Optimization of Contactless Planar Actuator With Manipulator

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This paper describes the optimization of a contactless electromagnetic planar actuator (6 degree-of-freedom) with manipulator on top of the floating platform. The manipulator causes disturbance forces and torques that must be counteracted by the magnetic bearings. In addition, the energy necessary to operate the manipulator is transferred by means of an inductive coupling, which is integrated in the magnetic bearings. The requirements for the planar actuator in such a system are discussed in this paper as well as the optimization variables, goals, and constraints. In addition, the influence of the accuracy of the combined analytical-numerical model of the planar actuator on the optimization is addressed. Finally, the topology is presented that meets all criteria.

Index Terms—Contactless, magnetic levitation, magnetic suspension, optimization, planar actuator.

I. INTRODUCTION

CONTACTLESS planar actuators are being developed for the next generation high-precision machines [1]–[6]. These actuators have six degrees-of-freedom (6DOF) and are suspended by magnetic bearings, which also generate the propulsion forces. Long-stroke movement is achieved in an x–y plane, while short-stroke movements in z-direction and small rotations remain possible. Since the movers of these actuators operate without any mechanical or electrical contact with the stationary part, they are suitable for operation in vacuum.

In most applications the planar actuator has a static payload, e.g., a wafer on top of the planar actuator mover. However, in other cases, the planar actuator is part of a larger system and can contain a measurement system or manipulator on top of it (parallel processing). These systems cause dynamic disturbance forces and torques to act on the planar actuator. In addition, these systems add weight to the planar actuator, which has to be compensated by the magnetic bearings. Energy needs to be transferred to the moving platform in order to power the systems on top of it.

In Fig. 1, a drawing of the system is shown that is currently under development at Eindhoven University of Technology. This system consists of a planar actuator with moving magnets, stationary coils, and a manipulator on top. The manipulator is an H-drive with two linear motors for translating the beam and a rotary motor on the beam with an arm to create a x–y manipulator. Possible applications are measurement, inspection, or manufacturing tasks on the platform, possibly in synchronization with other robots on the fixed world.

II. CONTACTLESS ENERGY TRANSFER (CET)

The energy necessary to operate the manipulator, power electronics and control systems is done by means of CET [9], [10]. The coils on the fixed world, therefore, have a dual function. When a coil is covered by the magnets, it will generate forces and torques. If it is overlapped by the secondary coil, the coil will act as a primary coil of an inductive coupling. Separate power supplies are used to realize both functions with the same coil. Additionally, the CET requires an ac current of 50–200 kHz to ensure sufficient efficiency, which requires the coils to be made of litz wire. Litz wire is a stranded wire bundle, where each strand is separately isolated to prevent eddy current losses due to the skin and proximity effect. The main drawback is a low filling factor of the coil (approximately 50% less than a solid wire coil), which results in a higher power dissipation in the coils. It is assumed that only 30% of the coil cross-section is actually copper, i.e., a filling factor of 0.3.

III. OPTIMIZATION OF THE PLANAR ACTUATOR

The number of variables involved in finding an optimal design is enormous, it includes magnet array topology (e.g., Halbach or N-S array), coil topology (e.g., number of phases), and the dimensions of the magnets and coils involved. Limits such as maximum current, maximum back-EMF, maximum temperature, and maximum condition number should be included in the optimization problem as constraints.

It is difficult, if not impossible, to include topology optimization (e.g., Halbach or N-S, 2-phase, or 3-phase), shape optimization (round, rectangular, or square coils) and geometrical optimization (magnet height, coil height, etc.) into one optimization routine. Therefore, the best approach would be to choose several topologies with fixed shapes and then to do a geometrical optimization for each problem to find the optimal solution.

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IV. Optimization Variables

Due to the complexity of the planar actuator design, the optimization is reduced to a geometric optimization for a fixed coil topology and fixed magnet topology. The Halbach magnet topology is fixed by the number of poles in the array (e.g., 8 × 8 or 9 × 9) and the pole pitch. The coil topology is fixed by the number of phases in the coil array, which is determined by the electrical degrees between each coil with the pole pitch being equal to 180 electrical degrees.

It is possible to use rectangular coils if the magnet array is 45 degrees rotated with respect to the coil array [3]–[5]. However, as rectangular coils can only generate forces in two directions, there are two orientations of rectangular coils necessary to generate forces in three directions. This results in an irregular pattern of coils that complicates the contactless energy transfer. Therefore, only topologies, where the magnet array and the coil array are aligned, are taken into account in the optimization. The N-S array is not considered as a possible array in this optimization since it produces less force than the Halbach array [5]. The variables that cannot be included in an optimization routine are varied by means of a parametric search. For a certain set of variables the geometric optimization is carried out and by comparing the results for the different topologies in the set a final selection is made.

The following variables are included by means of parametric search.

1) Pole Pitch \( \tau \): The pole pitch is varied in steps of 5 mm.
2) Number of Magnet Poles: \( n \times n \) for \( n = 8, 9, 10 \).
3) Coil Phases: Three different coil phase systems are considered in the optimization, with coils that are shifted 225, 240, and 270 electrical degrees, respectively.

Since \( \tau \) represents 180 electrical degrees, a coil that is shifted 240 electrical degrees has a coil width \( c_{w} \) of \( \frac{240}{180} \tau \).

With the topology and the pole pitch defined the remaining variables that are included in the optimization are as follows.

1) Magnet Ratio: The magnet ratio \( r_{m} \) between the width of the N-S magnets in the Halbach array \( (m_{w}) \) and the pole pitch \( \tau \) is defined by
   \[
   r_{m} = \frac{m_{w}}{\tau}. 
   \] (1)

2) Coil Bundle Ratio: The ratio between the coil bundle width \( c_{l_{co}} \) and the coil width \( c_{w} \) is defined by
   \[
   r_{c} = \frac{c_{l_{co}}}{c_{w}}. 
   \] (2)

3) Magnet Height: The height of the magnets \( m_{h} \) is included in the optimization.
4) Coil Bundle Height: The height of the coil bundle \( c_{l_{co}} \) is included in the optimization.

The geometrical variables are shown in Fig. 2.

V. Optimization Constraints

The constraints are two geometrical and one thermal inequality constraint. In addition, there are other considerations that are not hard constraints, but will be taken into account when deciding which final topology is chosen. First, the constraints are discussed as follows:

1) \( m_{w} < \tau \); 2) \( 2c_{l_{co}} < c_{w} \); 3) \( T_{ct} < 120 \degree C \); where \( T_{ct} \) is the coil top surface temperature. A thermal network is used to calculate the temperatures in the coil.

VI. Optimization Objective

The total weight of the levitated system \( F_{z} \) results in a high power dissipation in the coils. Therefore, the losses in the coils should be minimized. Since the planar actuator consists of a large set of modular coils with separate amplifiers, it is in fact a combination of many 1-DOF actuators. Due to the fact that electromagnetically this system is linear (no iron, no saturation), the principle of superposition is valid for force calculation. Moreover, optimization of \( |F| \) means an optimization of \( F_{z} \). To achieve this, a single coil is placed underneath the magnet array with the center of the coil aligned with a magnet pole, where it only generates lift force. Then the required current \( i_{c} \) in the coil is calculated to compensate \( F_{z} \). The optimization routine then minimizes the resulting resistive losses \( P_{\text{loss}} \) in that single coil

\[
P_{\text{loss}} = \min_{K_{c} = K} \frac{\varphi^{2} R}{K_{c}F_{z}} 
\] (3)

where \( K \) is the constant that expresses the force per ampere.

VII. Additional Considerations

Besides the losses and temperatures, there are practical issues that affect the optimal design, which is the total levitated mass, the availability of amplifiers, the control complexity, the integration of the contactless energy transfer, and the manufacturability of all components.

A. Control Complexity

The planar actuator is over actuated and thus requires a large number of coils to generate the desired force and torque on the platform. The controller should be able to calculate all these coil currents within one sample time.

B. Levitated Mass and Stiffness

The moving platform should be stiff in order to prevent flexible modes and resonances, which will limit the performance. In general, the stiffness of the platform reduces when it becomes
larger and additionally the mass increases. Since resonance frequencies scale with $\sqrt{k/m}$, a higher mass $m$, and a lower stiffness $k$, result in resonances at lower frequencies. Therefore, the platform should be reasonably small, stiff, and light. The levitated mass is estimated by the total mass of the magnets, a glue filling in between the Halbach magnets, an aluminum backplate of 10 mm behind the magnets, and a total load of the manipulator of 6 kg.

C. CET

The contactless energy transfer is influenced by the optimization of the planar actuator, since the inductance of the actuator coil determines part of the CET characteristics. The inductance $L$ and hence, the number of turns $N$ is an important characteristic. The energy transfer occurs at a high frequency ($f_{\text{res}} = 50–200$ kHz) and the voltage over the coil in the resonance circuit is set by these parameters according to

$$V_{\text{coil}} = 2\sqrt{2\pi f_{\text{res}}} LI_1$$

where $I_1$ is the root mean square (RMS) current through the coil. A high inductance results in a high resonance voltage and thus a high voltage over each winding. Several other factors determine the behavior of the CET, such as secondary coil inductance, load impedance, and resonance frequency [9], [10]. However, an estimate of the expected resonant voltage over the primary coil is done to verify the feasibility of contactless energy transfer.

D. Amplifier Specification

The choice of $N$ for the primary coil depends on the maximum number of amperes turns that are necessary to levitate and accelerate the platform and the amplifier used to supply the current. In addition, the amplifiers use switching electronics to control the current in the coil. If the inductance becomes too low (i.e., $< 0.5$ mH), the switching results in significant current ripples that reduce the performance of the system. Furthermore, amplifiers work at a certain voltage $V_a$ which has to be sufficient to overcome the back-EMF due to the movement of the magnet array, the resistive losses in the coils and the voltage drop due to the time derivative of the current in the coil

$$V_a = R_i + L \frac{di}{dt} + E_{\text{back-EMF}}.$$  

If the number of turns in the coil is large, the back-EMF will be too high for the amplifier to generate the desired $(di/dt)$.

VIII. OPTIMIZATION APPROACH

The optimization of the planar actuator is split in two parts: a geometrical optimization and a parametric search, described as follows.

1) Geometrical Optimization: For each topology that is considered the optimal dimensions of the coils and magnets are calculated, that minimizes the loss in a single coil according to (3).

2) Parametric Search: Using the dimensions from the geometrical optimization the behavior of the entire planar actuator is calculated using a combined analytical numerical model from which the thermal and CET characteristics are derived.

A. Geometrical Optimization

The Lorentz force principle is used to calculate the force $F_c$ that is applied on the coil by numerically integrating the outer product of the current density in the coil $J_c$ and the magnetic flux density $B_{m1}$ in the volume of the coil $V_c$ generated by the magnet array

$$F_c = \int_{V_c} J_c \times B_{m1} dV_c.$$  

The magnetic field density can be calculated using the surface charge model as described in [5], [6], and [8]. An analytical spatial harmonics representation of the magnetic field is used as described in [6]. Moreover, only the first harmonic of the magnetic field is included in the analysis. Higher harmonics do not greatly effect the optimal dimensions. The change of the dimensions by using more accurate models (by using higher harmonics or surface charge) is in the order of the manufacturing tolerances of the coil and is, therefore, useless to include. The surface charge model is only used to verify the outcome of the numerical Lorentz force calculation after optimization using the first order harmonic model. All models were used experimentally in a previous setup [7].

A sequential quadratic programming routine (fmincon in MATLAB) is used to find the optimal dimensions which minimizes the power dissipation in the single coil. The geometrical constraints are included as bounds in the optimization routine. Since the pole pitch and coil width are fixed, the bounds do not depend on the optimization variables. Since it is easier to manufacture round coils than square coils and the shape of the square coil converges to almost round coils during initial tests, it was decided to only consider round coils in the optimization.

B. Parametric Search

The geometrical optimization is done for several topologies as is discussed in Section IV. Using the dimensions from the geometrical optimization, the combined analytical numerical model [6] is used to calculate the behavior of the entire planar actuator including end effects. The model predicts the currents necessary in each coil to lift the platform at a grid of points in the workspace of the planar actuator. From that analysis, the worst case power dissipation in the actual planar actuator is calculated. The dimensions of the coil and the dissipated power are fed into a thermal model of the planar actuator coils to calculate the surface temperature of the coil. Since not all topologies will satisfy the thermal constraint ($T_{C} < 120{\degree}C$), this results in a set of solutions. Finally, the additional considerations determine which of these solutions is most feasible.

IX. OPTIMIZATION RESULTS

First, the corresponding coil surface temperatures are analyzed for the three different coil phase systems and different number of magnet poles, of which the dimensions are optimized. The results are shown in Fig. 3. It is clear that increasing the pole pitch leads to lower coil surface temperatures. The temperature constraint specified in Section V of a maximum surface temperature of 120 °C, rules out most of the topologies. Only for the coils of 240 electrical degrees
(3-phase), a significant set stays below the temperature constraint. The other coil topologies are neglected for the reminder of the optimization.

The topologies that satisfy the coil surface temperature constraint are now compared using different characteristics. These parameters are listed in Tables I and II. It can be concluded that a higher inductance will lead to a higher resonant voltage. The topologies with 10 × 10 magnets have lower surface temperatures and lower resonant voltages and are therefore a more suitable design choice. However, this comes at a cost of higher control complexity, but tests have shown that the controller has sufficient computing power. The surface temperature (see Fig. 3) decreases only marginally, if the pole pitch is increased from 40 to 50 mm, but the levitated mass increases by 50%, reducing stiffness. Finally, it was found that the inductance was small enough for all topologies to operate the amplifiers at 60 V.

Therefore, the final choice is a 3-phase system with 10 × 10 magnet poles and a pole pitch of 40 mm, since it is the best tradeoff between temperature, resonant voltage, and total levitated mass. The dimensions of the final topology are \( r_m = 0.64 \text{ m}, r_c = 0.41 \text{ m}, m_b = 10.3 \text{ mm} \) and \( c_{db} = 11.3 \text{ mm} \).

X. CONCLUSION

The optimization of a contactless electromagnetic planar actuator (6DOF) with manipulator on top of the floating platform is discussed in this paper. The integration of contactless energy transfer to the moving platform adds complexity to optimization of the planar actuator. Therefore, the optimization is split in two parts. First, a geometrical optimization is done for each topology using numerical integration and sequential quadratic programming. Second, a parametric search is done to compare the different characteristics of different topologies. Finally, a choice is made that satisfies all design requirements.

TABLE I

<table>
<thead>
<tr>
<th>magnet poles</th>
<th>( \tau )</th>
<th>Inductance</th>
<th>Resistance</th>
<th>Resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 × 9</td>
<td>50 mm</td>
<td>2.15 mH</td>
<td>1.6 ( \Omega )</td>
<td>1.87 kV RMS</td>
</tr>
<tr>
<td>9 × 9</td>
<td>55 mm</td>
<td>2.87 mH</td>
<td>1.7 ( \Omega )</td>
<td>2.50 kV RMS</td>
</tr>
<tr>
<td>10 × 10</td>
<td>35 mm</td>
<td>0.76 mH</td>
<td>1.1 ( \Omega )</td>
<td>0.66 kV RMS</td>
</tr>
<tr>
<td>10 × 10</td>
<td>41 mm</td>
<td>0.97 mH</td>
<td>1.1 ( \Omega )</td>
<td>0.85 kV RMS</td>
</tr>
<tr>
<td>10 × 10</td>
<td>45 mm</td>
<td>1.37 mH</td>
<td>1.2 ( \Omega )</td>
<td>1.20 kV RMS</td>
</tr>
<tr>
<td>10 × 10</td>
<td>50 mm</td>
<td>1.89 mH</td>
<td>1.4 ( \Omega )</td>
<td>1.65 kV RMS</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>magnet poles</th>
<th>active coils</th>
<th>( \tau )</th>
<th>magnet mass</th>
<th>total mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 × 9</td>
<td>8 × 8</td>
<td>50 mm</td>
<td>16.0 kg</td>
<td>27.6 kg</td>
</tr>
<tr>
<td>9 × 9</td>
<td>8 × 8</td>
<td>55 mm</td>
<td>19.6 kg</td>
<td>32.4 kg</td>
</tr>
<tr>
<td>10 × 10</td>
<td>9 × 9</td>
<td>35 mm</td>
<td>8.8 kg</td>
<td>18.2 kg</td>
</tr>
<tr>
<td>10 × 10</td>
<td>9 × 9</td>
<td>40 mm</td>
<td>11.7 kg</td>
<td>22.1 kg</td>
</tr>
<tr>
<td>10 × 10</td>
<td>9 × 9</td>
<td>45 mm</td>
<td>15.0 kg</td>
<td>26.6 kg</td>
</tr>
<tr>
<td>10 × 10</td>
<td>9 × 9</td>
<td>50 mm</td>
<td>18.8 kg</td>
<td>31.7 kg</td>
</tr>
</tbody>
</table>

REFERENCES


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