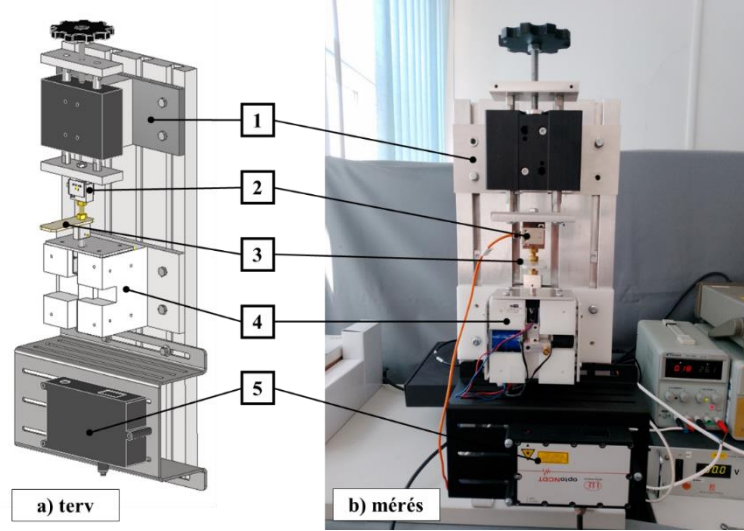


Figure 3.2. Structure of the mechanical unit for force measurements

Figure 3.3 a) shows the static F_z measured force values as a function of current and position if iron core, while part b) shows the force function F_{ex} approximated by interpolation.

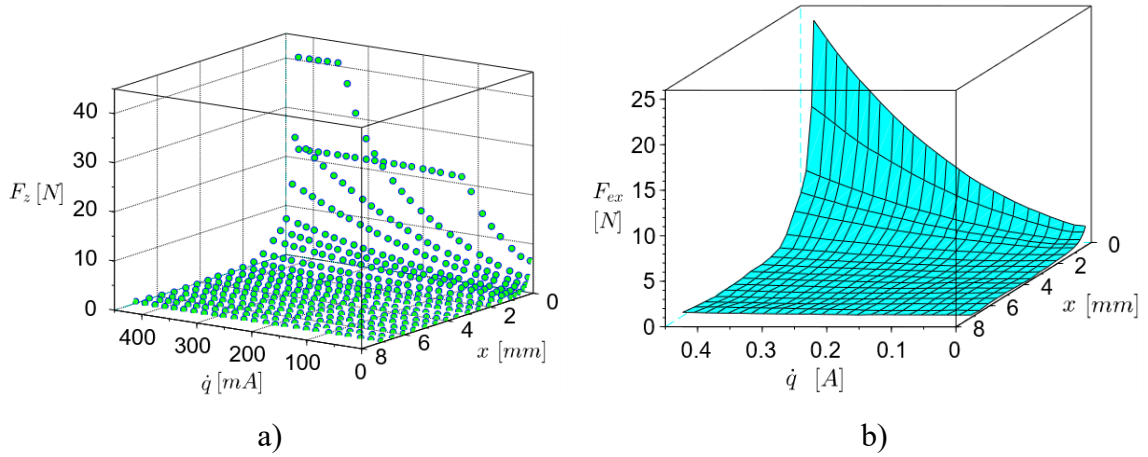


Figure 3.3. Static force values as a function of current strength and core position
a) measured, b) interpolated

Based on the force measurements, the components of the complex magnetic co-energy $W_{m\Sigma}^*(x, \dot{q})$ according to expression (2.1) can be obtained by integrating over location [18] as a function of the iron core position and the current

$$W_{mp}^*(x) = \int_x^{x_h} (F_{ex}(\xi, 0) - mg) d\xi, \quad (3.1)$$

$$W_{me}^*(x, I_s) = W_{me}^*(x_h, I_s) + \int_x^{x_h} F_e(\xi, I_s) d\xi, \quad (3.2)$$

where at location x_h with inductance L_h determined from the time constant of the current measurement curve based on [4]

$$W_{me}^*(x_h, I_s) = \frac{1}{2} L_h I_s^2, \quad (3.3)$$

along with the fixed current values $\dot{q} = I_s$ ($s = 1, \dots, M$), where M is the number of given current measurement points. Under the permissible operating conditions of the electromagnet ($\dot{q} < I_M$), the current values I_s need to be recorded at equidistant points, therefore that the magnetic co-energy can be determined over the entire range. The measurement of the force F_{ex} is done at discrete positions ($x_r = x_1, x_2, \dots, x_h$), therefore the integration in equation (3.2) can be performed numerically. On the resulting set of points ($x_r = x_1, x_2, \dots, x_h$) and $\dot{q} = I_s$ ($s = 1, \dots, M$), the magnetic co-energy $W_{me}^*(x_r, I_s)$ can be approximated by cubic spline interpolation, from which $W_{me}^*(x, \dot{q})$ becomes known at an arbitrary position and current value within the given range.

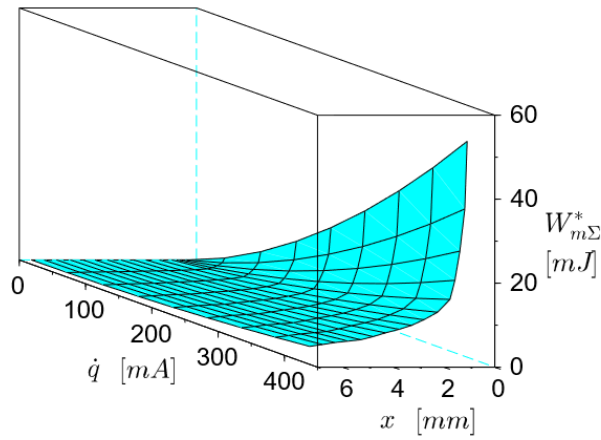


Figure 3.4. Function of magnetic co-energy

The complex magnetic co-energy $W_{m\Sigma}^*(x, \dot{q})$ is shown in Figure 3.4, the partial derivatives in equations (2.11) – (2.13) can also be determined. The second partial derivative with respect to the current on the left-hand side of equation (2.11) provides the dynamic inductance, which is illustrated in Figure 3.5.

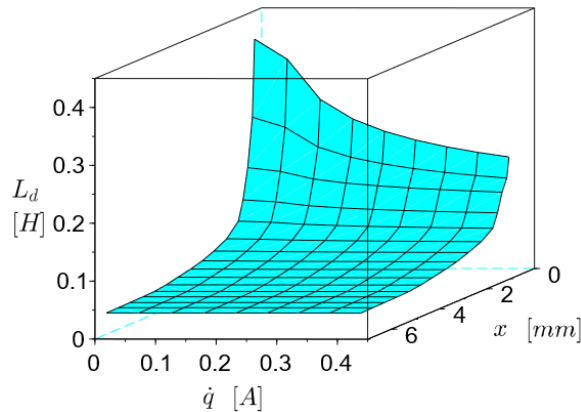


Figure 3.5. Dynamic inductance

The mixed partial derivative on the left side of equation (2.11) gives the coefficient of the electromotive force, the function of which is shown in Figure 3.6.

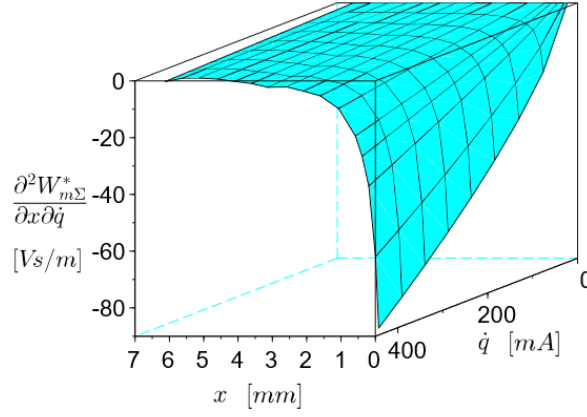


Figure 3.6. Coefficient of the electromotive force

The remaining terms of the system of differential equations (2.11) – (2.13) still need to be derived. The flux of the permanent magnet and the damping factor are determined by parameter identification from drop tests. The electromechanical model valid during the drop tests is shown in Figure 3.7.

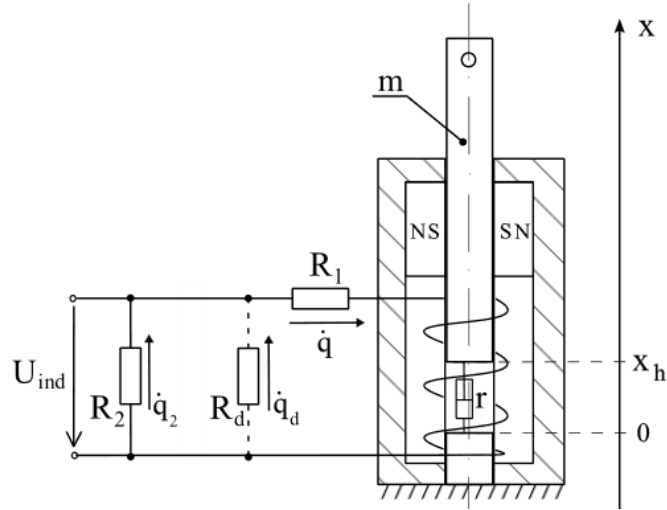


Figure 3.7. Electromechanical model of the drop tests

The resistance of the coil is denoted by R_1 , while the oscilloscope's $1 \text{ M}\Omega$ input resistance is denoted by R_2 . The R_d connected by a dashed line in the figure represents the latent resistance applied intuitively. In this case, the differential equations of the mathematical model are obtained as detailed in the dissertation

$$\frac{\partial^2 W_{m\Sigma}^*(x, \dot{q})}{\partial \dot{q}^2} \frac{d\dot{q}}{dt} + \frac{\partial^2 W_{m\Sigma}^*(x, \dot{q})}{\partial x \partial \dot{q}} \frac{dx}{dt} + (R_1 + R_d)\dot{q} = R_d \dot{q}_2 - \lambda'_p(x)\dot{x}, \quad (3.4)$$

$$m\ddot{x} + r\dot{x} = \frac{\partial W_{m\Sigma}^*(x, \dot{q})}{\partial x} + \lambda'_p(x)\dot{q} - mg, \quad (3.5)$$

$$0 = -R_2 \dot{q}_2 + R_d(\dot{q} - \dot{q}_2). \quad (3.6)$$

In the parameter identification, equations (3.4) – (3.6) are repeatedly solved according to the flow chart illustrated in Figure 3.8 to obtain the damping factor r and the parameter β , which is related to the flux of the permanent magnet, and based on [3]

$$F_p(x) = \beta \lambda_p^2(x). \quad (3.7)$$

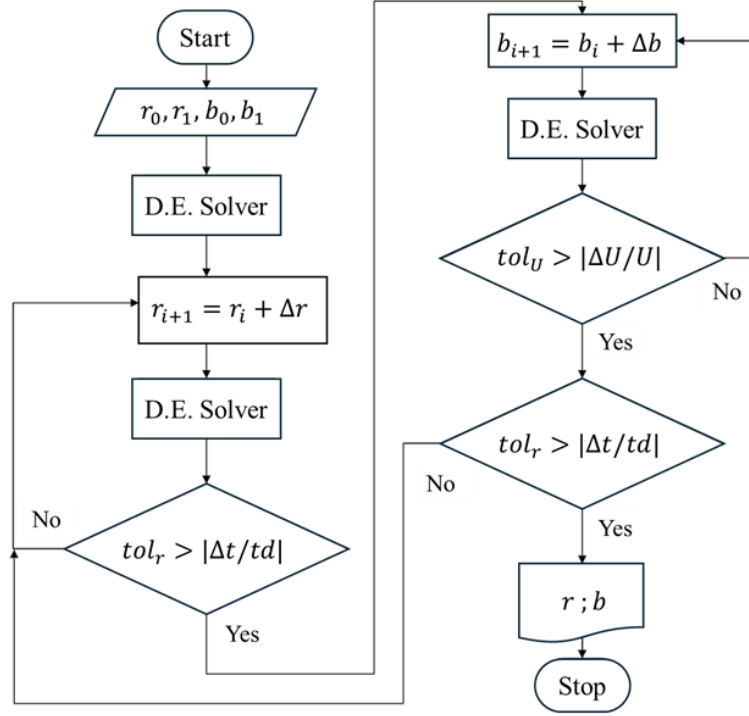


Figure 3.8. Flowchart of parameter identification

Before the iteration cycle, the impact time t_0, t_1 and the induced voltage U_0, U_1 must be determined for the value pairs (r_0, b_0) and (r_1, b_1) , where $r_0 = 0$, $b_0 = 0.005$ and $r_1 = 0.25$, $b_1 = b_0$. In Figure 3.8, the increments of the Δr damping and the Δb parameter are given as

$$\Delta r = r_i \frac{t_m - t_i}{t_i - t_0}, \quad (3.8)$$

$$\Delta b = b_i \frac{U_m - U_i}{U_i}, \quad (3.9)$$

where t_m and t_i are the measured and simulated impact times, respectively, and the relationship between the parameters b_i and β_i is

$$\beta_i = \frac{1}{b_i^2}. \quad (3.10)$$

The force function $F_p(x)$ of the permanent magnets obtained from the static force measurements and the flux $\lambda_p(x)$ determined by parameter identification are shown in Figure 3.9.

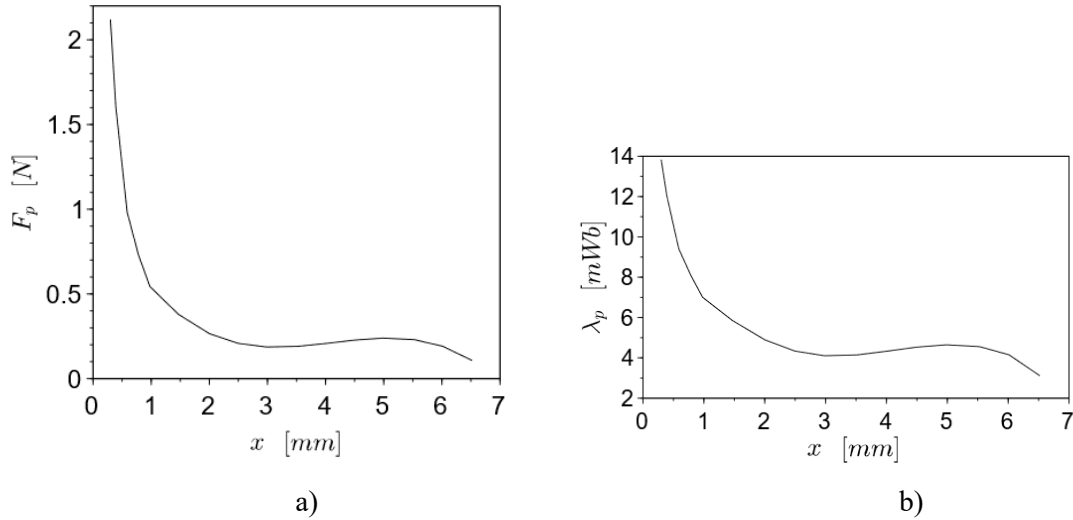


Figure 3.9. Permanent magnet a) pulling force and b) flux as a function of the position of the iron core

Once all the necessary coefficients and the spring force functions have been derived, the simulation and measurement of the operating behavior can be compared. It can be seen in Figure 3.10 that the simulation and measurement show good agreement for both quantities.

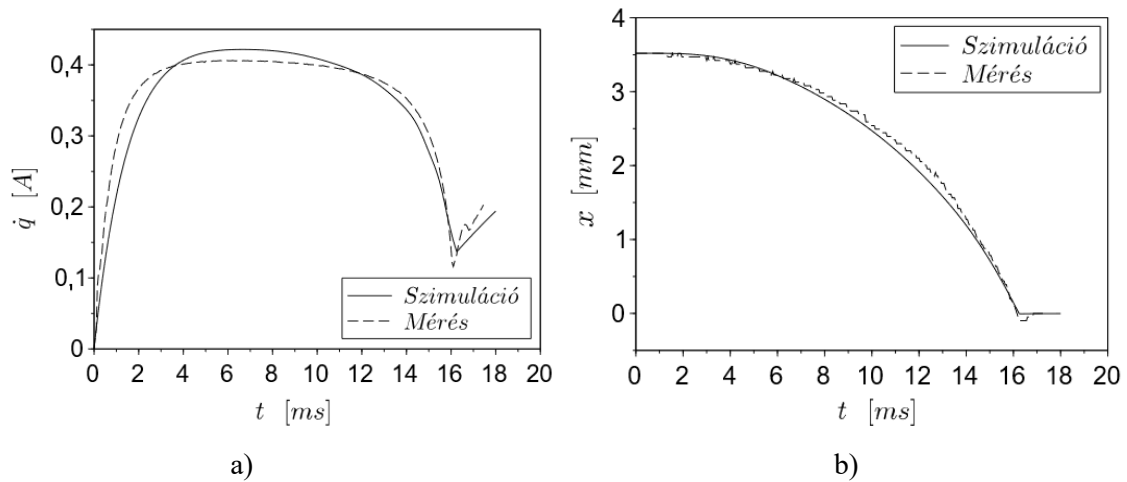


Figure 3.10. a) Current and b) Displacement curves of the simulation and measurement of the operation

The average errors, the root mean square of the current and position, respectively, can be determined using the following formulae

$$e_{RMS\dot{q}} = \sqrt{\frac{1}{T_{sim}} \int_0^{T_{sim}} (\dot{q}_{sim}(t) - \dot{q}_{meas}(t))^2 dt} = 0,024 \text{ A}, \quad (3.11)$$

$$e_{RMSx} = \sqrt{\frac{1}{T_{sim}} \int_0^{T_{sim}} (x_{sim}(t) - x_{meas}(t))^2 dt} = 0,084 \text{ mm}, \quad (3.12)$$

where \dot{q}_{sim} , x_{sim} and \dot{q}_{meas} , x_{meas} are the simulated and measured current and core displacement, respectively, and T_{sim} is the simulated operating time.

4. THESES – NEW SCIENTIFIC RESULTS

THESIS 1: It has been clarified the magnetic co-energy components appearing on diagram of nonlinear constitutive law of a solenoid which contains permanent magnets: the $W_{mp}^*(x)$ of the permanent magnets is ab ovo present, while the $W_{me}^*(x, \dot{q})$ is due to the excitation of the coil. Furthermore, a parameter identification method has been developed based on drop tests to determine parameter β , which relates the permanent magnetic force $F_p(x)$ and the flux $\lambda_p(x)$.

Related publications: [S3], [S4]

THESIS 2: The following statements apply to the coefficients in the equations of the mathematical model describing the operation of the permanent magnet-enhanced latching solenoid:

- a) The induced voltage from the movement of the iron core comes from the magnetic co-energy of the coil $W_{me}^*(x, \dot{q})$ and from the flux of the permanent magnet $\lambda_p(x)$. The latter one also produces an induced voltage when there is no external voltage source connected to the coil.
- b) The pulling force of latching solenoid comes from three sources: the force of the permanent magnets, the force of the excited coil, and, according to Lenz's law, the induced voltage generated by the iron core moving in the magnetic fields.
- c) The dynamic inductance $L_d(x, \dot{q})$, calculated from the second partial derivative of the magnetic co-energy of the coil $W_{me}^*(x, \dot{q})$ with respect to the current. The L_d is primarily affected by the technical parameters of the coils (number of turns, diameter, length, material of iron core, etc.), the permanent magnet enhances the nonlinear behavior. The inductance has a peak value in the retracted position of the iron core, when the coil current approaches zero. This statement is confirmed by the trends of time constants and inductances determined from the current curves measured in the retracted position of the iron core.

Related publications: [S3], [S4]

THESIS 3: The mathematical model of an electromechanical system of the latching solenoid with permanent magnets has been derived using energy-based approach based on Lagrange's equation of second kind. The mathematical model of the nonlinear system is described by three coupled partial differential equations, assuming that the impact of the iron core is perfectly inelastic.

Related publication: [S3]

THESIS 4: A method has been developed based on static force measurements to determine the magnetic co-energy $W_{m\Sigma}^*(x, \dot{q})$ of latching solenoid with permanent magnet. Firstly, the magnetic co-energy of the permanent magnet $W_{mp}^*(x)$ is determined by measuring the magnetic force acting on the iron core in discrete positions in the unexcited state of the coil performing numerical integration with respect to position. Secondly, the magnetic co-energy of the coil $W_{me}^*(x, \dot{q})$ is determined as a function of the position of the iron core and current by repeating numerical integration with the force measurements in excited states of the coil with given current values in discrete points. By fitting a bidirectional cubic interpolation spline function to the given set of points, the function value and its necessary partial derivatives are obtained at any point in the examined domain.

Related publications: [S3], [S5]

APPLICATION OF THESES AND POSSIBILITY FOR FURTHER DEVELOPMENT

The direct result of the research work is a simulation program that can examine the operation of a permanent magnet latching solenoid as an actuator in an embedded application already in the design phase. Furthermore, the method based on the theory presented here is suitable for the dynamic modeling of electromechanical systems containing permanent magnets.

The dissertation only tangentially deals with the consideration of the hysteresis phenomenon, for this a further developed device will be needed.

LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

- [S1] Kapitány P., Szabó T.: *Erőmérő cella illesztése a PSoC platformhoz*, Doctoral Students' Forum, 2022, Miskolc, pp. 54-58., 5p. (in Hungarian)
- [S2] Kapitány P.: *Mérőeszköz fejlesztése állandó mágneset tartalmazó elektromágnes vizsgálatához*, XXVI. Tavaszi Szél Conference, 2023, Collection of papers I., pp. 494-500., 7p. (in Hungarian)
- [S3] P. Kapitány, T. Szabó, L. Rónai: *Modelling of Latching Solenoid Including Permanent Magnets*, International Review of Applied Sciences and Engineering (IRASE), (accepted, in press), (**Q2, SJR: 0.261**)
- [S4] P. Kapitány, T. Szabó, L. Rónai: *Parameter Identification of Latching Solenoid Including Permanent Magnets*, 2025, Strojnický Casopis, Journal of Mechanical Engineering, Vol.75 No. 2, pp. 31-38., 8p., DOI: 10.2478/scjme-2025-0021, (**Q3, SJR: 0.351**)
- [S5] Kapitány P., Szabó T., Rónai L.: *Elektromágnesek modellezéséhez szükséges mérőberendezés fejlesztése*, 2025, GÉP Vol. 76, No. 3-4, pp. 63-66. 4p. DOI: 10.70750/GEP.2025.3-4.15, (in Hungarian)

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