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Design and Experimental Analysis of a Selfbearing Double-Stator Linear-Rotary Actuator

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Abstract—Linear-rotary actuators (LiRAs) are today used in industry applications where a controlled linear and rotary motion is necessary such as pick-and-place robots, servo actuation of gearboxes or tooling machines. However, in special industry applications that require high purity and/or high precision positioning, the usage of conventional LiRAs with mechanical bearings is limited. Therefore, in this paper a LiRA with integrated magnetic bearings, i.e. a selfbearing/bearingless LiRA, is analyzed. The actuator employs concentrically arranged linear and rotary stators placed inside and outside a cylindrically shaped mover, which results in a so-called selfbearing double-stator (SBDS) LiRA. A FEM geometry optimization of the SBDS LiRA is performed and Pareto performance plots concerning linear force and torque generation are obtained. A SBDS LiRA hardware demonstrator and an 18-phase inverter power supply hardware prototype are built and their operation is experimentally verified by rotary and linear position step response measurements.

Index Terms—GaN Inverter, Linear-Rotary Actuators, Machine Geometry Pareto Optimization, Magnetic Bearings, Selfbearing, Bearingless

I. INTRODUCTION

In systems that simultaneously require controlled linear and rotary motion, direct drive linear-rotary actuators (LiRAs) are typically used. Examples of such systems are servo actuation of gearboxes [1], pick-and-place robots in semiconductor industry [2] and robot joints [3], to mention a few. LiRAs may be realized by coupling linear and rotary actuators in different ways, e.g. the rotary actuator can move the whole linear actuator or the linear and the rotary actuators can share the same mover [4]. An overview of possible LiRA coupling options can be found in [5]. Also, it is possible to have the stators displaced radially and/or arranged concentrically, resulting in a double-stator (DS) LiRA as shown in [6]. In this paper such type of the actuator, i.e. a DS LiRA, is analyzed. Compared to a conventional LiRA system, the analyzed DS LiRA has integrated magnetic bearings (MBs), as shown in Fig. 1. MBs offer several advantages such as possible usage in high purity applications and longer lifetime as no mechanical wear occurs or mover tilting control, advantageous in high precision pick-and-place applications [7]. Particularly, in food or pharmaceutical industries, actuators require high-purity and regular high-pressure washdowns, for what typically mechanical bearings have to be disassembled, resulting in larger downtimes and cost [8]. Advantageously, washdowns of SBDS LiRAs could be directly performed, without a need to disassemble any part, since an air gap between the mover and the stator is maintained with magnetic bearing forces.

In the following sections the proposed selfbearing DS (SBDS) LiRA design and optimization (cf. Sec. II), hardware prototype manufacturing (cf. Sec. III), inverter power supply design and manufacturing (cf. Sec. IV) and measurement results of the experimental analysis of a hardware demonstrator (cf. Sec. V) are presented.

II. ACTUATOR TOPOLOGY AND GEOMETRY

A. SBDS LiRA Geometry Parameters

The analyzed SBDS LiRA is shown in Fig. 1, where the outer rotary stators generate the torques $T_1$ and $T_2$ and the bearing forces $F_{b1}$ and $F_{b2}$, while the inner linear stator generates the linear (axial) force $F_z$ on the mover. Typically, the total generated torque on the mover is equally divided between the rotary stators, i.e. $T_{z1} = T_{z2} = T_z/2$, where the bearing forces $F_{b1}$ and $F_{b2}$ may be different and depend on the desired tilting of the mover and the radial load on the mover.

To determine an optimal SBDS LiRA geometry, an optimization based on a grid search method is performed. The method evaluates all possible designs for a given discrete design space of the parameters and it does not need any cost function. As both, magnetic and thermal performance of the SBDS LiRA depend on its geometry, it is necessary to establish magnetic (2D FEM) and thermal (analytic) models and evaluate them for each discrete point of the design space. The considered SBDS LiRA geometry parameters are shown in Fig. 2. Some of the parameters are kept fixed and some are swept in the optimization. The fixed parameters are given...
in Tab. I, where the swept parameters are listed in Tab. II. Some of the swept parameters are dependent by an expression to other geometrical parameters, as denoted in the last column in Tab. II.

**B. Geometry Optimization**

Prior to performing a geometry optimization it is necessary to establish magnetic and thermal models. The magnetic model is a magnetostatic 2D FEM model, which is formed by coupling MATLAB and ANSYS, i.e. a MATLAB script is written that creates a 2D FEM model in ANSYS, performs magnetostatic simulations, saves results and closes the ANSYS program. The thermal model is a lumped parameter steady-state model that consists of copper loss sources and thermal resistances calculated based on the assumed thermal conductivities given in Tab. I. The detailed calculation of each thermal model element is omitted here as it is a basic task once the thermal conductivities are assumed. Accordingly, only an equivalent thermal model is given in Fig. 3, where at the temperature measurement point $T_x$ (cf. Fig. 2) the heat flows from the outer rotary stator and the inner stator merge. The thermal resistances $R_{th,rot}$ and $R_{th,lin}$ are the total thermal resistances between the winding hot spot temperatures ($T_{w-1-6}$ for the rotary stator and $T_{c12}$ for the linear stator, cf. Fig. 2) and $T_x$, i.e. the region where both stators are mechanically attached. Further, $R_{th,ep}$ represents a thermal resistance of the aluminum end plate, which is proportional to the end plate thickness $r_{case}$. Finally, a thermal resistance between the SBDS LiRA end plate and the ambient is estimated assuming a pin fin heatsink with a diameter of 98 mm, a height of 50 mm and forced convection with 2 m/s air speed, which results in

**TABLE I:** Fixed geometry parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>Active length</td>
<td>100 mm</td>
</tr>
<tr>
<td>$D$</td>
<td>Outer diameter</td>
<td>100 mm</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>Axial stroke</td>
<td>30 mm</td>
</tr>
<tr>
<td>$r_{ag}$</td>
<td>Air gap</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>$D_{h}$</td>
<td>Cu pipe inner diam.</td>
<td>8 mm</td>
</tr>
<tr>
<td>Magnetic/Electric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_1$</td>
<td>PM magnetization</td>
<td>1.3 T</td>
</tr>
<tr>
<td>$\mu_{r,fo}$</td>
<td>Iron core rel. perm.</td>
<td>400</td>
</tr>
<tr>
<td>$k_T$</td>
<td>Wind fill factor</td>
<td>0.6</td>
</tr>
<tr>
<td>$N_{p,rot}$</td>
<td>Num. of rot. poles</td>
<td>16</td>
</tr>
<tr>
<td>$N_{p,lin}$</td>
<td>Num. of lin. poles</td>
<td>16</td>
</tr>
<tr>
<td>$N_{s,rot}$</td>
<td>Num. of rot. slots</td>
<td>6</td>
</tr>
<tr>
<td>$N_{s,lin}$</td>
<td>Num. of lin. slots</td>
<td>12</td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{amb}$</td>
<td>Ambient temperature</td>
<td>35 °C</td>
</tr>
<tr>
<td>$T_{w,\text{max}}$</td>
<td>Max. winding hot spot temp.</td>
<td>140 °C</td>
</tr>
<tr>
<td>$\lambda_w$</td>
<td>Therm. cond. of wind.</td>
<td>2 W/(mK)</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>Therm. cond. of copper</td>
<td>385 W/(mK)</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>Therm. cond. of iron</td>
<td>20 W/(mK)</td>
</tr>
<tr>
<td>$\lambda_{alu}$</td>
<td>Therm. cond. of alum.</td>
<td>200 W/(mK)</td>
</tr>
<tr>
<td>$\lambda_{ex}$</td>
<td>Therm. cond. of epoxy</td>
<td>0.1 W/(mK)</td>
</tr>
</tbody>
</table>

**TABLE II:** Swept geometry parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Range</th>
<th>Step</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{in,out}$</td>
<td>0.18, ..., 0.9</td>
<td>0.02</td>
<td>$D_{m}/D$</td>
</tr>
<tr>
<td>$k_{cu-fe,rot}$</td>
<td>0.78, ..., 0.9</td>
<td>0.02</td>
<td>$1 - \alpha_{co}(\lambda_{cu} - \lambda_{i})$</td>
</tr>
<tr>
<td>$k_{cu-fe,lin}$</td>
<td>0.5, ..., 0.7</td>
<td>0.01</td>
<td>$\tau_{in}/(\tau_{in} - \tau_{i})$</td>
</tr>
<tr>
<td>$k_{pm,rot}$</td>
<td>0.7, ..., 0.9</td>
<td>0.1</td>
<td>$\alpha_{pm}/(2\pi/N_{p,rot})$</td>
</tr>
<tr>
<td>$k_{pm,lin}$</td>
<td>0.8, ..., 0.9</td>
<td>0.1</td>
<td>$\tau_{pm}/(L/N_{p,lin})$</td>
</tr>
<tr>
<td>$r_{m}$</td>
<td>2.5, ..., 4 mm</td>
<td>0.5 mm</td>
<td>-</td>
</tr>
<tr>
<td>$r_{pm}$</td>
<td>2, 2.5 mm</td>
<td>0.5 mm</td>
<td>-</td>
</tr>
<tr>
<td>$r_{pipe}$</td>
<td>2, ..., 3 mm</td>
<td>0.5 mm</td>
<td>-</td>
</tr>
</tbody>
</table>

**Fig. 2:** SBDS LiRA parametrized geometry used in the optimization.

**Fig. 3:** Lumped parameter steady-state thermal model. Important temperature measurement points ($T_{w-1-6}$, $T_{c12}$, $T_x$, $T_{eq}$) are denoted in Fig. 2 in the SBDS LiRA geometry.

**Fig. 4:** Geometry optimization algorithm where first the admissible copper losses are calculated based on the established thermal model (cf. Fig. 3). From the admissible copper losses current stresses are obtained, which are used for the magnetic 2D FEM models where the torque $\vec{T}$ and the linear force $\vec{F}$ are calculated. This sequence of calculations is repeated for all geometry options defined by the discrete design space. The electrical resistance of a single rotary/linear coil is denoted as $R_{rot}/R_{lin}$. The considered current stress is twice as high than allowed by the stationary thermal properties of the SBDS LiRA, such that a chosen design finally features a factor of 2 of overload capability, without saturation of the magnetic parts occurring.
The chosen design has the following continuous operation performance:

- The scaling laws for the outer rotary and inner linear actuators, cf. [5].
- The expected trade-off between torque and linear force can be given. The expected trade-off between torque and linear force can be seen, since e.g. increasing the size of the inner stator reduces the outer stator size, and vice versa. This design trade-off can also be shown by scaling laws for the outer rotary and inner linear actuators, cf. [5]. The chosen design has the following continuous operation performance: torque - 6.24 Nm, linear force - 181.5 N, circumferential acceleration - 5.3 krad/s² and linear acceleration - 123.5 m/s².

![Circumferential Acceleration](image1)

**Fig. 5:** Pareto performance plots obtained using the optimization algorithm shown in Fig. 4. Torque $\vec{T}_z$ versus linear force $\vec{F}_z$ where by color (a) circumferential and (b) linear (axial) accelerations are given. The expected trade-off between torque and linear force can be seen, since e.g. increasing the size of the inner stator reduces the outer stator size, and vice versa. This design trade-off can also be shown by scaling laws for the outer rotary and inner linear actuators, cf. [5]. The chosen design has the following continuous operation performance: torque - 6.24 Nm, linear force - 181.5 N, circumferential acceleration - 5.3 krad/s² and linear acceleration - 123.5 m/s².

- The allowed copper losses per rotary stator, $P_{cu,rot}$, and in the linear stator, $P_{cu,lin}$, can be calculated from the obtained thermal resistances and the assumed winding hot spot $(T_{w1-6} = T_{c12} = T_{w,\text{max}})$ and ambient temperatures $T_{\text{amb}}$, where $T_{w,\text{max}}$ and $T_{\text{amb}}$ are given in Tab. I. By solving the circuit in Fig. 3, copper losses are calculated as

\[
P_{cu,\text{rot}} = \frac{R_{th,\text{lin}}}{2R_{th,\text{par}}(R_{th,\text{rot}} + R_{th,\text{lin}})}(T_{w,\text{max}} - T_{\text{amb}}),
\]

\[
P_{cu,\text{lin}} = \frac{R_{th,\text{lin}}}{R_{th,\text{par}}(R_{th,\text{rot}} + R_{th,\text{lin}})}(T_{w,\text{max}} - T_{\text{amb}}),
\]

where

\[
R_{th,\text{par}} = \frac{R_{th,\text{rot}}R_{th,\text{lin}}}{R_{th,\text{rot}} + R_{th,\text{lin}}} + R_{th,\text{ep}} + R_{th,\text{amb}}.
\]

After the thermally permissible electrical loading of the SBDS LiRA windings is determined, the allowed ampere turns for the rotary and linear stators are calculated, as shown in the optimization algorithm in Fig. 4. From the ampere turns, the current density in the SBDS LiRA rotary and linear stators is obtained and it is used for 2D FEM magnetic simulations where the torque $\vec{T}_z$ and the linear force $\vec{F}_z$ are calculated, cf. Fig. 4. In post processing, all the necessary data, such as mass, volume of the parts and circumferential and linear accelerations, are calculated.

**C. Optimization Results**

The optimization results are shown in Fig. 5, where torque versus linear force is plotted and the related accelerations are given by the color of the dots. The total number of design combinations in the discrete design space is 24192, but in Fig. 5 only the performance of 158 parameter combinations is shown. These are the only valid designs where the saturation of the iron core parts does not occur. More specifically, the flux density level in any point of the SBDS LiRA magnetic parts satisfies the following: $< 2.1 \text{T}$ for the outer stator (electrical steel), $< 1.4 \text{T}$ for the inner stator (steel ST52) and $< 2.1 \text{T}$ for the mover back iron (soft iron). Additionally, it should be mentioned that the shown designs feature a factor of 2 of overload capability, i.e. for a short time the SBDS LiRA may generate twice the torque/force that is thermally possible in continuous operation. The chosen design in Fig. 5 does not feature the maximum possible linear force as according

![Linear Acceleration](image2)

![3D FEM flux density distribution of the chosen design, cf. Fig. 5. The simulation is done for twice the thermally allowed current ($N_{rot} I_{rot} = 2028.6 \text{Aturns}$ and $N_{lin} I_{lin} = 685.2 \text{Aturns}$), in order to check for eventual saturation of the SBDS LiRA iron parts.](image3)
D. Effect of the Copper Pipe on Cooling

To show the effect of the copper pipe on the cooling of the inner linear stator of the SBDS LiRA, the chosen design is simulated. The inner stator of the SBDS LiRA is held from one axial end with a mechanical assembly, which is also used for cooling, i.e. an axial conductive heat flow through the inner stator is assumed. A consequence of the axial heat flow is a temperature difference along the inner stator, which can be rather high. In order to reduce this temperature difference and also the total axial thermal resistance, a design with a copper pipe inserted inside the inner stator back iron is proposed, as shown in Fig. 7(a). Due to around 20 times higher thermal conductivity of the copper compared to the stator iron core the total axial thermal resistance reduces, but the reduction of cross section of the magnetic iron core material potentially causes magnetic saturation of the inner stator and limits its overload capability. Therefore, there is an optimum amount of ‘magnetically’ and ‘thermally’ conductive materials in the inner linear stator that leads to a maximum linear force per unit of copper loss, which is determined in the established optimization routine. The effect of the copper pipe on the cooling of the inner stator is clearly shown in Fig. 7, where the optimized design geometry is simulated with and without a copper pipe.

III. SBDS LiRA HARDWARE REALIZATION

After the SBDS LiRA geometry is optimized and all geometrical parameters are determined, a CAD model of the prototype is established. In Fig. 8 the model of the outer rotary stator is shown. In order to magnetically levitate the mover of the SBDS LiRA, position sensors are needed on both axial ends of the actuator, which are realized on a PCB. Therefore, two sensor PCBs, SB1 and SB2, are assumed. For the winding power connections, also a PCB is used as there are 2 stators × 6 coils × 2 wire ends = 24 wire connections.

The chosen SBDS LiRA design (see Pareto plot in Fig. 5) is realized in hardware. In Fig. 9 the outer rotary stator core without and with the concentrated windings is shown. The stator core is realized from electrical steel laminations and it is insulated from the windings with Kapton tape. The windings are built from a self-bonding wire such that no coil former is needed, where the wire diameter and the number of turns \(N_{rot}\) are determined from the following considerations. The upper limit on the wire diameter is obtained by considering skin effect and/or the skin depth \(\delta_{cu,rot}\) =
\[ \sqrt{2 \rho_{\text{cu}}/(\mu_0 \cdot \omega)} = 3.26 \text{ mm}, \] where \( \rho_{\text{cu}} = 1.68 \times 10^{-8} \Omega \text{m}, \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) and the angular frequency is calculated assuming a maximum rotor speed of \( \omega = \omega_{\text{rot}} = N_{p,\text{rot}} \cdot (\pi/30) \cdot 3000 \text{ rpm} = 2513.3 \text{ rad/s} \); \( N_{p,\text{rot}} = 16 \) is the number of PM poles of the mover on the outer rotary side, cf. Tab. I. Typically, in electric machine design, the maximum wire diameter is set such that it is smaller than either a half \( (< \delta_{\text{cu,rot}}/2) \) or a quarter \( (< \delta_{\text{cu,rot}}/4) \) of the expected skin depth \( \delta_{\text{cu,rot}} \). Since the SBDS LiRA stator has open tooth and the windings are exposed to the PM field, the wire diameter is chosen considering \( D_{\text{wire,rot}} < \delta_{\text{cu,rot}}/4 = 0.81 \text{ mm} \), resulting in \( D_{\text{wire,rot}} = 0.8 \text{ mm} \). The number of turns \( N_{\text{rot}} \) is estimated from the available winding window area \( A_{w,\text{rot}} = 148.7 \text{ mm}^2 \) as \( N_{\text{rot}} = \text{round}(k_{\text{ff}} \cdot A_{w,\text{rot}}/D_{\text{wire,rot}}) = 187 \text{ turns}, \) where \( k_{\text{ff}} = 0.6 \) is the fill factor and \( A_{w,\text{rot}} = \pi D_{\text{wire,rot}}^2/4 = 0.5 \text{ mm}^2 \) is the wire cross section area. Finally, the prototype is built with \( N_{\text{rot}} = 190 \text{ turns}, \) cf. Fig. 9. The maximum expected induced voltage in the rotary coil is estimated using the total flux in the tooth \( \Phi_{\text{rot}} = 0.11 \text{ mWb} \) (calculated using 3D FEM simulation), as \( E_{\text{rot}} = N_{\text{rot}} \cdot \omega_{\text{rot}} \cdot \Phi_{\text{rot}} = 52.5 \text{ V}. \) From the thermally allowed ampere turns, the phase current peak value is \( I_{\text{rot}} = 1014 \text{ Aturns}/N_{\text{rot}} = 5.3 \text{ A}. \) The values for the induced voltage and the phase current, \( E_{\text{rot}} \) and \( I_{\text{rot}} \), are used later for the inverter design.

A similar winding design approach is applied for the inner linear stator of the SBDS LiRA. The maximum electrical frequency is calculated as \( \omega_{\text{lin}} = (2\pi/\tau_{\text{pp}})v_z = 502.6 \text{ rad/s}, \) where \( \tau_{\text{pp}} = 2L/N_{p,\text{lin}} = 12.5 \text{ mm} \) is the linear actuator pole pair size and \( v_z = 1 \text{ m/s} \) is the assumed maximum linear speed. For this angular frequency, the skin depth is \( \delta_{\text{cu,lin}} = 7.3 \text{ mm}, \) which imposes the limit on the maximum wire diameter \( D_{\text{wire,lin}} < \delta_{\text{cu,lin}}/4 = 1.82 \text{ mm}. \) As a wire of such large diameter would be difficult to wind onto the stator core, the wire diameter is estimated such that a similar induced voltage is obtained as for the rotary winding, which allows to supply both windings (rotary and linear) from the same DC link inverter. Therefore, in the first step the number of winding turns is obtained as \( N_{\text{lin}} = \text{round}(E_{\text{lin}}/(\omega_{\text{lin}} \cdot \Phi_{\text{lin}})) = 156 \text{ turns}, \) where \( E_{\text{lin}} = E_{\text{rot}} = 52.5 \text{ V} \) and \( \Phi_{\text{lin}} = 0.672 \text{ mWb} \) (obtained from 3D FEM simulation). The wire cross section area is calculated as \( A_{\text{wire,lin}} = k_{\text{ff}} \cdot A_{w,\text{lin}}/N_{\text{lin}} = 0.18 \text{ mm}^2, \) which results in a wire diameter of \( D_{\text{wire,lin}} = 2\sqrt{A_{\text{wire,lin}}/\pi} = 0.48 \text{ mm}, \) which also satisfies the skin depth condition. Finally, the inner linear stator winding is realized with a wire diameter of \( D_{\text{wire,lin}} = 0.5 \text{ mm}, \) cf. Fig. 10. The prototype employs \( N_{\text{lin}} = 150 \text{ turns per coil}, \) where two coils constitute a phase winding, e.g. two coils around a tooth are carrying the same phase current but in opposite directions, as denoted for phase A in Fig. 10. For the prototype realization of the inner linear stator (cf. Fig. 10), the stator iron core is used as ‘coil former’ where individual coils are wound on the stator core pieces and afterwards all coils are pressed with a pin nut to form the overall stator. The copper pipe is press fitted into the stator iron core, such that a good thermal contact is established.

The mover hardware prototype realization is shown in Fig. 11. The rotary set of PMs is glued on the outer side of the mover back iron and covered with an aluminum sleeve, cf. Fig. 11(a). Mounting of the inner set of PMs was performed in two steps: first the PMs are glued onto a thin aluminum tube which is then inserted into the cylindrical mover, cf. Fig. 11(b). The assembled mover shows a mass of \( m = 1.24 \text{ kg} \) and a moment of inertia of \( J = 0.00145 \text{ kgm}^2. \)

Before assembly, the rotary stator core with windings is inserted into an aluminum case (cf. Fig. 8) and potted with epoxy: WEVOPOX 2513 mixed with WEVODUR HC1003 in ratio 100 : 13. In the next step, the outer and the inner stators (cf. Fig. 9 and Fig. 10) are mechanically assembled as shown.
in Fig. 12. The connection box has two cable glances, one for the power cable [12] and another one for the sensor cable [13]. The cable duct is used to connect the PCB integrated position sensors SB 2 with the inverter control, cf. Fig. 8.

IV. 18-PHASE INVERTER HARDWARE REALIZATION

In order to supply the SBDS LiRA, an inverter stage is designed and realized in hardware. In Fig. 13 a schematic of a single inverter phase with an LC output filter is shown. On one hand, the output filter reduces high frequency noise in the output current and provides a ‘smooth’ output voltage to the SBDS LiRA stator windings, which also increases the signal-to-noise ratio of integrated position sensors which is important for precise position control and high control bandwidth of the actuator (cf. [15]). On the other hand, the output filter due to its low pass nature limits the output voltage $v_{out}$ and consequently the output current $i_{out}$ control dynamics. Additionally, it complicates the current controller design as three cascaded control loops have to be implemented: (1) inner $i_L$ current control loop; (2) middle $v_{out}$ output (capacitor) voltage control loop and (3) outer $i_{out}$ output current control loop.

Based on the voltage and current requirements of the SBDS LiRA, the specifications for the inverter design and optimization are defined and given in Tab. IV. The switching frequency is selected as $f_{sw} = 140$ kHz as typical for 400 V GaN inverter systems. A total of 15 phases of the SBDS LiRA are to be supplied. As the inverter features 18 phases it could also be used to supply other types of actuators such as magnetically levitated tubular linear actuators with 18 phases [16].

The inverter hardware prototype is shown in Fig. 14. whose heatsink and output filter inductor have been optimized for efficiency and power density. The used power semiconductors are $600 \text{ V}$, $70 \text{ m}\Omega$ CoolGaN-MOSFETs [17]. The inductor is realized with ferrite N87 RM12 core, which has $80 \text{ m}\mu\text{H}$ inductance achieved with $23 \text{ turns}$ of $1.8 \text{ mm}$ diameter litz wire ($300 \times 71 \text{ m}\mu\text{m}$ strands).

V. EXPERIMENTAL ANALYSIS

The SBDS LiRA (cf. Fig. 12) is mounted into a customized test-bench where the mover can be held via auxiliary mechanical bearings until the magnetic bearings are commissioned. The test-bench features a torque sensor (cf. [18]), force sensors for the bearing force measurements (cf. [19]) and a force sensor for the linear force measurement (cf. [20]).

![Diagram showing the connection box with two cable glances, one for the power cable and another one for the sensor cable. The cable duct is used to connect the PCB integrated position sensors SB 2 with the inverter control.](image)

**Fig. 12:** SBDS LiRA prototype with the outer rotary (cf. Fig. 8 and Fig. 9) and the inner linear (cf. Fig. 10) stators assembled.

![Diagram showing the SBDS LiRA circuit schematic of an inverter phase with output filter inductor $L = 80 \mu\text{H}$ and filter capacitor $C = 4.8 \mu\text{F}$. The damping resistance $R_d = 6 \Omega$ and capacitance $C_d = C$ are chosen according to [14], considering $n = 1$.](image)

**Fig. 13:** SBDS LiRA circuit schematic of an inverter phase with output filter inductor $L = 80 \mu\text{H}$ and filter capacitor $C = 4.8 \mu\text{F}$. The damping resistance $R_d = 6 \Omega$ and capacitance $C_d = C$ are chosen according to [14], considering $n = 1$.

**Fig. 14:** Top and bottom view of the SBDS LiRA inverter prototype. The inverter has a single power input supplied from a 400 V DC source and features $6 \times 3$ phase outputs. The inverter features a UART communication interface and a position sensor interface. The low voltage circuitry is supplied from a 12 V auxiliary supply.

**TABLE IV: SBDS LiRA Inverter Specifications.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}$</td>
<td>DC link voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>Output phase current peak</td>
<td>10 A</td>
</tr>
<tr>
<td>$f_{out}$</td>
<td>Output fundamental frequency</td>
<td>400 Hz</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>Switching frequency</td>
<td>140 kHz</td>
</tr>
<tr>
<td>$N_{ph}$</td>
<td>Number of phases</td>
<td>18</td>
</tr>
</tbody>
</table>

![Diagram showing the inverter hardware prototype with heatsink, output filter inductor, UART communication interface, auxiliary 12V supply, positions sensor interface, fans, and electrolytic DC-link capacitors.](image)
A. Torque/Force Constant Measurement

In order to verify the FEM models used for the optimization of the SBDS LiRA, flux linkages ($\Psi_{\text{rot}}$ and $\Psi_{\text{lin}}$) and torque/force constants ($K_T$ and $K_L$) are measured. The measured flux linkage for the rotary actuator is estimated in a first step from the voltage constant measurement (cf. Fig. 15(a)), where the voltage constant is equal to $K_{V,\text{rot}} = (N_{p,\text{rot}}/2) \cdot \Psi_{\text{rot}}$. Therefore, the measured flux linkage of the rotary stator is equal to $K_{V,\text{rot}} \cdot (2/N_{p,\text{rot}}) = 0.1657 \text{ V/(rad/s)} / 8 = 0.2071 \text{ mWb}$, as given in Tab. V. The larger relative error for the torque constant can be attributed to mechanical friction of the auxiliary bearings that are used during these initial measurements. Since for the linear stator the flux linkage measurement is estimated from the linear force constant as $\Psi_{\text{lin}} = K_L \cdot \tau_{\text{pp}}/(3\pi)$, cf. [21], the relative error has the same value. Finally, Tab. V shows that the FEM simulation results and measurements are in good agreement, which verifies the used models.

B. PID Controller of the Rotary and Linear Position

To verify the operation of the SBDS LiRA and its inverter power supply, rotary position control and linear position control are analyzed separately. The implemented position controls are employing PID-type controllers.

In Fig. 16 a step response of the rotary angle $\alpha$ is shown (see Fig. 1 for the angle notation). The reference $\alpha^*$ follows a sigmoid shaped function with the rise time of around 50 ms.

The rotational PID controller gains are equal to $K_{p,\text{rot}} = 25 \text{ N/rad}$, $K_{i,\text{rot}} = 99 \text{ N rad/s}$ and $K_{d,\text{rot}} = 0.8 \text{ N s/rad}$, where the proportional gain is chosen such that a stable and highly dynamic control is achieved, which resulted in good reference tracking (cf. Fig. 16). The maximum occurring speed $n_{\alpha}$ is around 700 rpm.

In Fig. 17 a step response of the linear position $z$ is depicted, where the reference $z^*$ shows a sigmoid shape with a rise time of around 150 ms. Again, a PID controller is tuned for high bandwidth, which results in the following gain values: $K_{p,\text{lin}} = 125 \text{ N/m}$, $K_{i,\text{lin}} = 5862 \text{ N m/s}$ and $K_{d,\text{lin}} = 1 \text{ N s/m}$. The maximum occurring linear speed is around 0.1 m/s. The peculiar time behavior of the linear force results from the cogging forces, which show peak values of ±30 N.

The results shown in Fig. 16 and Fig. 17 verify the SBDS LiRA rotary and linear operation. In future work, a simultaneous rotary-linear operation will be tested.

VI. CONCLUSIONS

In this paper a design procedure for a self-bearing double-stator linear-rotary actuator (SBDS LiRA) is shown. The axial heat flow of the inner stator of the actuator is enhanced with an inserted copper pipe. A geometry optimization is performed which uses 2D FEM models coupled with an analytic thermal model. From the axial force $F_x$ vs. axial torque $T_x$ Pareto plots a design candidate is chosen and a hardware prototype...
is assembled. To supply the SBDS LiRA, an 18-phase inverter supply is designed and a hardware prototype is built. Initial measurement results verify the used FEM models where the simulated and the measured SBDS LiRA torque constants differ by 8.7%. Measurement results of rotary and linear position step responses verify the SBDS LiRA rotary and linear stator operation.

Future work focuses on the simultaneous operation of the SBDS LiRA rotary and linear stators with full magnetic levitation. Furthermore, a detailed verification of the thermal properties and the maximum torque and force generation will be carried out.

**REFERENCES**


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