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Analysis, physically motivated Modeling and System Identification of Electromagnetic Force Compensated Balances (EMFC)

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ABSTRACT

This contribution deals with the precise physically motivated modelling of an electromagnetic force compensated balance (EMFC) in preparation for a controller design process.

A precise knowledge of the subsystem's dynamic and static characteristics provides the possibility to obtain additional information from the measured physical quantities. Additionally, the system's reaction to different input signals was investigated. Besides the excitation at the voice coil of the EMFC balance, an experimental setup was designed that excites the system at the weighing pan. This enables the modelling of the interrelationship between the lever deflection and the force on the weighing pan. In typical application cases the force on the weighing pan is unknown and hence the knowledge of these characteristics is useful for measuring a mass within short periods of load. Based on these detailed investigations a two-beam model was designed, which is able to describe the balance's behavior. Despite the model's simplicity a good conformity with the measured behavior was achieved. For fast data acquisition a FPGA-based signal processing system was utilized to obtain a high sample frequency in combination with a synchronous measurement and excitation.

Index Terms – electromagnetic force compensated balance, modelling of a mechatronic system, system identification, real time hardware system

1. INTRODUCTION

Electromagnetic compensated weighing cells are common if high accuracy has to be achieved in weighing applications. In some applications there is an increasing demand for a good dynamic performance of the weighing cell. For example such applications are check weigher and balances in filling plants.

The working principle of an EMFC balance is shown in Figure 1: the force applied on the weighing pan causes a deflection of the transmission lever. This deflection is detected by a position sensor which provides the input signal for the controller. The current driven by the controller through the coil generates a Lorentz force in the electromagnetic actuator. In stable condition, where the deflection is zero, the Lorentz force compensates the applied force and hence the necessary current is proportional to the applied force.

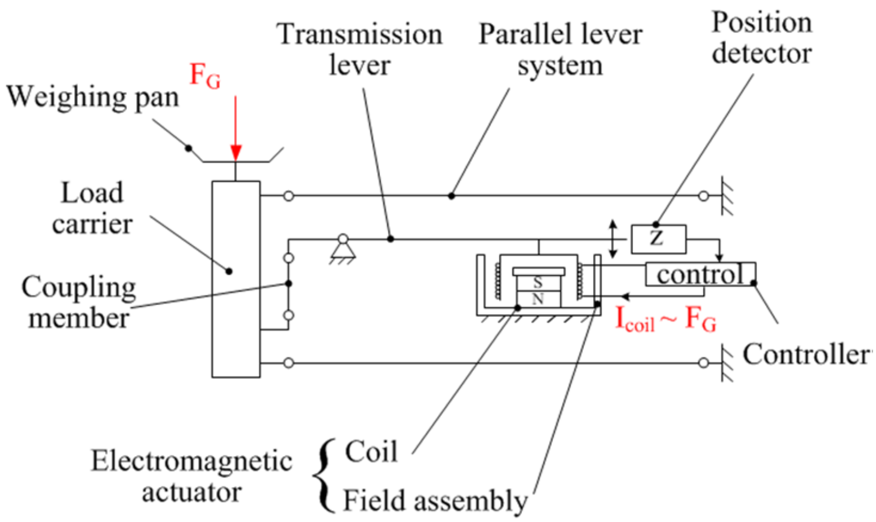

Figure 1: Scheme of an EMFC balance

2. EXPERIMENTAL SET-UP

2.1 Mechanical Setup

For a controller design process an accurate and broad knowledge of the system behavior is advantageous. The presented investigations were performed using a Sartorius standard OEM weighing cell of type WZA224 [7]. The balance's mechanical parts such as the parallel lever system, load carrier and transmission lever are built as a monolithic system out of aluminum. It includes also all joints shown in Figure 1 built up as flexure hinges. The actuator coil as well as the position sensor are attached at the end of the transmission lever and are surrounded by the field assembly of the actuator.

As shown in [1] a second voice coil actuator is used to excite the weighing cell at the weighing pan. For adjustment of the coil position the second coil is attached to a linear guide unit and the field assembly is applied on the weighing pan.

2.2 Sensor and Actuator System

The actuator coil and the position sensor are attached at the end of the transmission lever and are surrounded by the field assembly of the actuator. The field assembly provides a magnetic field permeating the coil of the actuator. The position sensor is built up out of a vent in the transmission lever, an infrared LED and a differential photodiode. The LED and the diode are attached to the base frame and are also surrounded by the field assembly. The light emitted by the LED partly passes the vent and causes photoelectric currents in the differential diode, which halves are operating in reverse bias. The currents are transformed into a voltage signal by a bridge circuitry and an instrumentation amplifier. The position signal equals zero, if the two diodes receive the same amount of light. This condition is fulfilled, if the vent of the transmission lever covers the middle of the differential diode. The described setup provides a measurement range of approximately 200 µm and a resolution of several nanometers.

In order to provide the compensation current with the needed precision a proprietary developed linear analog amplifier was utilized to provide the current for the voice coils with the needed precision (see section 2.3.1). The amplifier is built up as an analog current controller composed of a low-noise operational amplifier of Type LT1007 in combination with several power transistors. The current set point is provided by the signal processing system via a high-impedance voltage signal. The amplifier provides the actuator current in a range of ±100 mA and the dynamic behavior depends on the inductivity of the electromagnetic actuator. The performed investigations showed that the balance's actuator reveals proportional behavior up to 2 kHz. A second power electronic with similar characteristics is used to provide the actuator current for excitation on the weighing pan.

2.3 SIGNAL PROCESSING SYSTEM

The modular and scalable commercial off the shelf hardware platforms are often used for the development and deployment of control and measurement systems for industrial applications. These platforms are utilized to strongly reduce the recurring development time and effort. In addition, they reduce the risks and costs connected with adaption to changing requirements [2]. In this section the usage of a highly modular PXI-based platform is described for the prototype development of a signal processing system for the EMFC weighing cell. In order to realize a high-performance system, reconfigurable hardware like a FPGA (Field Programmable Gate Array) is the first choice. The main advantage of FPGAs for real-time application is the implementation of a direct interface for the process periphery, e.g. analog-digital and digital-analog converters. Furthermore, modifications in the requirements can be easily adapted in the reconfigurable hardware (FPGA), permitting very low latency and reduced costs of the entire deployment [3].

2.3.1 Development platform

In this research work, we have used the industrial standard PXI hardware platform of National Instruments, which consists of a PXI-Chassis with a real-time embedded controller NI PXIe-8102 RT and an additional Multifunction Reconfigurable I/O module NI PXI-7854R with Virtex-5-LX110 FPGA. This module features eight analog inputs (750 kHz and 16 bit resolution), eight analog outputs (1 MHz and 16 bit resolution), 96 digital in/outputs (40 MHz) and three DMA channels for high-speed data streaming.

The connection between the weighing cell and the signal acquisition and processing unit is realized by input and output ports (data acquisition and output signals) located on the FPGA module. The PXI controller is used as a monitoring and a data storage system. Thereby, the saved measurement data is processed on the FPGA.

The applied software for the realization of data acquisition and processing on the FPGA-based system is the proprietary development environment LabVIEW (with extensions LabVIEW RT and FPGA). This environment provides a graphical data flow oriented system development and supports the design of algorithms on FPGA. Nonetheless, it exhibits a few limitations like restricted data types, operations and obviously the available resources [4].

2.3.2 Target program

This section explains the implemented program on the FPGA (see center of Figure 2). The main task of the program is the testing and the system identification of the presented EMFC weighing cell. The following functionality is realized in LabVIEW with a 40 MHz base clock of FPGA target:

- Acquisition of the measurement data takes place via four independent parallel analog-digital inputs with sampling rates up to 300 kHz. The analog inputs are configurable and can be set in differential or single-ended mode. The sampled data channels are multiplexed and transmitted via FIFO DMA to host (real time controller).
- The system to be identified can be excited using a function generator implemented on the FPGA (e.g. sinus, chirp, pseudo random noise) or prior generated test data transferred via DMA channel from host to target.
- The signal matching allows to modify the used test signal, where the gain and the offset parameters are adjustable. In particular, highly resolved calculations require mathematical operations in double precision (multiplication and addition), which are realized using the proprietary developed floating-point libraries [4].
- The generated test signal is sent via the analog output channel to the EMFC weighing cell. This signal is used for the excitation of the relevant measurement parts of the system.

2.3.3 Host program

The realized program of the monitoring and the data storage system on the PXI embedded real time controller is presented in a simplified schematic form in Figure 2. This program establishes the connection to the program running on the FPGA and receives the configuration for the testing and the system identification of the EMFC balance. After the launch of the FPGA target, the system parameters (sample frequency, measurement time, gain, offset) are sent to the FPGA chip. Then the test signal is created using a text file or a function generator. On one hand, the generated signal is sent to the FPGA target via FIFO DMA with a fixed size of the information block (1000 elements per iteration loop and data precision of 64 bits). On the other hand, the configuration of the function generator (e.g. amplitude, frequency) is transferred to the FPGA. The second DMA channel is used for the data reception. The host side receives the information block (1000 elements) once per iteration loop. This block contains the sampled data from four analog-digital inputs. These measured data is saved on the hard drive of the PXI controller and can be displayed on the diagram panel in LabVIEW.

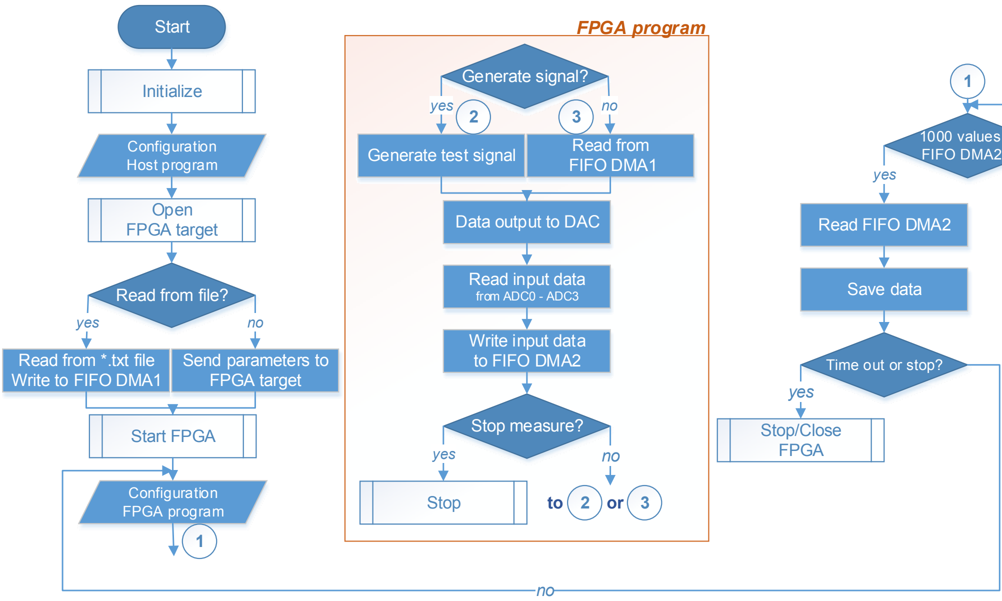

Figure 2: Flowchart of the developed program

3. MODELLING OF THE EMFC WEIGHING CELL

3.1 Mechanic Model

For control design purposes the modelling of the physical plant is an essential step because the model is the basis for the following control design process. Hence choosing an appropriate level of abstraction is an important aspect while modelling. By means of the weighing cell the mechanic structure was reduced to a compact model. As shown in Figure 3 the weighing cell is modelled as transmission lever. The mechanic structure made of levers and flexure hinges is reduced in this model. Damping and stiffness characteristics of the flexure hinges are integrated in the revolute joint. Furthermore the numerous lever transmissions of the real mechanics structure are modelled as one overall transmission ratio defined by l_2/l_1. The electromagnetic force F_{em} acts on the end of the lever. Due to the fact, that the natural state of the lever arm is not zero position, an additional offset force F_{off} on the left side of the lever is included.

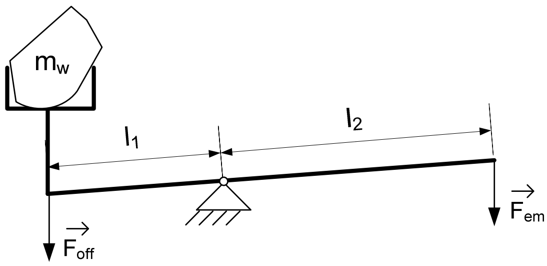

Figure 3: Compact model of the weighing cell

The right side (l_2) of the lever is explored more detailed to conceive the properties of the weighing cell in motion. In order to model the stiffness the revolute joint l_2 was split in two beams (see Figure 4). Attached to the right beam there is an additional mass m_3, which models the mass of the coil. Rotary stiffness and damping are defined by c_2 and d_2. In the origin of the coordinate system the stiffness and damping characteristics of the mechanic structure left to the joint are defined by d_1 and c_1. The impressed torque M_0 can be derived by the cross product of the gravitation force F_{mw}, the offset force F_{off} and lever arm l_1. Concerning only the working range of the cell around zero position M_0 can be determined as follows:

$$M_0 = (F_{mw} + F_{off}) \cdot l_1 \qquad (1.0)$$

Regarding Figure 4 one has to deal with a multibody-system. In literature exist some approaches to describe such systems mathematically. In this case the equations of motion for each body expressed as

$$\ddot{\vec{p}}_i = m_i \cdot \ddot{\vec{r}}_{S_i}$$
$$\vec{L}_i = \mathbf{I_i} \cdot \dot{\vec{\omega}}_i + \vec{\omega}_i \times \mathbf{I_i} \cdot \vec{\omega}_i \tag{1.0}$$

result in a standard approach of the Newton-Euler Equations. These can be formulated as follows [5]:

$$J^T \begin{bmatrix} \mathbf{M_1} & 0 \\ 0 & \mathbf{M_2} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \boldsymbol{\omega} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \boldsymbol{\omega} \times \mathbf{M_2} \cdot \boldsymbol{\omega} \end{bmatrix} - \begin{bmatrix} \mathbf{f} \\ \mathbf{m} \end{bmatrix} = \mathbf{0}$$

with

$$\mathbf{J} = [\mathbf{J}^{\mathbf{T}}_{\mathbf{T_1}}, \mathbf{J}^{\mathbf{T}}_{\mathbf{T_2}}, ..., \mathbf{J}^{\mathbf{T}}_{\mathbf{T_N}}, \mathbf{J}_{\mathbf{R_1}}, \mathbf{J}_{\mathbf{R_2}}, ..., \mathbf{J}_{\mathbf{R_N}}]^T \tag{1.0}$$
$$\mathbf{M_1} = \text{diag}(m_1 \cdot \mathbf{E_3}, m_2 \cdot \mathbf{E_3}, ..., m_N \cdot \mathbf{E_3})$$
$$\mathbf{M_2} = \text{diag}(\mathbf{I_1}, \mathbf{I_2}, ..., \mathbf{I_3})$$

As proposed in Eqn. (1.0) the forces **f** and the torques **m** act on the center of mass of each body. The Jacobi matrix **J** includes the translational and rotary Jacobi matrices. The vectors **r** and **ω** represent the position vector and the angular velocity vector of all bodies respectively.

Synthesizing Eqn. (1.0) induces two nonlinear differential equations of motion, whereby each of them describes the dynamic behaviour of the two generalized coordinates q_1 and q_2. These are the angles of the beams shown in Figure 4. Due to the two beam approach the system is able to reflect vibrations resulting in special eigenforms indicated in Figure 4, too.

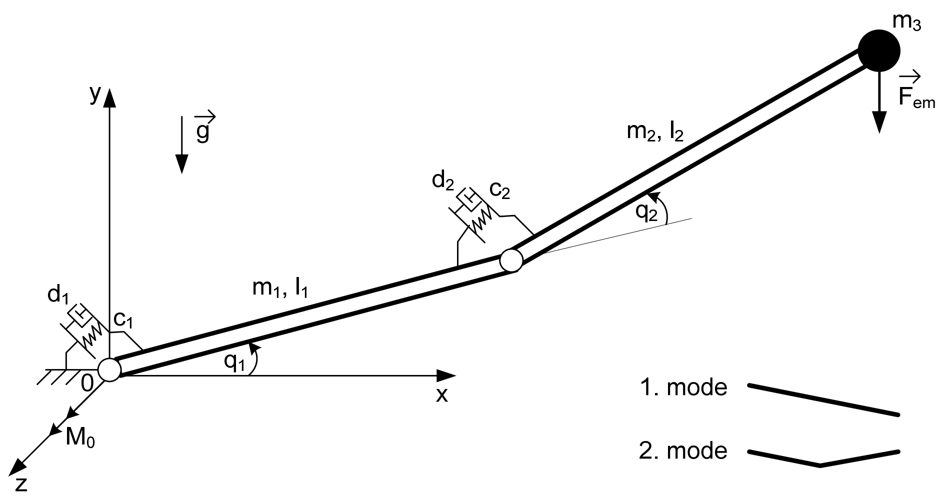

Figure 4: Two beam model of the weighing cell

3.2 Linearizing to State Space Representation

By dint of the mechanical model the characteristics of the EMFC weighing cell are conceived. The representation of a nonlinear system in general is defined as:

$$\frac{d\underline{x}}{dt} = \underline{f}(\underline{x}(t), \underline{u}(t))$$
$$\underline{y} = \underline{h}(\underline{x}(t), \underline{u}(t)) \tag{1.1}$$

Here, $\underline{f}$ depicts the nonlinear system of differential equations and $\underline{h}$ is the output equation. In case of control design it is indispensable to derive a linear state space representation by linearizing the nonlinear equations at the operating point:

$$\frac{d\underline{x}}{dt} = \underline{f}(\underline{x}_{op}(t), \underline{u}_{op}(t)) + \frac{\partial}{\partial \underline{x}} \underline{f}_{op} \cdot (\underline{x} - \underline{x}_{op}) + \frac{\partial}{\partial \underline{u}} \underline{f}_{op} \cdot (\underline{u} - \underline{u}_{op})$$

$$\underline{y} = \underline{h}(\underline{x}_{op}(t), \underline{u}_{op}(t)) + \frac{\partial}{\partial \underline{x}} \underline{h}_{op} \cdot (\underline{x} - \underline{x}_{op}) + \frac{\partial}{\partial \underline{u}} \underline{h}_{op} \cdot (\underline{u} - \underline{u}_{op}) \tag{1.1}$$

Assuming that at the operating point all states and inputs are zero the following linear state space representation reflects the system behavior:

$$A = \frac{\partial}{\partial \underline{x}} \underline{f}_{op}, B = \frac{\partial}{\partial \underline{u}} \underline{f}_{op}$$

$$C = \frac{\partial}{\partial \underline{x}} \underline{y}_{op}, D = \frac{\partial}{\partial \underline{u}} \underline{y}_{op} \tag{1.2}$$

3.3 Overall Plant Model

Due to the fact, that the real system in- and outputs are electrical variables the mechanical subsystem has to be augmented with peripheral components. The described mechanical subsystem is embedded within the plant consisting of the subsystems shown in Figure 5. The subsystem “Linear Analog Amplifier” transforms a desired input voltage to a desired output current. The weighing cell actuator is represented by the subsystem “Position Dependent Motor Coefficient”, which determines the induced force on the basis of the desired current with respect to the current lever position. The mechanical model has two system inputs, the force of the weighing cell actuator and the force, which is generated by the load on weighing pan. Solving the differential equations and integrating the state variables yield in the position of the lever end point. The subsystem “Position Sensor” calculates the position equivalent voltage signal by dint of the sensor’s position-voltage characteristic.

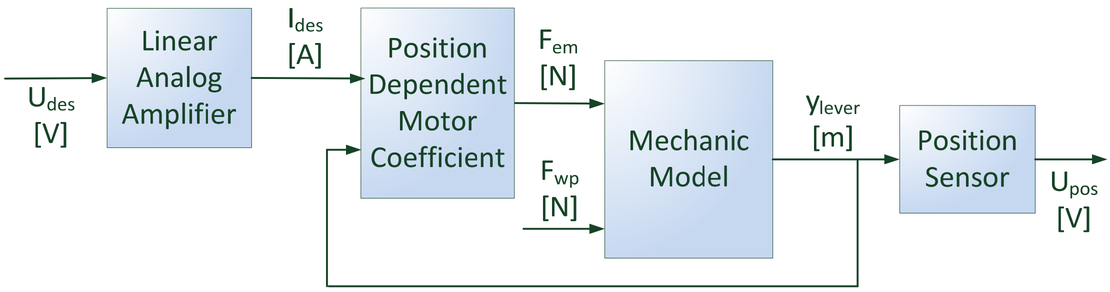

Figure 5: Plant model

4. Identification Process

4.1 Parameter Identification Approach

In this contribution the previously presented parametric model is used containing the dynamic and static characteristics of the balance and the used analog circuitry. For parameter identification two ways of excitation were used. These are the excitation of the weighing cell actuator as well as the excitation of the weighing pan. First, the force of electromagnetic actuator was modulated by a chirp signal and a pseudo random binary signal. The lever deflection was observed in order to identify the open-loop transfer function of the system. The second way of excitation is described in [1]. Here, an additional actuator is used to apply a defined force to the weighing pan. Also in this experiment the load was varied with a chirp behavior in order to identify the frequency response of the system. Additionally, in both experiments the current through the actuator coil was measured in order to observe the characteristics of the power amplifier (see section 2.2). Hence it is possible to distinguish between the dynamic characteristics of the mechanical and electrical subsystems. Besides the dynamic system behavior, several static system characteristics were determined through special experiments. For instance the motor constant of the load change actuator was identified. For this purpose a force was applied on the weighing pan and the current though the load change actuator was measured. Out of the comparison between the needed compensation current and the current though the load change actuator the motor constant of the load change actuator could be determined as (0.91 ± 0.01) N/A. Also the motor constant of the balance actuator was determined with respect to the lever deflection and the applied force on the weighing pan. The experimental setup was similar to the determination of the load changer motor constant. Another important system parameter is the interrelationship between the lever deflection and the output voltage of the sensor system. In order to determine the sensor characteristic a special experimental setup was developed. The position sensor was coupled to a piezo actuator and the motion was measured with the position sensor as well as with an interferometer [8].

4.2 Frequency Response

The measured data are used to estimate the frequency response of the system. The utilized algorithm is part of the System Identification Toolbox of Matlab/Simulink® and calculates the amplitude as well as the phase response at selected frequencies. The frequency response of the EMFC weighing cell is shown in Figure 6. The upper graph shows the amplitude response in case of excitation of the weighing cell actuator and the lower graph shows the system behavior if the weighing pan is excited by a load. In both cases the actuator current of the unused actuator (weighing cell actuator or load change actuator respectively) is forced to zero by the analog power amplifier.

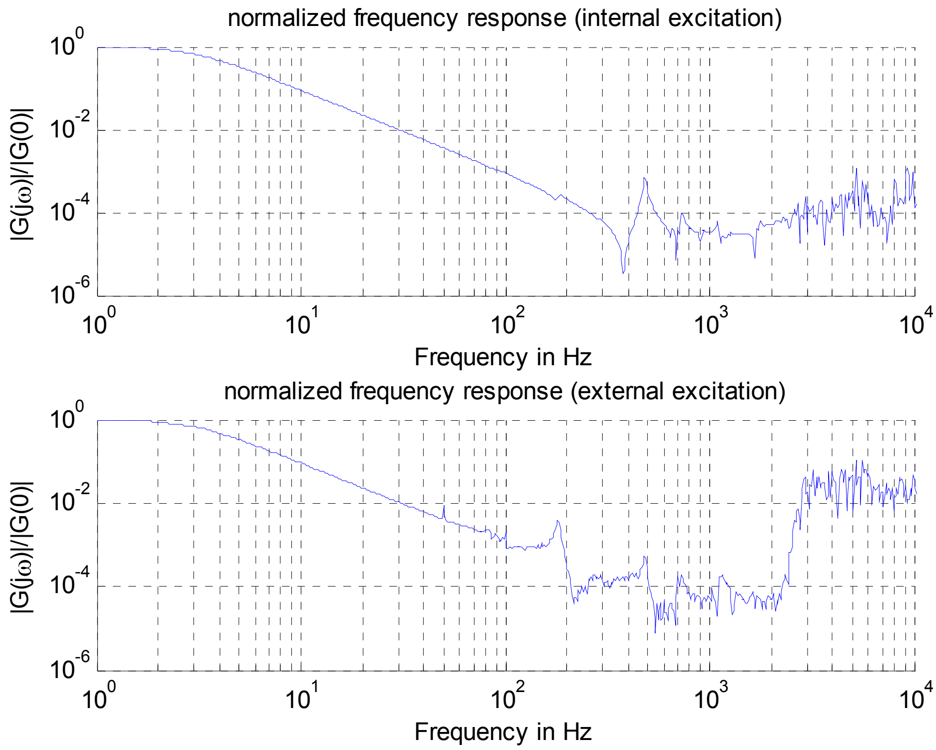

Figure 6: Frequency response spectrum of the EMFC-weighing cell

In both cases the magnitude decreases with rising frequency. The frequency responses exhibit peaks around 400 Hz evoked by excitation of mechanical resonant frequencies. It can be seen, that the resonance frequency of the external excitation is lower than of the internal excitation. Possible reasons are the differently sized masses as well as differences of the moved mechanical structure. The external excitation is denoted by moving masses from the weighing pan to the transmission lever whereas the load of the internal excitation is applied to the transmission lever. Additionally an antiresonant notch can be observed, directly nearby the resonant frequencies. This phenomenon is characteristic for mechanical systems and it appears in case of internal excitation as well.

4.3 Parametric Plant Model

As basis for identification the model depicted in Figure 4 was utilized. Beside the frequency responses the parameters of the characteristic curves of the peripheral subsystems were identified (Linear Analog Amplifier, Position Sensor, Load Changer). Hence single experiments were carried out in order to acquire data, which describes the input output behavior. The parameters of the characteristic curves were identified by least mean square methods resulting in the equations shown in Table 1. Using the characteristic curves of the peripheral subsystems the nonlinear mechanic model was prepared for estimation. The identification of the mechanic model parameters was conducted by a patternsearch optimization algorithm [6]. This algorithm is more efficient in terms of nonlinear parameter estimation problems.

Table 1: characteristic functions of the sensor and actuator components

Characteristic	Equation
Linear Analog Amplifier (Current-Voltage)	$I(U) = -6,964\cdot 10^{-6}\frac{\mathrm{A}}{\mathrm{V}^2}\cdot U^2 + 0,010\frac{\mathrm{A}}{\mathrm{V}}\cdot U + 7,552\cdot 10^{-6}\,\mathrm{A}$
Position Dependent Motor Coefficient (Force-Current)	$F(I,y) = \left(-5,273\cdot 10^{-3}\frac{\mathrm{N}}{\mathrm{A}\cdot\mathrm{m}^2}\cdot y^2 + 0,012\frac{\mathrm{N}}{\mathrm{A}\cdot\mathrm{m}}\cdot y + 21,692\frac{\mathrm{N}}{\mathrm{A}}\right)\cdot I$
Position Sensor (Voltage-Position)	$U(y) = 4,31\cdot 10^{17}\frac{\mathrm{V}}{\mathrm{m}^5}\cdot y^5 + 6,84\cdot 10^{13}\frac{\mathrm{V}}{\mathrm{m}^4}\cdot y^4 - 1,10\cdot 10^{11}\frac{\mathrm{V}}{\mathrm{m}^3}\cdot y^3 - 1,39\cdot 10^{6}\frac{\mathrm{V}}{\mathrm{m}^2}\cdot y^2 + 1,95\cdot 10^{17}\frac{\mathrm{V}}{\mathrm{m}}\cdot y$
Load Changer (Force-Current)	$F(I) = -0,904\frac{\mathrm{N}}{\mathrm{A}}\cdot I + 3,982\cdot 10^{-4}\,\mathrm{N}$

Remembering the offset force F_{off} (see Figure 3), which is applied to the model at the weighing pan, the identification of the system model in the operating point zero is feasible. Since the model is supposed to be identified around the operating point zero according to linearizing aspects the mass has to be elongated in zero position. There are two possibilities to realize this equilibrium state. First it is possible to actuate the voice coil of the weighing cell, but this will affect the whole system behavior. The other strategy is loading the weighing pan with mass pieces to obtain approximately zero position. For the identification process the second method was applied.

As excitation chirp and steps signals were utilized. According to Figure 7 the identification trajectory is composed of four sections. In relation to the first two sections the weighing cell is actuated separately with a chirp, each input gets a signal whereby the other is zero. The last two sections are simultaneous excitations composed of chirp and step signals.

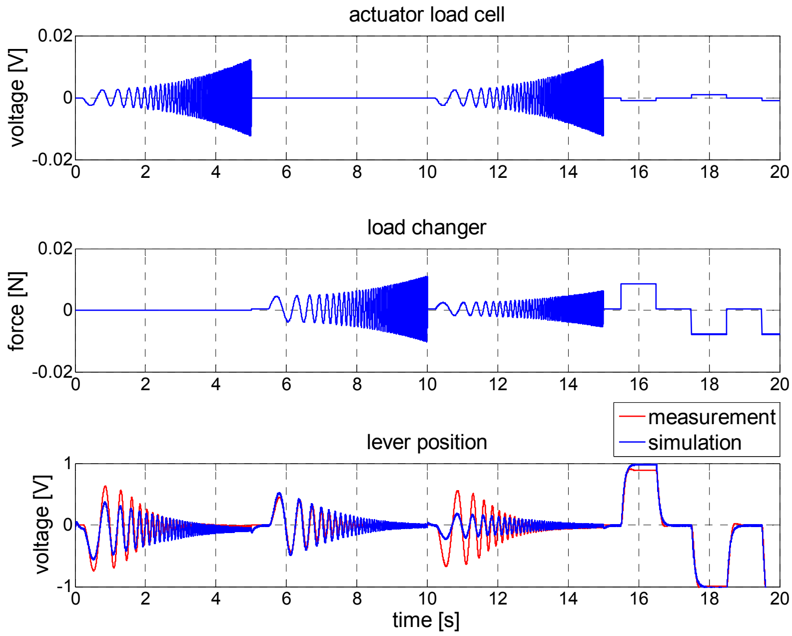

Figure 7: Identification curves: Inputs: weighing cell, load changer. Output: lever position

Considering the results the first two actuated single phases showed a very good match. The simultaneous excitation exhibits more differences, but the qualitative behavior equals the measurement. The step responses reveal almost accordance. Hence, the identified model is available for control design purposes.

5. Conclusion

In this paper, an analytical model of complex mechatronic system, an EMFC weighing cell, was presented, analyzed and identified. Before exploring the mechanical system analyzing the peripheral subsystems was essential. Then the experimental set-up was extended by a load changer in order to actuate the weighing pan and the signal processing PXI development system was interfaced to the weighing cell. Thereby a FPGA-based embedded system was used. On this platform a program was created to excite the weighing cell and to record the sensor data. Based on the experimental data the parameters of a beforehand developed physically motivated system model were identified using sophisticated parameter estimation techniques. The results of the identification process show a good conformity between model and reality and hence a valid model of the EMFC weighing cell is now available for further analysis or development of model-based control algorithms.

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