Resistance estimation algorithm for self-sensing magnetic levitation systems

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and published in *Proceedings of the 5th IFAC Symposium on Mechatronic Systems*.

Cite this article as:

T. Glück, W. Kemmetmüller, C. Tump, and A. Kugi, "Resistance estimation algorithm for self-sensing magnetic levitation systems", in *Proceedings of the 5th IFAC Symposium on Mechatronic Systems*, Boston, USA, Sep. 2010, pp. 32–37. DOI: 10.3182/20100913-3-US-2015.00025

BibTex entry:

```
@InProceedings{GlueckMech2010,
  Title = {{Resistance estimation algorithm for self-sensing magnetic levitation systems}},
  Author = {T. Glück and W. Kemmetmüller and C. Tump and A. Kugi},
  Booktitle = {Proceedings of the 5th IFAC Symposium on Mechatronic Systems},
  Year = {2010},
  Address = {Boston, USA},
  Month = {Sept. 13-15},
  Pages = {32-37},
  Doi = {10.3182/20100913-3-US-2015.00025},
  Url = {http://www.ifac-papersonline.net/Detailed/45299.html}
}
```

Link to original paper:

http://dx.doi.org/10.3182/20100913-3-US-2015.00025
http://www.ifac-papersonline.net/Detailed/45299.html

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Resistance estimation algorithm for self-sensing magnetic levitation systems

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Abstract: An algorithm for the estimation of the electric resistance for self-sensing magnetic levitation systems is presented. The development of this novel estimation algorithm is based on the position estimator proposed in Glück et al. (2010). Based on the mathematical model of the considered magnetic levitation system, the main ideas of the position estimation algorithm are summarized. A detailed analysis shows that the estimation error of the electric resistance can be deduced from the results of the position estimation algorithm. This observation leads to the design of a new resistance estimation algorithm. The performance of the proposed algorithm is demonstrated by means of measurement results on a test bench.

Keywords: magnetic levitation system, self-sensing, position estimation, switching control, electric resistance estimation, least squares identification

1. INTRODUCTION

Magnetic levitation enables suspension with no support other than a magnetic field. The magnetic force resulting from the magnetic field supports the levitated object and counteracts the gravitational force. Especially due to the low friction and the possibility to actively change both the position of the levitated object and the characteristics (stiffness and damping) of the suspension, magnetic levitation is applied to various practical applications as e.g. magnetic bearings. However, magnetic levitation systems are inherently unstable, which is why the position of the levitated object must be controlled. The measurement of the position makes magnetic levitation systems relatively cost-intensive and decreases the reliability in view of possible sensor failures. To overcome these deficiencies, so-called sensorless or self-sensing magnetic levitation systems have been developed in recent years replacing the position sensor by a position estimation algorithm. These estimation algorithms make use of the voltage and current measurement and are based on the change of the inductance as a function of the position of the levitated object. Self-sensing approaches can be divided into two basic working principles: (i) state observer approach and (ii) parameter estimation approach. In the following, a short overview of possible estimation algorithms is given.

The classical state observer approach is based on the Luenberger state observer. The reported approaches are almost exclusively designed using a linearized model of the magnetic levitation system, see, e.g., Vischer (1988). Major shortcomings of this approach concern the robustness with respect to changes of the parameters, especially the electric resistance, and external disturbances (Thibeault and Smith, 2002; Maslen and Montie, 2006).

More recent works deal with the parameter estimation approach to determine the position of the levitated object. They can be further subdivided into three categories:

(a) One approach is based on the injection of a high frequency sinusoidal voltage test-signal. The inductance and thus the position of the levitated object is inferred from the amplitude of the resulting current signal. The choice of an appropriate frequency for the test-signal enables to decouple the control from the estimation task (Sivadasan, 1996). The substantial disadvantage is the additional hardware effort for supplying and evaluating the test-signal. In addition, the implementations of this approach typically make use of linear amplifiers with a low energy efficiency (Sivadasan, 1996).

(b) Another approach involves hysteresis amplifiers, see, e.g., Mizuno and Hirasawa (1998). By switching on and off the supply voltage and keeping the resulting amplitude of the current ripples constant, the position of the levitated object is calculated from the switching frequency of the hysteresis amplifier. The frequency is typically measured by a phase-locked loop circuit. The drawback of this approach is that it is not capable of accurately estimating high-dynamic position changes.

(c) Today's research is increasingly focused on energy efficiency, which is why pulse-width modulation (PWM) controlled switching amplifiers are mostly used for the control of magnetic levitation systems. In this context, most of the contributions dealing with the position estimation rely on a harmonic analysis of the voltage and the current signals (Kucera, 1997; Noh and Maslen, 1997; Schammass et al., 2005; Park et al., 2008). Although practical implementations have been reported in literature, the first

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harmonic is certainly only a rough approximation of the real time evolution of the current and the voltage signal. It is well known that fast changes of the duty ratio or a fast motion of the levitated object result in estimation errors. Furthermore, the influence of the electric resistance of the coil is generally neglected. Kucera (1997) proposes to approximately compensate for these effects by means of look-up tables. A least squares estimation to obtain an estimation of the inductance was performed in Pawelczak (2005), where the dependence on the electric resistance is systematically included. However, a change of the duty ratio or a motion of the levitated object again yields estimation errors. Also in this contribution, a look-up table is used to approximately compensate for this effect.

In Glück et al. (2010) a self-sensing position estimation algorithm for magnetic levitation systems based on least squares identification was proposed. It is shown that the influence of the electric resistance, the change of the duty ratio and a motion of the levitated object can be approximately eliminated by means of the proposed position estimation strategy. However, the knowledge of the actual value of the electric resistance is important in practical implementations for the following reasons: The electric resistance increases with the temperature of the coil. Thus, an estimation of the electric resistance allows for the monitoring of the coil temperature. Furthermore, if a model-based controller design is used, the performance of the controller relies on an exact knowledge of the system parameters including the electric resistance. Finally, in spite of the fact that the influence of the estimation error of the electric resistance can be suppressed, increasing errors of the electric resistance still yield a reduction of the position estimation accuracy. In this work, an extension of the basic position estimation algorithm presented in Glück et al. (2010), which enables the estimation of the electric resistance, is proposed.

The paper is organized as follows. In Section 2, the mathematical model of the considered magnetic levitation system is given. A summary of the position estimation scheme proposed in Glück et al. (2010) is outlined in Section 3, where at first only a stationary object is considered. The position estimation is then augmented for the case of a moving levitated object. Based on these results, the resistance estimation algorithm is derived. Measurement results on a test bench are presented in Section 4. Here, the estimation performance of the position estimation algorithm from Glück et al. (2010) in combination with the proposed resistance adaptation are outlined.

2. MATHEMATICAL MODEL

Fig. 1 depicts a schematic sketch of the considered magnetic levitation system. It comprises the levitated object, which in the considered case is a ball with mass m, and the magnetic core with the coil (N turns). The ball and the magnetic core are made of ferrite with a relative permeability $\mu_r \gg 1$. A voltage v applied to the terminals of the coil results in a current i which in turn yields a magnetic field in the air gap between the core and the levitated object. The resulting magnetic force f_m is used to control the position s of the levitated object. In order to achieve a good estimation performance a precise mathematical model of the magnetic levitation system is needed. The mathematical model of the levitation system is based on the equivalent magnetic circuit given in Glück et al. (2010). In this work, a position dependent reluctance $\mathcal{R}(s)$ was developed and parameterized by means of measurements. Given $\mathcal{R}(s)$, Faraday's law results in

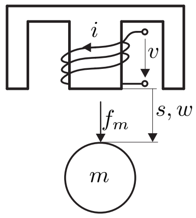

Fig. 1. Schematic diagram of the levitation system.

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi = -Ri + v, \tag{1}$$

where R denotes the electric resistance and ψ is the flux linkage. With the velocity $w = \dot{s}$ of the levitated object, the inductance

$$L(s) = \frac{N^2}{\mathcal{R}(s)}, \tag{2}$$

and the relation $\psi = L(s)i$, (1) can be formulated in the form

$$\frac{\mathrm{d}}{\mathrm{d}t}i = \frac{1}{L(s)}\left(-Ri - \frac{\partial L(s)}{\partial s}wi + v\right). \tag{3}$$

In order to achieve a high energy efficiency, magnetic levitation systems are usually driven by a switching amplifier. In the considered application, an H-bridge comprising 4 MOSFETs is used to supply the coil placed in the cross-path of the bridge. Using a suitable control strategy for the four transistors of the H-bridge, either the supply voltage v_{bat} or the negative supply voltage $-v_{bat}$ can be applied to the coil. A pulse-width modulated voltage v of the form

$$v(t) = \begin{cases} v_{bat} & \text{for} \quad kT_{pwm} < t \leq (k+\chi)T_{pwm} \\ -v_{bat} & \text{for} \quad (k+\chi)T_{pwm} < t \leq (k+1)T_{pwm} \end{cases} \tag{4}$$

$k = 0, 1, 2, \ldots$ is used. Here, $0 \leq \chi \leq 1$ is the duty ratio and T_{pwm} is the modulation period. Due to the switching actuation by means of a PWM voltage, a repeated charging and discharging of the coil takes place, see Fig. 2.

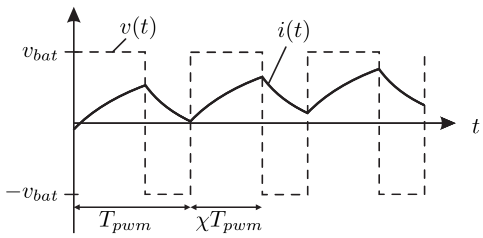

Fig. 2. PWM waveform and resulting current ripple.

3. POSITION AND RESISTANCE ESTIMATION

In this section the position estimation algorithm proposed in Glück et al. (2010) is summarized and extended by an estimator for the electric resistance. The first part

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of this section outlines the main idea for estimating the inductance of a static levitated object. It is shown that motions of the levitated object and deviations of the electric resistance from its nominal value lead to wrong estimated inductances. Therefore, an extension of the basic algorithm is proposed in the second part. The derivation of an estimation algorithm for the electric resistance in the third part relies on an analysis of the extended position estimation algorithm. As will be shown, the estimation error of the electric resistance can be directly obtained from values which are already calculated in the position estimation algorithm. Thus, the proposed estimation algorithm for the electric resistance can be easily incorporated in the existing position estimation scheme.

3.1 Estimation of the inductance for a static levitated object

Considering Faraday's law (1) for a constant electric resistance R and taking into account the time dependence of the inductance L, i.e. $L(t) = L(s(t))$, integration of (1) from time t_s to time t_e yields

$$\int_{t_s}^{t_e} \frac{\mathrm{d}\psi}{\mathrm{d}t}\mathrm{d}t = \int_{t_s}^{t_e} \frac{\mathrm{d}L}{\mathrm{d}t} i \,\mathrm{d}t + \int_{t_s}^{t_e} L\frac{\mathrm{d}i}{\mathrm{d}t}\mathrm{d}t = \int_{t_s}^{t_e} (-Ri + v)\,\mathrm{d}t. \tag{5}$$

For the time being it is assumed that the levitated object is not moving, i.e. $\dot{s} = w = 0$, which results in a constant inductance L ($\dot{L} = 0$). Then, (5) is given in the form

$$i(t_e) = i(t_s) + \frac{1}{L}\underbrace{\int_{t_s}^{t_e} (-Ri + v)\,\mathrm{d}t}_{\Delta\psi}. \tag{6}$$

In the following, an estimation algorithm will be derived which can be easily implemented in a digital real-time hardware. For this, the measurements of the voltage v and the current i are sampled with a sampling time T_s, which is significantly smaller than the modulation period T_{pwm}. The overall time period T_{pwm} can be subdivided into the charging phase (index I) where $v \approx v_{bat}$ and the discharging phase (index II) where $v \approx -v_{bat}$, cf. Fig. 3. Instead of calculating a single estimation of the inductance L every modulation period T_{pwm}, separate estimated values L^I and L^{II} are calculated for the charging and the discharging phase, respectively. As will be shown later, a suitable averaging of these two values can be used to approximately cancel out the influences of a motion of the levitated object or an estimation error of the electric resistance. In the subsequent derivations only the charging phase I is considered, since the results for the discharging phase II can be obtained in a similar way.

In order to avoid the influence of the switching glitches due to the non-ideal switching amplifier only measurements in the time interval (t_s^I, t_e^I), with the start time t_s^I and the end time t_e^I, of the overall charging phase $(t_0, t_0 + \chi T_{pwm})$ are used for the estimation $\hat{L}^I$ of the inductance. This time interval corresponds to sampled measurement data with indices $m_s^I, \ldots, m_e^I$. With these prerequisites, the change of the flux linkage $\Delta\psi_{k^I} = \Delta\psi(k^I T_s)$, with $k^I = m_s^I, \ldots, m_e^I$, results from (6) in the form

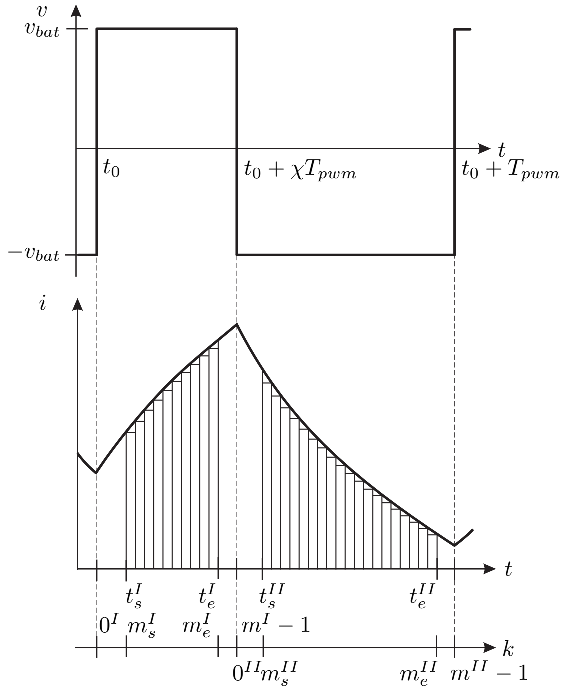

Fig. 3. Charging I and discharging II phase of a single PWM period.

$$\Delta\psi_{m_s^I} = 0 \tag{7a}$$

$$\Delta\psi_{k^I} = T_s \sum_{j=m_s^I}^{k^I-1} (-Ri_j + v_j), \quad k^I = m_s^I + 1, \ldots, m_e^I \tag{7b}$$

and equation (6) for the current i reads as

$$i_{k^I} = i_{m_s^I} + \left(\tilde{L}^I\right)^{-1} \Delta\tilde{\psi}_{k^I}, \quad k^I = m_s^I, \ldots, m_e^I. \tag{8}$$

Here, the scaling $\Delta\psi_{k^I} = T_s\Delta\tilde{\psi}_{k^I}$ and $\left(L^I\right)^{-1} = \left(\tilde{L}^I\right)^{-1}/T_s$ is introduced, which is useful for the practical implementation of the estimation algorithm. Using $m_e^I - m_s^I + 1$ measurements of the current i and the voltage v, (8) can be reformulated in vector-notation in the form

$$\underbrace{\begin{bmatrix} i_{m_s^I} \\ i_{m_s^I+1} \\ \vdots \\ i_{m_e^I} \end{bmatrix}}_{\mathbf{y}^I} = \underbrace{\begin{bmatrix} 1 & \Delta\tilde{\psi}_{m_s^I} \\ 1 & \Delta\tilde{\psi}_{m_s^I+1} \\ \vdots & \vdots \\ 1 & \Delta\tilde{\psi}_{m_e^I} \end{bmatrix}}_{\mathbf{S}^I} \underbrace{\begin{bmatrix} \tilde{i}_{m_s^I} \\ \left(\tilde{L}^I\right)^{-1} \end{bmatrix}}_{\boldsymbol{\theta}^I}, \tag{9}$$

where $\mathbf{y}^I \in \mathbb{R}^{m_e^I - m_s^I + 1}$ denotes the measurement vector, $\mathbf{S}^I \in \mathbb{R}^{(m_e^I - m_s^I + 1)\times 2}$ is the regression matrix and $\boldsymbol{\theta}^I \in \mathbb{R}^2$ is the parameter vector to be determined. Obviously, the resulting set of equations is over-determined and thus cannot be solved exactly. The best approximation $\hat{\boldsymbol{\theta}}^I$ of the parameter vector $\boldsymbol{\theta}^I$ in the least squares sense is given by the pseudo-inverse

$$\hat{\boldsymbol{\theta}}^I = \left(\left(\mathbf{S}^I\right)^T \mathbf{S}^I\right)^{-1} \left(\mathbf{S}^I\right)^T \mathbf{y}^I. \tag{10}$$

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With this, an estimation of the initial value of the current $\hat{\bar{i}}_{m_s^I} = \hat{\theta}_1^I$ and of the inductance $\hat{L}^I = T_s/\hat{\theta}_2^I$ are obtained for the charging phase I. The same approach can be used for the discharging phase II yielding the estimations $\hat{\bar{i}}_{m_s^{II}} = \hat{\theta}_1^{II}$ for the initial value of the current and $\hat{L}^{II} = T_s/\hat{\theta}_2^{II}$ for the inductance.

The estimated values for the inductance $\hat{L}^I$ and $\hat{L}^{II}$ are identical only if the measurements are exact, the electric resistance R is exactly known and the levitated object is at rest, i.e. $w = 0$. In practical applications none of these assumptions is fulfilled. Especially, the electric resistance R of the system changes during operation due to electrical heating. Since it is desired to control the position of the levitated object, the assumption of a resting levitated object is very limiting. Thus, the influence of a moving levitated object and an inexact knowledge of the electric resistance R on the estimated values $\hat{L}^I$ and $\hat{L}^{II}$ is investigated in the next subsection.

3.2 Estimation of the inductance for a moving levitated object

In this subsection, the assumptions of a static levitated object and a known electric resistance are dropped. The real value R of the electric resistance is supposed to take the form

$$R = \hat{R} + \Delta R, \tag{11}$$

with the deviation ΔR from its nominal value $\hat{R}$ resulting e.g. from temperature variations. Furthermore, the velocity of the levitated object does not vanish, i.e. $w \neq 0$. According to (5) this results in

$$\int_{t_s^I}^{t_e^I} \frac{\mathrm{d}L}{\mathrm{d}t} i \mathrm{d}t + \int_{t_s^I}^{t_e^I} L \frac{\mathrm{d}i}{\mathrm{d}t} \mathrm{d}t = \int_{t_s^I}^{t_e^I} (-Ri + v) \,\mathrm{d}t, \tag{12}$$

describing the current i for the charging phase I. In comparison, the least squares estimation described in the last subsection is based on

$$\hat{L}^I \int_{t_s^I}^{t_e^I} \frac{\mathrm{d}i}{\mathrm{d}t} \mathrm{d}t = \int_{t_s^I}^{t_e^I} \left(-\hat{R}i + v\right) \mathrm{d}t, \tag{13}$$

where only the nominal value $\hat{R}$ was used. Since the change of the electric resistance is generally rather slow, R can be assumed constant over the integration time $t_s^I - t_e^I$. Using this assumption in (11), (12) and (13) the relation

$$\int_{t_s^I}^{t_e^I} \frac{\mathrm{d}L}{\mathrm{d}t} i \mathrm{d}t + \int_{t_s^I}^{t_e^I} L \frac{\mathrm{d}i}{\mathrm{d}t} \mathrm{d}t = \hat{L}^I \int_{t_s^I}^{t_e^I} \frac{\mathrm{d}i}{\mathrm{d}t} \mathrm{d}t - \Delta R \int_{t_s^I}^{t_e^I} i \mathrm{d}t \tag{14}$$

is inferred. In order to analyze (14) two additional assumptions are made, cf. Glück et al. (2010). First, the time derivative $\dot{L}$ of the inductance is presumed constant over one PWM-period $t_0 < t \leq t_0 + T_{pwm}$. Note that this assumption is more general than the previous assumption of a static levitated object, i.e. $\dot{L} = 0$. Secondly, the current i in each phase is almost triangular [1], i.e.

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{i(t_e^I) - i(t_s^I)}{t_e^I - t_s^I} = \frac{\Delta i^I}{\Delta t^I}. \tag{15}$$

[1] This approximation is valid if the modulation period T_{pwm} is chosen sufficiently fast. Then, it can be shown that the errors resulting from this assumption are very small.

Based on these assumptions, (14) can be rewritten in the form

$$\Delta i^I \frac{1}{\Delta t^I} \int_{t_s^I}^{t_e^I} L \mathrm{d}t = \hat{L}^I \Delta i^I - \left(\Delta R + \dot{L}\right) \int_{t_s^I}^{t_e^I} i \,\mathrm{d}t. \tag{16}$$

The definition of the average value $\bar{L}$ of the inductance L and the average value $\bar{i}^I$ of the current i in the form

$$\bar{L} = \frac{1}{\Delta t^I} \int_{t_s^I}^{t_e^I} L \,\mathrm{d}t \quad \text{and} \quad \bar{i}^I = \frac{1}{\Delta t^I} \int_{t_s^I}^{t_e^I} i \,\mathrm{d}t \tag{17}$$

finally yields

$$\bar{L} = \hat{L}^I - \left(\Delta R + \dot{L}\right) \frac{\bar{i}^I}{\Delta i^I} \Delta t^I. \tag{18}$$

With this, the average value $\bar{L}$ of the inductance is given by the estimation $\hat{L}^I$ and an additional term depending both on the error ΔR of the electric resistance and the change $\dot{L}$ of the inductance. Note that ΔR and $\dot{L}$ influence the average value $\bar{L}$ in the same way and that large errors may result from $\Delta R \neq 0$ and $\dot{L} \neq 0$. A similar analysis can be performed in the discharging phase II, which results in

$$\bar{L} = \hat{L}^{II} - \left(\Delta R + \dot{L}\right) \frac{\bar{i}^{II}}{\Delta i^{II}} \Delta t^{II}. \tag{19}$$

The combination of (18) and (19) allows to calculate the average value $\bar{L}$ by canceling the influence of ΔR and $\dot{L}$, i.e.

$$\bar{L} = \frac{\hat{L}^I \Delta i^I \bar{i}^{II} \Delta t^{II} - \hat{L}^{II} \Delta i^{II} \bar{i}^I \Delta t^I}{\Delta i^I \bar{i}^{II} \Delta t^{II} - \Delta i^{II} \bar{i}^I \Delta t^I}. \tag{20}$$

In (20), the values of Δi^I, Δi^{II}, $\bar{i}^I$ and $\bar{i}^{II}$ need to be known, which can be directly estimated from measurements of the current i, cf. Glück et al. (2010).

3.3 Estimation of the electric resistance

The estimation algorithm derived in the last two subsections allows to cancel out the influence of the electric resistance on the estimation of the average inductance $\bar{L}$ and thus on the estimation of the position of the levitated object. In practical implementations, however, the knowledge of the actual value of R might be important, e.g. for monitoring the coil temperature or for a model-based controller design. On that score, an estimation algorithm for the electric resistance is proposed. It was shown in the previous subsection that both the motion of the levitated object and the estimation of an incorrect resistance have the same influence on the error of the estimated inductances $\hat{L}^I$ and $\hat{L}^{II}$, that is

$$\Delta \hat{L} = \hat{L}^{II} - \hat{L}^I \tag{21a}$$

$$= \left(\Delta R + \dot{L}\right) \left(\frac{\bar{i}^{II}}{\Delta i^{II}} \Delta t^{II} - \frac{\bar{i}^I}{\Delta i^I} \Delta t^I \right). \tag{21b}$$

In order to distinguish between a wrong estimated electric resistance and a motion of the levitated object, the dynamics of these effects are analyzed in more detail. Naturally, the dynamics of the change of the electric resistance due to electrical heating is much slower than the dynamics of the levitated object's motion. Thus, using a low-pass filter of the form

$$\frac{\mathrm{d}}{\mathrm{d}t} \Delta \bar{L} = -\frac{1}{T_f} \left(\Delta \bar{L} - \Delta \hat{L} \right), \tag{22}$$

with the time constant $T_f > 0$, allows the suppression of the influence of $\dot{L}$ (i.e. the motion of the levitated

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object). The filtered error $\Delta\bar{L}$ is then proportional to the estimation error ΔR of the electric resistance R. By using the following parameter update law

$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{R} = -\frac{1}{T_e}\Delta\bar{L}, \quad \hat{R}(0) = \hat{R}_0, \tag{23}$$

with the tuning parameter $T_e > 0$ and the initial condition $\hat{R}_0$, the estimation error ΔR is driven to zero. A trade-off between the suppression of measurement noise and a motion of the levitated object on the one hand, and the dynamics of the electrical heating of the coil on the other hand must be found when choosing the parameters T_f and T_e. A main advantage of the proposed estimation algorithm for the electric resistance is the fact that only quantities which have already been derived in the position estimation algorithm are used and thus an implementation of the algorithm can be made with little effort.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

In this section, measurement results on a test bench are given in order to prove the practical feasibility of the proposed position and resistance estimation algorithms. The considered test bench, cf. Fig. 4, consists of an

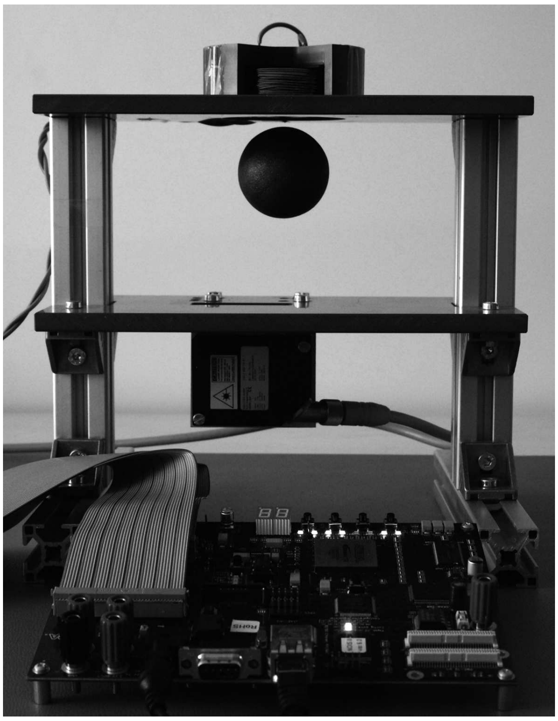

Fig. 4. Picture of the experimental test bench.

electromagnet comprising a ferrite cylindrical core with a plastic winding form wrapped in 452 turns of copper wire. The levitated object is a hollow ball with a mass of 94.83 g and a diameter of 40 mm. The supply voltage of the H-bridge is $v_{bat} = 11.4$ V. Two 12 bit analog-digital converters are used to measure the current and the supply voltage at a sampling rate of 1 MSamples/s. The whole control and estimation algorithm is implemented on an ALTERA STRATIX II FPGA test board with a connection to MATLAB for debugging and initialising. The estimation algorithm is partitioned in a fast and a slow calculation part as outlined in Glück et al. (2010). The update of the entries of $\mathbf{S}^T\mathbf{S}$, $\mathbf{S}^T\mathbf{y}$ from (10) both for the charging phase I and the discharging phase II is performed every sampling time T_s on the FPGA with fixed-point arithmetics. The resulting data is transferred to a floating point processor (e.g. a soft-core processor emulated on the FPGA) once every modulation period T_{pwm}. Here, the estimated values of the inductance $\hat{L}^I$, $\hat{L}^{II}$ according to (10) are determined. With this, the average inductance value according to (20) is calculated and the resistance estimation according to (22) and (23) is performed. Based on these results, the estimated position $\hat{s} = s(\bar{L})$ is calculated from the inverse inductance model. For testing, a cascaded controller, comprising a current controller in the inner loop and a position controller in the outer loop, is used, cf. Glück et al. (2010).

For the subsequent measurement results of the resistance estimation, the parameters of the resistance estimation are chosen as $T_f = 10$ s and $T_e = 0.5$ s. In Fig. 5a the estimated inductances $\hat{L}^I$, $\hat{L}^{II}$ and the average value $\bar{L}$ are depicted for a constant position $s = 5$ mm. At time $t = 50$ s a wrong estimated electric resistance is set to $\hat{R} = 1.5\,\Omega$, which results in an error between $\hat{L}^I$ and $\hat{L}^{II}$. The inductance error in Fig. 5b shows that the resistance estimation algorithm drives the inductance error to zero and thereby estimates an electric resistance of $\hat{R} \approx 1.6\,\Omega$, which corresponds to the real value R, cf. Fig. 5c. In order to show that the algorithm produces accurate results also for changing positions of the levitated object, in Fig. 6a the same experiment is shown for fast changes of the setpoint from $s = 4$ mm to $s = 6$ mm. As in the case of a constant position, the wrong estimated electric resistance at $t = 50$ s is corrected by the resistance estimation algorithm, cf. Fig. 6b.

5. CONCLUSION

In this work, an extension of the self-sensing position estimation scheme for magnetic levitation systems proposed in Glück et al. (2010) is given. Based on a separate inductance estimation for the charging and the discharging phase of a pulse-width modulation controlled coil of a magnetic levitation system, it is shown that the resulting inductance error is proportional to the electric resistance. The inductance error was utilized to derive a novel estimation algorithm for the electric resistance. Furthermore, it was briefly outlined how the proposed estimation algorithm can be easily embedded in the position estimation scheme presented in Glück et al. (2010). In the last part, the accuracy of the resistance adaptation was shown by means of measurement results.

Post-print version of the article: T. Glück, W. Kemmetmüller, C. Tump, and A. Kugi, "Resistance estimation algorithm for self-sensing magnetic levitation systems", in *Proceedings of the 5th IFAC Symposium on Mechatronic Systems*, Boston, USA, Sep. 2010, pp. 32–37. DOI: 10.3182/20100913-3-US-2015.00025
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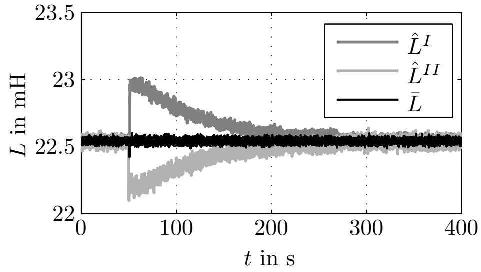
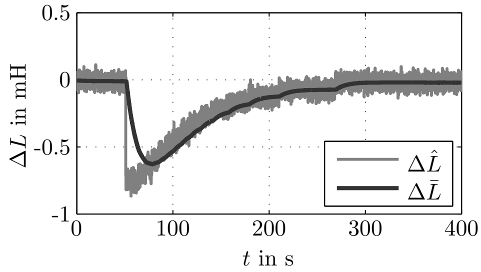
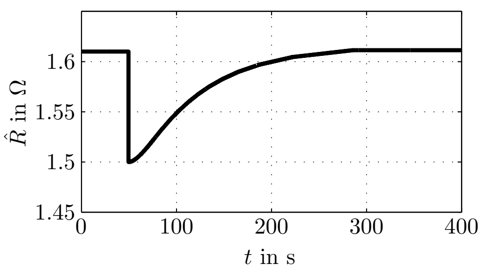


(a) Estimated inductance.

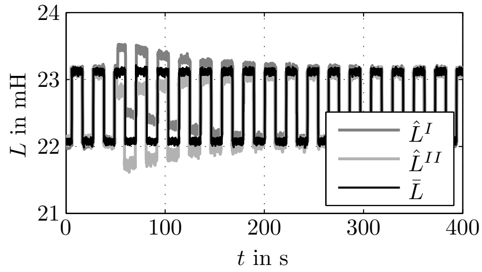


(b) Estimated inductance error and filtered inductance error.

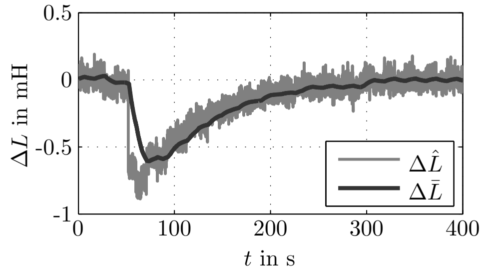


(c) Estimated electric resistance.

Fig. 5. Experimental results for a constant position and a wrong initialized electric resistance of $\hat{R} = 1.5\,\Omega$ at time $t = 50\,$s.



(a) Estimated inductance.



(b) Estimated inductance error and filtered inductance error.

Fig. 6. Experimental results for a setpoint change and a wrong initialized electric resistance of $\hat{R} = 1.5\,\Omega$ at time $t = 50\,$s.

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