Investigations on the "Direct Digital Inductance Estimation"-concept for self-sensing AMBs under influence of eddy currents

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***Abstract*—This article states the challenges connected with eddy-currents by use of the direct digital inductance estimation (DDIE) concept for self-sensing active magnetic bearings. Starting with a short introduction to the estimation algorithm, the negative influences of eddy currents on the position estimation are described step by step. Such influences are an increasing position noise as well as an interval and duty cycle dependent position error. The article closes with an outlook on additional investigations to further separate, quantify, and reduce the associated position error in order to extend the performance of the DDIE-concept.**

I. Motivation

Based on the broad advantages of self-sensing active magnetic bearings (above all higher degree of integration, lower investment costs and installation space) a variety of different self-sensing concepts can be found in literature. Following the classification of [1], two main groups can be identified:

The "State Estimation Approach" accounts for the fact to be able to stabilize the active magnetic bearing (AMB) by measuring the coil current alone. Unfortunately, this concept group is inherently less robust compared to a sensor driven configuration [2].

A generally higher grade of robustness can be obtained with the "Modulation Approach". If the AMB is driven by a switching power amplifier, the resulting high frequency current ripple is inherently modulated by the changing inductance due to a changing magnetic air gap. By demodulating this interrogation signal, the air gap can be obtained. An overview of different demodulation algorithms can be found in [3]. Most of them use analog low- and band-pass filters which add a phase lag to the estimated position and thus reducing the robustness.

In order to overcome the limitations of the referred self-sensing schemes, a new and promising DDIE-concept group was identified. To rate their possible higher degree of performance, the DDIE-concept developed in [4] was successfully implemented on a uniaxial test rig (Fig.1). In [5] a detailed description of this test rig as well as the essential enhancements and adaptations of the estimation algorithm are given. A first insight during the implementation phase implies a non-negligible impact of eddy currents (EC) on the estimated position. According to that, the impact of eddy currents on the estimated position are investigated, their different effects are quantified, and possible improvement measures are drawn.

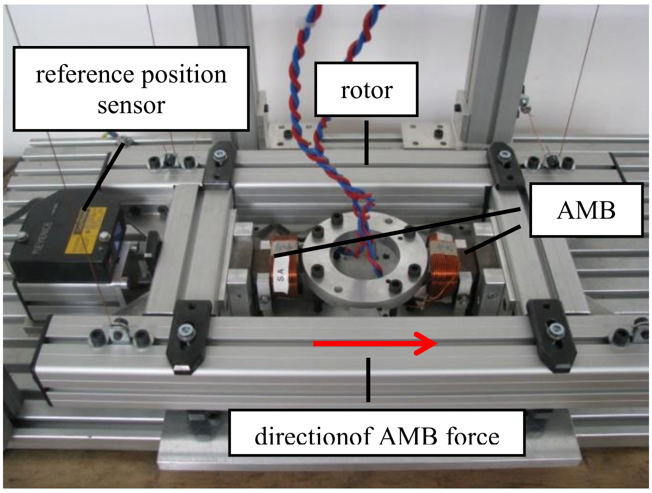

Figure 1. Uniaxial test rig with differential inner actuators and a horizontal lifted outer rotor

II. DDIE-concept

The basic idea behind the DDIE-concepts is to estimate the inductance and therefore the position of the rotor by means of the current ripple resulting from a two-stage switching power amplifier. Every current ripple is evaluated digitally in the time domain without additional low- and band-pass filters. This causes the estimated position to be of minimum phase lag contrary to other self-sensing concepts [1], [3]. Furthermore, the utilized DDIE-concept also accounts for a time dependent coil resistance, the rotor velocity and measurement noise [4], [5].

The sequence of the position estimation algorithm is shown in Fig. 2. The electromagnetic core equation (a) serves as the basis for the estimation. Here u is the coil voltage, i the coil current, s the air gap, $\hat{R}$ the estimated coil resistance, ΔR the estimation error of the coil resistance, Ψ the magnetic flux linkage and L_d the differential inductance of the magnetic bearing. Since (a) cannot be directly evaluated due to the unknown rotor velocity ds/dt and ΔR, both are initially neglected. In case of a sampling rate over 100 times higher than the switching frequency f_{PWM}, the truncated equation (b) can now be evaluated by means of a least square estimation. If

(b) is evaluated for two different intervals of the ripple e.g. its rising and $\hat{L}'_d$ falling edge $\hat{L}''_d$ (c) the resulting estimation error due to the truncation of (a) can be compensated (d). The compensation holds true, if the unknown rotor velocity ds/dt and ΔR are equal for both consecutive intervals.

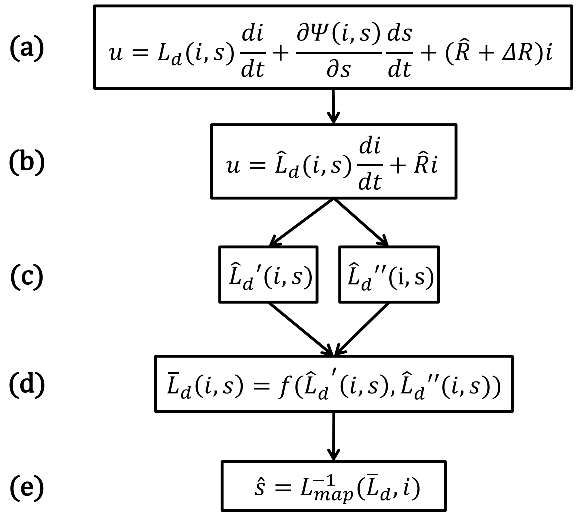

Figure 2. Sequence of the utilized DDIE – concept

By mapping the estimated average differential inductance $\overline{L_d}$ with means of the inverted inductance map L_{map}^{-1} the position of the rotor i.e. the estimated air gap $\hat{s} = L_{map}^{-1}(\overline{L_d}, i)$ can be obtained (e). The inverted inductance map can be understood as a calibration of the magnetic bearing as a sensor. Fig. 3 shows the measured inductance map of one electromagnet of the bearing. The inductance is estimated by the algorithm for different mean coil currents and for different constant air gaps (measured by a reference position sensor).

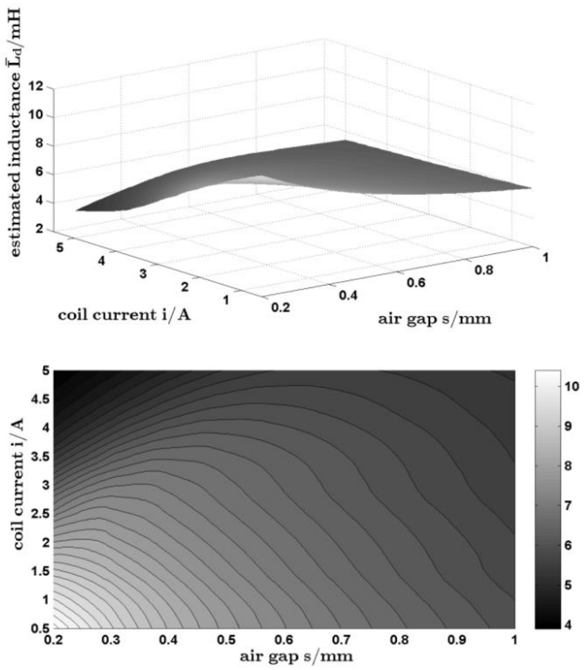

Figure 3. Inductance map of one electromagnet of the bearing

III. INFLUENCES OF EDDY-CURRENTS

Eddy-currents arise out of the switching of the power amplifier itself (PWM-EC) as well as out of the changing duty cycle (CDC-EC) i.e. the changing control current. They both effect the inductance estimation in several ways.

A. Increasing position noise

In case of a switching power amplifier, the presence of eddy currents can be seen equally by a varying current gradient or by a varying inductance. With increasing eddy currents, the inductance tends towards zero and the current gradient raises or respectively drops depending on the sign of the coil voltage. This effect can be seen right after each switching of the power amplifier (Fig. 4).

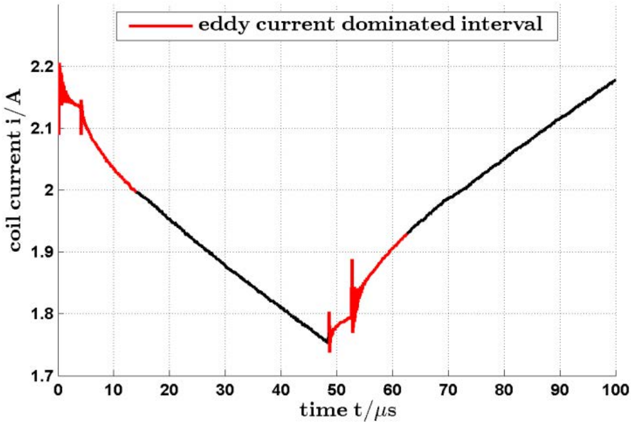

Figure 4. Current ripple with eddy current dominated intervals (air gap s = 0.5 mm, f_{PWM} =10 kHz)

Within the mentioned intervals, the current ripple is mainly dominated by eddy currents and not by the air gap. Thus, causing the position estimation to fail [5]. As a consequence, the most influenced interval of the current ripple right after each switching has to be omitted for the inductance estimation. The truncation reduces the remaining interval width Δt_{est} (i.e. the number of current samples N_{cs} when considering a fixed sampling period T_{sample}) for the inductance estimation. Since the current noise sensitivity of the estimated inductance rises with a reduced number of current measurements, the unwanted noise of the estimated position will increase too. (cf. Fig. 5 and Eq. 1). As a consequence, as many current samples as possible should be used for the inductance estimation.

$$\Delta s_{noise} = \left|\frac{\partial s}{\partial L_d}\right| \Delta L_{noise} = \left|\frac{\partial s}{\partial L_d}\right| \frac{L_d^2}{|u|} \frac{\Delta i_{noise}}{T_{sample}\sqrt{\frac{N_{cs}{}^3 - N_{cs}}{12}}} \qquad (1)$$

Equation (1) expresses the mentioned dependency between the noise amplitude of the measured current (Δi_{noise}) and the resulting noise amplitude of the estimated air gap (Δs_{noise}). It considers the least square estimation but neglects the coil current and rotor velocity. Equation (1) as well as Fig. 5 also show a dependence of Δs_{noise} on the inductance of the bearing. Near the saturation of the magnetic material, the noise amplitude increases and becomes maximum which can be traced back to a near zero gradient of the inductance with respect to the air gap within this range ($\partial L_d/\partial s \approx 0$).

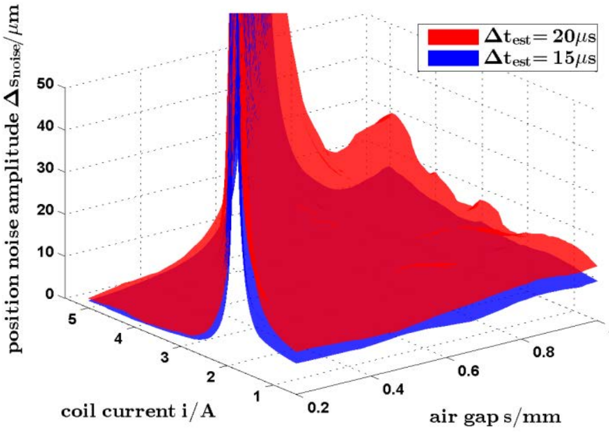

Figure 5. Position noise amplitude for different interval widths Δt_{est} used for the estimation of the inductance

B. Interval dependend position error

Eddy-currents induced by the switching of the amplifier (PWM-EC) drop in time, meaning not only the foremost samples of the ripple are influenced by them but almost the whole ripple. As a result, the modulus of the gradient of the ripple drops gradually until the next switching of the amplifier takes place. Since eddy currents are not considered by the estimation algorithm, the estimated inductance and therefore the position varies with the interval taken for the estimation. If the PWM-EC do not change from one estimation to another their influence can be compensated if the same interval of the ripple is used for the estimation as well as for the inverted inductance map.

TABLE I. MEASUREMENT CONFIGURATION OF FIG. 6

	Parameter	Value
$\bar{i}$	mean current	2 A
s	air gap	0.5 mm
Δt_{cut}	truncated time range after switching	14 µs
Δt_{map}	width of interval used for inverted inductance map	15 µs
Δt_{est}	width of interval used for estimation	10, 15 and 20 µs
T_{PWM}	modulation period	100 µs

In Fig. 6 the measured position error (reference sensor position minus estimated position) over 35 PWM periods for a constant air gap, a constant coil current (i.e. constant pulse width) and different interval widths is shown (see Table I). The data for $\Delta t_{est} = \Delta t_{map} = 15\mu s$ confirms the assumption to be able to compensate the influence of the PWM-EC in this special case. The remaining position error solely results from the current noise (III.A).

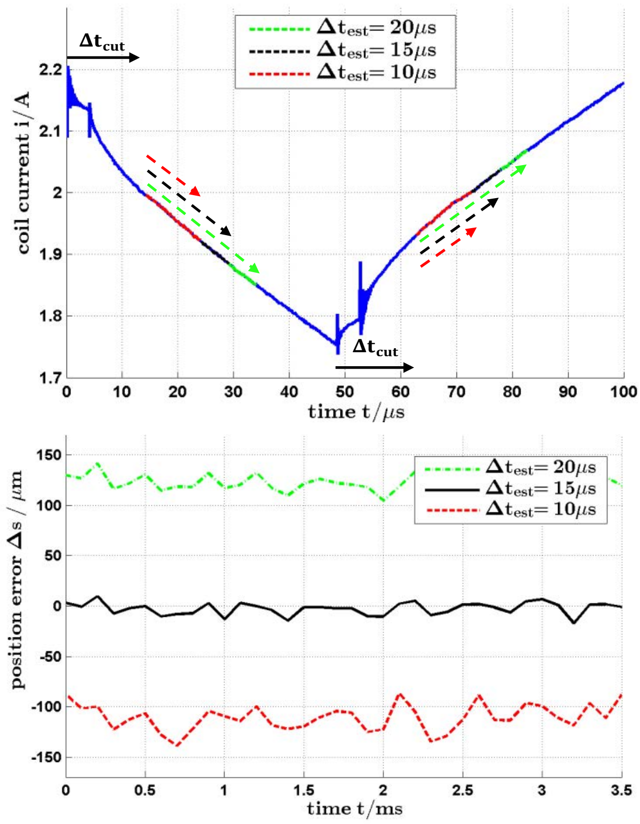

Figure 6. Influence of different sample intervals on the estimated position

The measurement further reveals the need of a compensation scheme since already less diverging intervals cause a high position error Δs. Unfortunately, a fixed interval after the switching for the compensation conflicts with a low current noise sensitivity for pulse widths differing from 0.5 (50% duty cycle). The maximum interval width and therefore N_{cs} is limited by the minimum pulse width for the rising edge i.e. maximum pulse width for the falling edge of the current ripple. Nevertheless, a low noise position estimation can be achieved if the inverted inductance map also depends on the pulse width. The solution has the benefit of an easy implementation in form of a three dimensional lookup-table but can only be obtained by a demanding and complex measurement (the inductance has to be measured for different air gaps, at different mean coil currents and for different duty cycles). For the following investigations only a fixed interval after the switching is used.

C. Duty cycle dependent position error

Eddy currents due to a changing duty cycle (CDC-EC) are also influencing the gradient of the current. Unfortunately, they cannot be compensated only by means of an inverted inductance map since the main frequency of the changing duty cycle and the amplitude of the oscillation are changing in time. Thus the inverted inductance map has to be frequency and amplitude dependent if their impact on the current ripple is dominant.

Nearly the same holds if the PWM-EC do not decay until the next switching takes place. An estimation of the inductance for a fixed interval width Δt_{est} of 15µs with a varying truncated time range Δt_{cut} from 9µs to 29µs for the current ripple of Fig. 6 is shown in Fig. 7. Thus the measurement shows the estimated inductance along the current ripple.

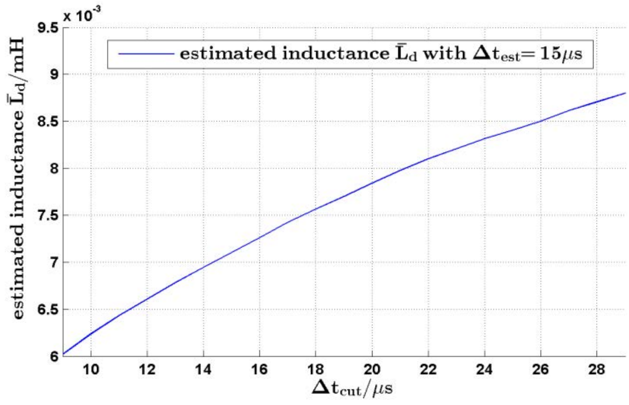

Figure 7. Estimated inductance along curent ripple with $\bar{i}$ = 2 A and s = 0.5 mm

The change of inductance and therefore the change of di/dt does not reach a constant level. As a result the PWM-EC are not decayed until the next switching takes place. Thus they do not only affect the ripple interval right after the switching but also the interval after the subsequent switching. A superposition of PWM-EC resulting from both switches in an estimation interval occurs. Unfortunately, the superposition varies with the duty cycle as the time between two switches varies accordingly. Until now the inverted inductance map is evaluated for duty cycles near 0.5, which causes it to be unable to compensate the influence of the PWM-EC in case of duty cycles differing from 0.5. A duty cycle dependent position error occurs.

In order to assess the resulting position errors due to the CDC and PWM-EC, a comparison measurement between a constant reference position and the estimated position for a sinusoidal changing coil current is done. The parameters of the measurement are summarized in Table II.

TABLE II. MEASUREMENT CONFIGURATION OF FIG. 8 & 9

	Parameter	Value
$\bar{i}$	mean current	1.8 A
Δi	current amplitude	0.9 A
f	frequency	125 Hz, 250 Hz
s	constant air gap	0.5 mm
Δt_{cut}	truncated time range after switching	14 µs
Δt_{map}	width of interval used for inverted inductance map	15 µs
Δt_{est}	width of interval used for estimation	15 µs
T_{PWM}	modulation period	100 µs

The measurement for $f = 250\ Hz$ (Fig. 8) reveals a high position error which varies almost chaotically in the range of low and high duty cycles (i.e. high coil current gradients). For a pulse-width near 0.5 (cf. t=2ms and t=6ms) the error is comparatively low. The observation indicates a duty cycle dependent position error which can be mainly assigned to a slow decay of the PWM-EC if the impact of the CDC-EC is low.

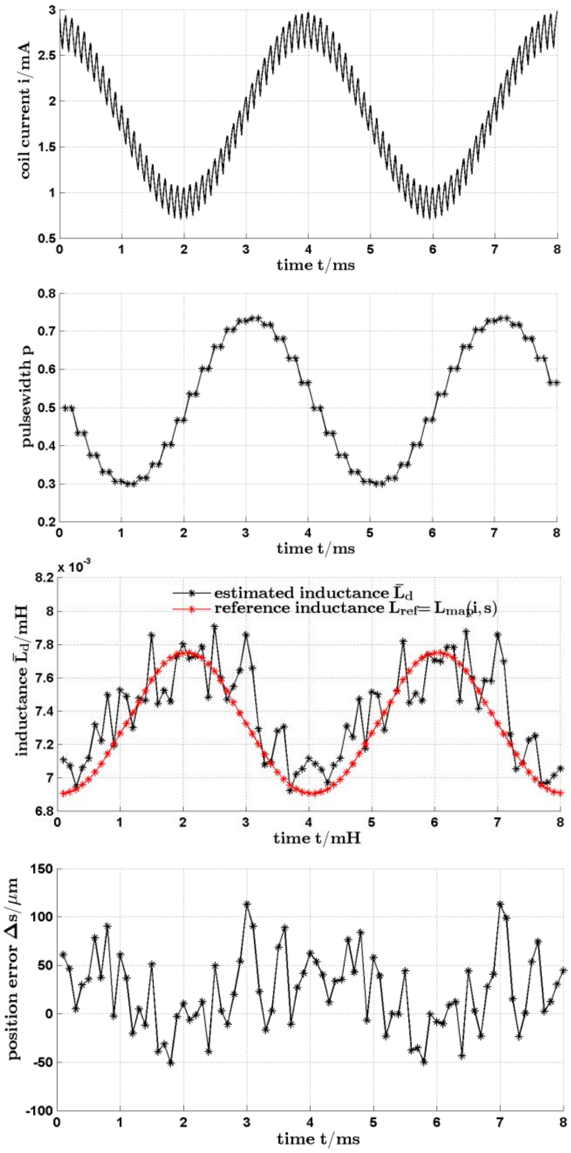

Figure 8. Position error for a fast changing coil current f = 250 Hz

A second measurement (Fig. 9) with a halved main frequency of 125 Hz confirms this assumption. Even though the theoretical eddy currents losses

$$P_{ec} \sim f^2 \quad (3)$$

of the CDC-EC should be divided by four compared to those of the previous measurement with 250 Hz, the resulting position error does not behave in the same way. The position error stays high, thus the impact of CDC-EC on the position error is comparatively low.

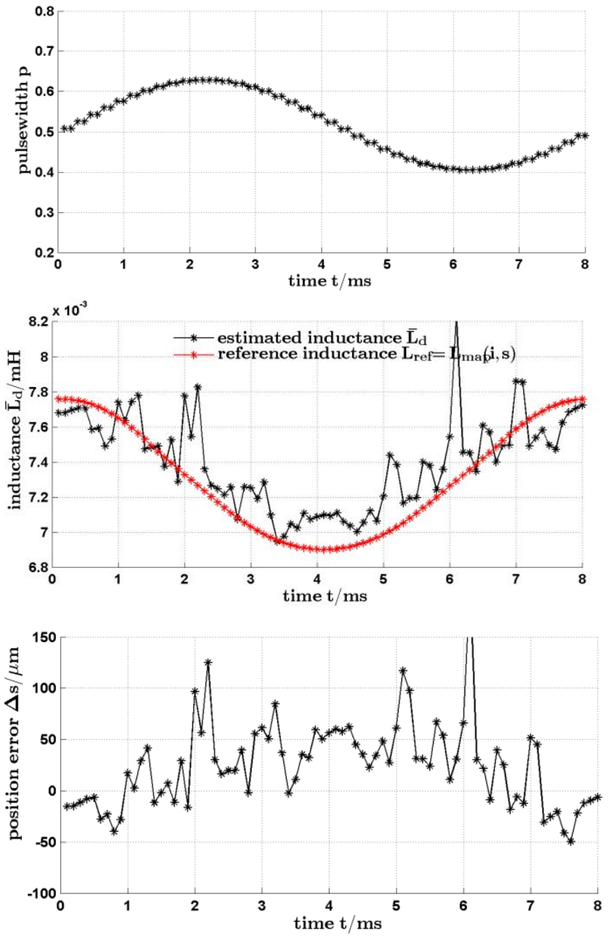

Figure 9. Position error for a fast changing coil current f = 125 Hz

The measurements also show an influence of the hysteresis. The position error distinguishes between the falling and rising edge of the fundamental oscillation of the control current i.e. it depends on the historical background of the magnetic material.

The measurements support the expected negative effect of eddy currents on the position estimation via the DDIE-concept. Nevertheless, a distinct quantitative assignment of the eddy currents arising out of the switching of the power amplifier (PWM-EC), out of the changing duty cycle (CDC-EC), or the hysteresis of the material to the resulting position error cannot be drawn yet. The following possible improvement measures are served to further support or disprove the shown dependencies:

- If the superposition of the PWM-EC influences the position error as proposed, a reduced PWM Frequency should decrease the superposition and as a result the duty cycle dependency of the position error. Thus the measurements will be repeated for a PWM Frequency of 5000 Hz instead of 10.000 Hz.
- A second procedure to further investigate the duty cycle dependent superposition of the PWM-EC and as a consequence of the position error can be an extension of the inverted inductance map by different duty cycles. Thus, the inverted inductance map will be able to account for this effect, and if the assumption holds true the resulting position error will decrease.

IV. Discussion and Conclusion

The suspected non-negligible impact of eddy currents on the estimation algorithm gave the impulse to this detailed investigation. Indeed, their negative impact is confirmed.

Eddy currents rising from the switching of the power amplifier cause an unacceptably high position error (~ 20% of the initial air gap of s=0.5) if the interval of the current ripple taken for the estimation does not equal the interval taken for the inverted inductance map. Both intervals can be kept equal even for a varying duty cycle with the drawback of an increasing position noise. With an extension of the inverted inductance map with respect to the duty cycle the trade-off can be reduced.

Until now the position error induced by a fast varying duty cycle represents the major challenge. The resulting position error of nearly 20% of the initial air gap is unacceptable. A quantitative assignment to the PWM and CDC-EC as well as to the hysteresis of the material is hard to draw. Nevertheless the measurements reveal a high impact of the superposition of PWM-EC on the position error. Thus, two improvement measures will be investigated in the future. First, the PWM frequency will be reduced. The PWM-EC have more time to decay until the next switching takes place. The resulting superposition and therefore the position error should decrease. Unfortunately, a reduced PWM frequency increases the phase lag of the position estimation as well as of the overall control of the AMB. Thus, it is a first workaround and serves mainly to support or disprove the shown dependencies. A second improvement measure is an extension of the inverted inductance map with respect to the duty cycle. Thus the varying superposition of the PWM-EC are considered by the overall estimation and the position error should decrease.

The soft magnetic material under consideration is an electrical steel of 0.35 mm thickness (M165-35S). Since eddy currents are frequency dependent, a magnetic material with lower core losses, especially in the high frequency domain, could also further reduce the negative effects of the PWM-EC on the estimated position. An electromagnet made out of soft magnetic composite (SMC) with the same dimensions as the laminated one is already built (Fig. 10) and will be investigated in the future.

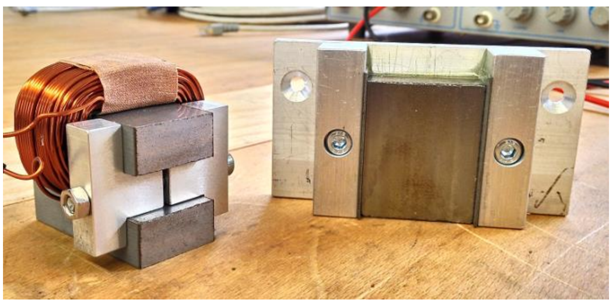

Figure 10. Electromagnet made out of SMC

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