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Automated parameter identification platform for magnetic levitation systems: case bearingless machine

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Abstract

This paper presents automated platform that can be used to identify parameters of magnetic levitated systems. Identification platform itself consists of 3-axis force measurement sensors and 2-axis stepper motors driven linear ball screw tracks. This kind of construction enables to measure the force produced by electromagnets in any angle and in any position in the air gap. Measurement system is controllable so the identification process can be automated. As a case study, self and mutual inductances of an interior permanent magnet bearingless machine are identified for the motor control purposes. Force sensors are used to measure the unbalance magnetic pull inflicted by the permanent magnets embedded in the rotor. Automated measuring procedure is used to determine self and mutual inductances of the bearingless motor. System functionality is validated by comparing the measured magnetic pull results to FEM analysis and inductance measurement to different prediction method based on standard motor drive identification process. Based on achieved results presented automated platform can be used to identify parameters of magnetically levitated system.

Keywords : Identification, Automated commissioning, Bearingless motor, Force measurement, Inductance measurement, Magnetic levitation, Permanent magnet motor

1. Introduction

It is important to validate the functionality of designed prototype or product. In the magnetic levitated systems one important parameter is the force production capability of electromagnets. One method, which is used to measure the force production of magnetic levitation system, is based on counterweight measurement. In this method a counterweigh is connected to the rotor trough a pulley and the produced force capabilities can be then determined (Antila, et al., 1998),(Zhang, et al., 2004),(Ooshima, et al., 2004). Counterweight method can be time consuming and changing the measurement angle accurately might be problematic. This paper presents automated parameter identification platform where generated electromagnetic forces can be measured with 3-axis force sensors. Force measurement sensors are placed at both ends of the rotor and forces in *xyz*-planes can be measured simultaneously. The force measurement sensors are connected to movers of two opposite 2-axis linear ball screw tracks. Rotor position can be controlled in the *xy*-plane in the airgap by stepper motors.

In this paper interior permanent magnet (IPM) bearingless machine is used as a magnetic levitation system (Inagaki, et al., 2000). Bearingless machines combine the magnetic levitation properties of the traditional magnetic bearings and torque production of the electrical motor. The considered bearingless machine includes two motor units. Each motor unit comprises torque and levitation windings, which are wound on the same stator stack. For successful levitation control, the permanent magnet bearingless machines require additional levitation control parameters compared to traditional magnetic bearing control systems. These parameters are ψ'_{PM}, M'_d and M'_q (Ooshima, et al., 2003, 2004). Levitation parameter ψ'_{PM} is caused by induced voltages of permanent magnets into suspension windings in a function of rotor position. Parameters M'_d and M'_q can be determined form the mutual inductances between motor and levitation windings in a function of rotor position. As the measurement of the mutual inductance between different coils needs to be performed at different rotor positions, this platform is ideal for such a measurements. Benefits of using the presented platform are fast and easily repeatable measurements by using the automated force and system parameter identification procedure.

2. Identification platform

Identification platform consist of two identical end plates, where 2-axis stepper motor drives are connected. Figure 1 illustrates the identification platform. Stepper motors are controlling the position of mover via the linear ball screw track. 3-axis force measurement sensors are placed on *y*-axis movers. The rotor is connected between the force sensors. With this setup rotor position can be controlled in *xy*–plane inside the airgap and in the same time force applied to the rotor can be measured.

Control of the servomotors and measurement signals are processed within an industrial embedded PC with suitable I/O modules. With this setup it is not possible to move the rotor in *z*-direction. However, the force applied to *z*-direction can be measured with the force sensor. Smallest step of the stepper motor is 1.36 µm, which is achieved by using maximum 64 micro steps per one full step. Resolution of the force measurement sensor in *xy*-plane is 0.32 N with measurement range from -1900 to +1900 N. In *z*-direction resolution of the sensor is 0.43 N and measurement range is from 0 to ± 3800 N.

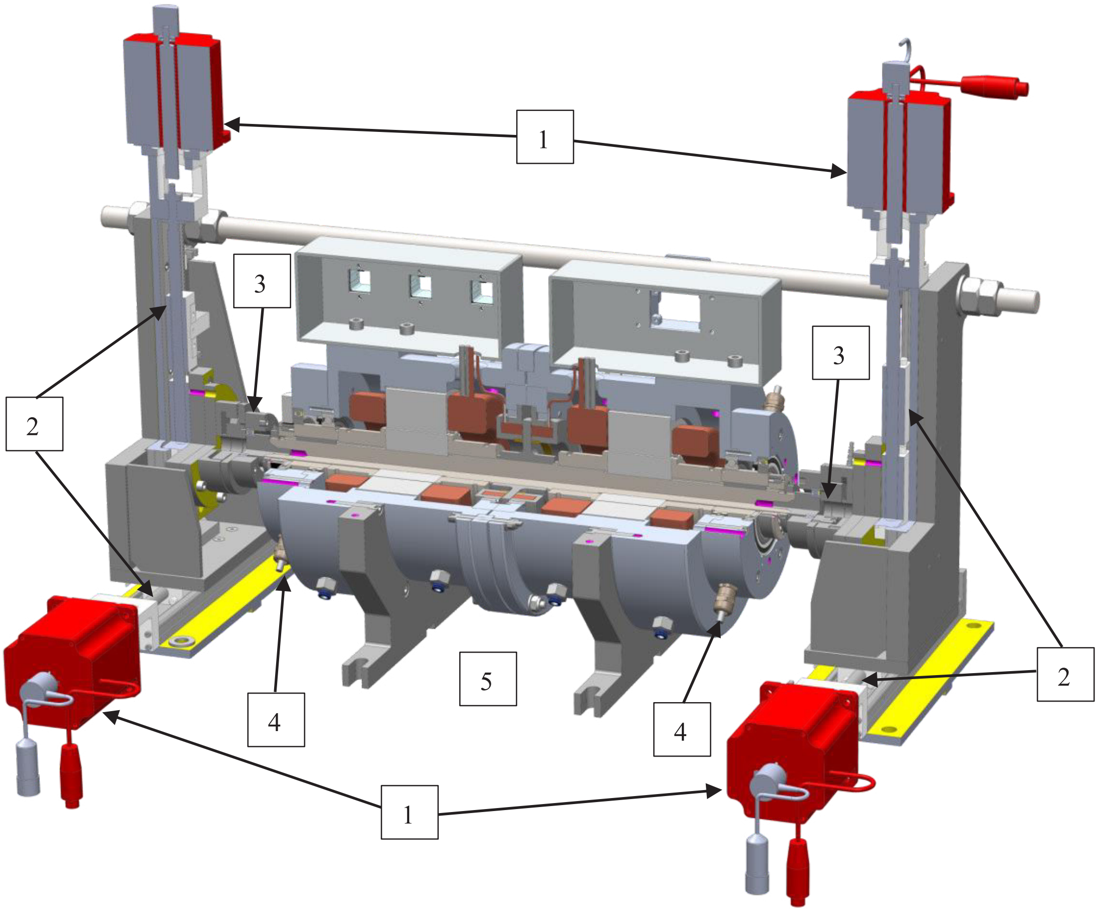


Fig. 1 Cutaway drawing of the identification platform. Main components: (1) Stepper motor, (2) Linear track, (3) Force sensor, (4) Position sensor, (5) Bearingless machine under identification process.

Control, measurement and mechanical components which are used in the identification platform are listed in Table 1.

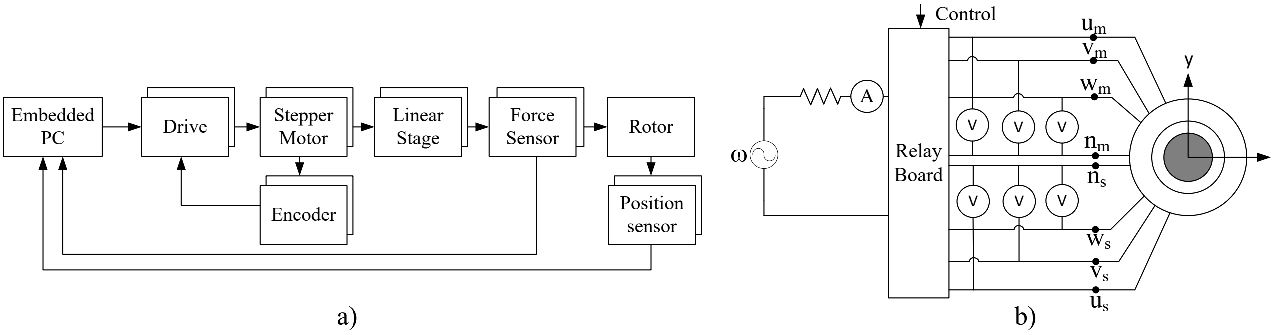
Table 1. Components used in the identification platform.

Component	Manufacturer and type
Embedded PC	Beckhoff C6930
Analog-to-digital converter	Beckhoff EL3702
Stepper motor	Beckhoff AS1060
Linear track	Hiwin KK60

3. Identification process

The industrial embedded PC is used for controlling and measuring purposes for the identification platform. Figure 2a illustrates the block diagram of the identification platform control system. Self and mutual inductances of the bearingless motor are determined by applying an excitation current into a one-phase winding and in the same time measuring applied current and induced voltages from every phase winding. In order to automate this measurement process a controllable relay board is used between the excitation current source and both winding sets. Figure 2b shows the setup to measure motor inductances. In order to be able to measure the effect of the mutual inductance between the different phase windings the rotor must be moved in the airgap. The bearingless machine includes eddy-current position measurement sensors that are used as a position feedback.

An unbalance magnet pull can be identified by moving the rotor in the airgap and measuring the force caused by the magnets.



a) b)

Fig. 2. a) Block diagram of the identification platform. b) Inductance measurement setup including amplifier, relay board, current and voltage measurement.

Functionality of the relay board is presented more exactly in Fig. 3. For simplicity voltage measurement is not shown. By controlling the position of the relays, every coil can be excited separately. Coil T1 is used with an amplifier circuit that disconnects from coils when induced voltages caused by the permanent magnets are measured from motor and suspension coils. In this case rotor is rotated by another motor. Separate relays sets are used before the voltage measurement to adjust the voltage dividers to set the voltage level to be suitable for the analog-to-digital converter when measuring the induced voltages.

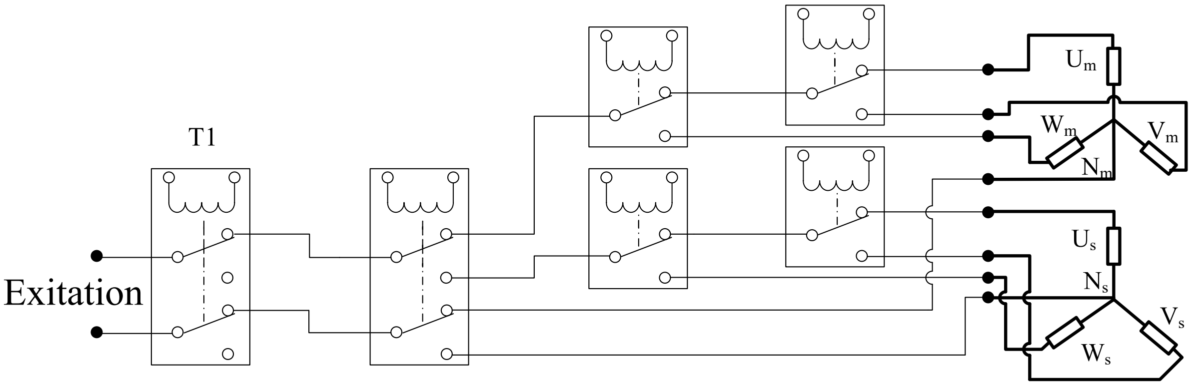


Fig. 3. Schematic of the relay connection, which is used to excite every phase coil separately to determine the inductances.

It is important to find the magnetic center of the rotor system as it is the ideal operation point. Magnetic center can be searched by rotating the first bearingless motor and measuring the induced voltage from the second motor levitation windings; and simultaneously moving the rotor in the airgap. The center point can be found by looking for the point where the induced voltage is zero in the levitation windings. Second method to determine the magnetic center is to use the force measurements. As the rotor comprises the permanent magnets the magnetic center can be found in the point where the net sum of the forces is zero after compensating for the gravity force vector acting on the *y*-axis. The second method was used to determine the magnetic center.

4. Parameter identification

Stable levitation control of bearingless machine is dependent on the machine parameters. For that reason machine identification is necessary. Inductance matrix where self and mutual inductances of the levitation and suspension windings are needed. Equation 1 shows the machine flux equations where self and mutual inductances between motor and suspension phases u,v, and w are revealed.. The required levitation force parameters H'_d and H'_q can be extracted from the mutual inductances, which are presented as a function of rotor position. The levitation force parameter ψ'_{PM} can be determined form an induced voltage of suspension winding as a function of the rotor position (Chiba, et al., 2015). Determination of ψ'_{PM} parameter is left out form this study due to rotation not being available during the measurements.

$$\begin{bmatrix} \psi_{um} \\ \psi_{vm} \\ \psi_{wm} \\ \psi_{us} \\ \psi_{vs} \\ \psi_{ws} \end{bmatrix} = \begin{bmatrix} L_{um} & M_{um-vm} & M_{um-wm} & M_{um-us} & M_{um-vs} & M_{um-ws} \\ * & L_{vm} & M_{vm-wm} & M_{vm-us} & M_{vm-vs} & M_{vm-ws} \\ * & * & L_{wm} & M_{wm-us} & M_{vm-vs} & M_{vm-ws} \\ * & * & * & L_{us} & M_{us-vs} & M_{us-ws} \\ * & * & * & * & L_{vs} & M_{vs-ws} \\ * & * & * & * & * & L_{ws} \end{bmatrix} \begin{bmatrix} i_{um} \\ i_{vm} \\ i_{wm} \\ i_{us} \\ i_{vs} \\ i_{ws} \end{bmatrix} \tag{1}$$

Inductance matrix is symmetrical. An asterisk mark describes that the mutual inductance values can be transposed to a lower triangle.

5. Inductance measurement

Inductance is determined with custom amplifier, which used to excite the target phase winding with sinusoidal current. The applied current is measured differentially from the amplifier output. At the same time the voltages over every phase winding are measured differentially. Based on the measured current and voltages together with the angular frequency of the excitation signal, inductances can be calculated. Self-inductance can be calculated using Eg. (2), which can be simply derived from Ohm's law of AC circuit. Similarly, mutual inductance can be calculated with Eq. (3) (Chiba, et al., 2015).

$$L = \frac{\sqrt{\frac{V^2}{I^2} - R^2}}{\omega} \tag{2}$$

$$M_{xy} = \frac{V_y}{\omega I_x} \tag{3}$$

Voltage and current used in Eq. (1) and (2) are RMS values. To achieve RMS value of the measured sinusoidal current and voltage signals in real-time the IQ-demodulation method is used. When digitally implemented this method is also called as digital lock-in detection (Masciotti, et al., 2004). In this modulation/demodulation method, the treated signal is divided to I (in phase) and Q (quadrature) components. Amplitude A, and the phase shift θ, can be calculated using the I and the Q components which are shown in Eq. (3) and (5). Figure 4a shows I and Q components in the unit circle.

$$A = \sqrt{I^2 + Q^2} \tag{4}$$

$$\theta = a\tan\frac{Q}{I} \tag{5}$$

IQ-demodulation is implemented as presented in Fig. 4b. The carrier signal which is supplied to the amplifier is marked as ε. The measured signal that is in this case a voltage is marked as V. R, is a reference signal that is fed to the amplifier. To get the I and Q components of measured signal it is multiplied with cosine and sine signals, respectively.

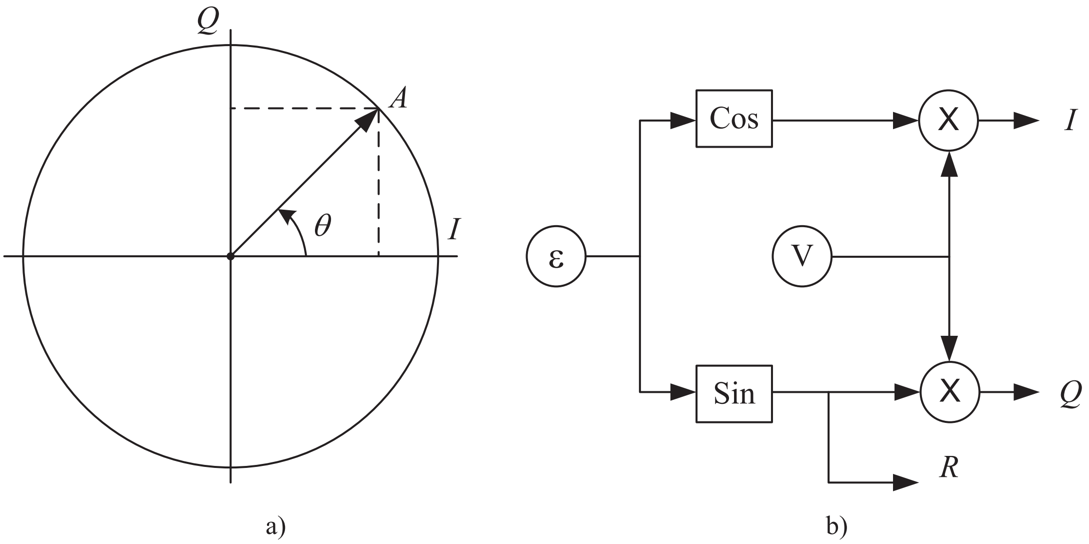


Fig. 4 a) Unit circle presentation of I and Q components which can be used to calculate the amplitude A and phase shift θ. b) Implemented digital lock-in detection to calculate I and Q components from measured signal V and excitation signal ε. Reference signal R is fed to the amplifier.

Employing the presented demodulation method and using the Eq. (2-5) self- and mutual inductances of the bearingless motor can be determined in real-time. However, only amplitude and phase values of voltages and current where measured and the inductances where calculated offline.

6. Measurement results

Inductance measurements where done by presented automated procedure. Rotor was moved in the air-gap from -150µm to +150µm with 30µm steps in x-axis. Measurement set consists only one angular position of the rotor. Measured self and mutual inductances are illustrated in Fig. 5 and 6.

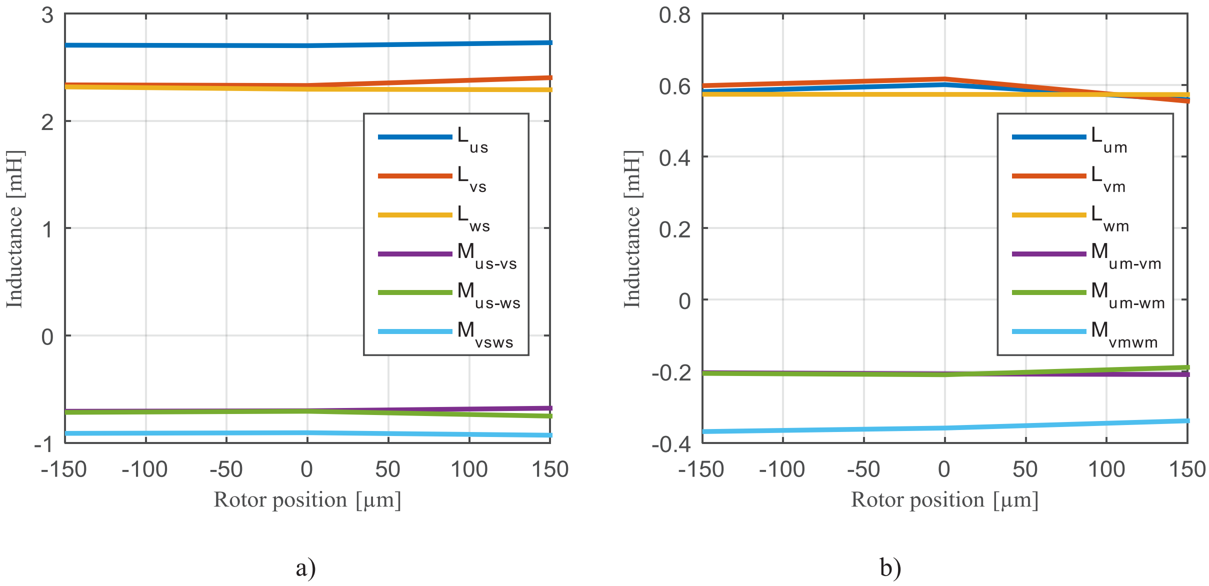


Fig. 5 Self and mutual inductance in function of rotor position in x-axis. a) Levitation windings b) Motor windings

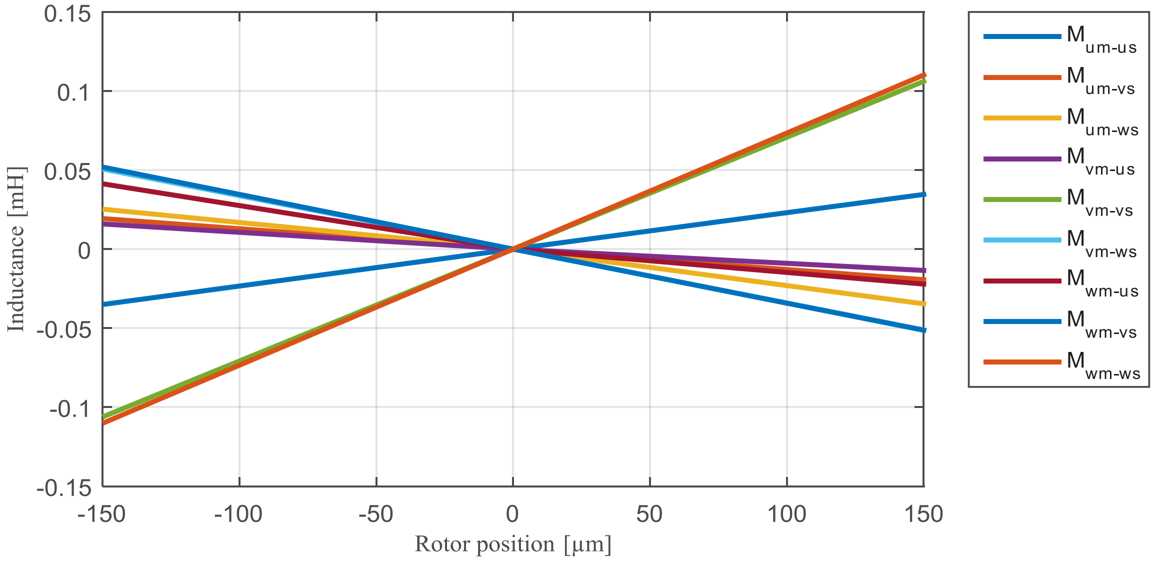
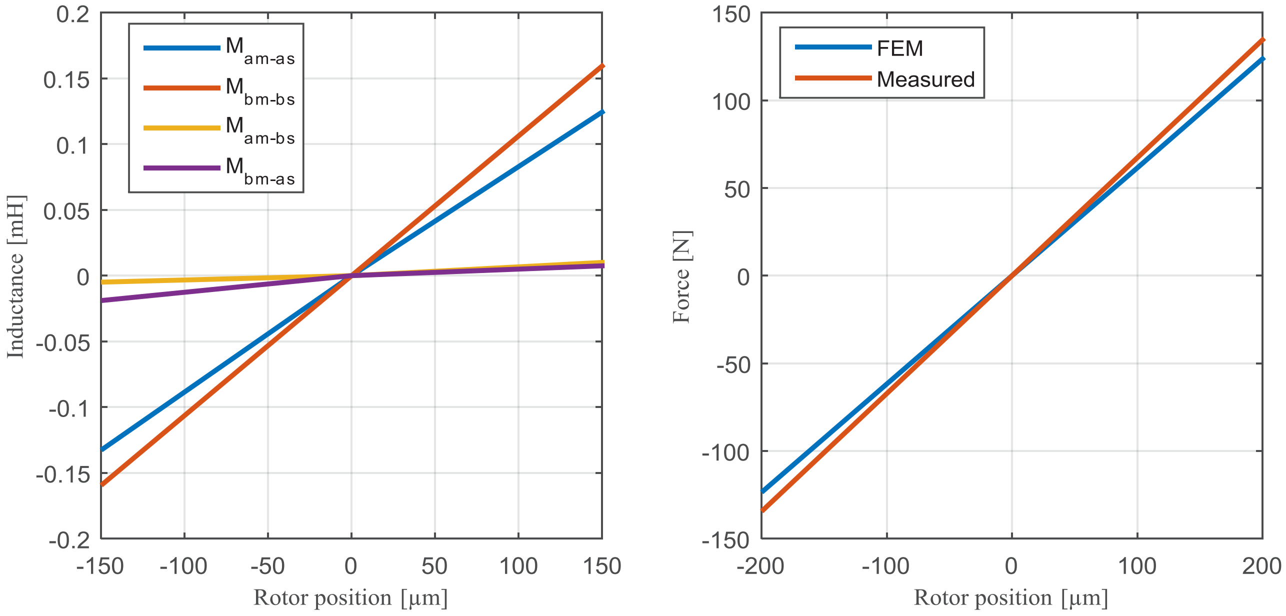


Fig. 6 Mutual inductances between motor and levitation windings in function of rotor position in x-axis.

Effect of the rotor saliency can be seen in Fig. 5. This shows that the inductance is varying when the rotor is rotating. Inductances must be measured with different rotor angles to determine this fluctuation. Mutual coupling in function of the rotor position in the Fig. 6 shows that the magnetic center was correctly found.

The self and mutual inductance presented in Eq. (1) are transformed from 3-phase presentation to 2-phase presentation for easier handling (Chiba, et al., 2015). The mutual inductances in 2-phase reference frame are shown in Fig. 7a. Also in here, the saliency of the rotor is affecting to the inductances. Parameters used in the levitation control can be derived from slopes of the mutual inductance values $M_{am\text{-}as}$ and $M_{bm\text{-}bs}$.

Unbalance magnetic pull (UMP) caused by the rotor permanent magnets were measured at the same time as voltages and current. Measurements are compared against the finite element modeling (FEM) software resulting in Fig. 7b. The achieved UMP is higher than in FEM simulation. This can be explained by mechanical manufacturing tolerances and permanent magnets remanent flux density variation.



a)

b)

Fig. 7 a) Mutual inductances in 2-phase reference frame. b) Unbalance magnetic pull form measurement and FEM analysis.

Motor windings where identified with using the ABB ACSM1 off-the-self motor drive which have a build-in identification procedure. Mechanical bearings where equipped during the identification. Inductances measured by the The identification results by ACSM1 drive and the presented inductance identification procedure in *dq*-reference frame are compared in Table 2. Small differences are caused by the measurement method.

Table 2. Comparison of motor *dq*-inductance measurements.

Inductance (method)	Value [mH]
I_d (Identification)	0.91
I_q (Identification)	0.93
I_d (ABB ACSM1)	0.91
I_q (ABB ACSM1)	0.97

7. Conclusion

The automated identification platform for magnetic levitation system is presented. Paper includes parameter identification of the double motor bearingless machine as a case study. Proposed identification platform can be used to identify the radial force generation capabilities of the magnetic levitation system. Automated measurement procedure improves the accuracy and significantly decreases the time used to find machine inductances compared to the manual measurement. Based on the achieved results it can be concluded that presented identification platform is suitable for force and inductance measurements. However, further measurements are needed to identify all parameters related to the IPM bearingless machine.

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