Magnetically suspending a conveyance system from the ceiling in a non-contact manner reduces the use of ground floor space and minimizes contamination of the air inside clean rooms. A structure for this so-called ceiling actuator, as shown in Fig. 1, is researched.

The ceiling actuator features:
- Single-sided active magnetic bearing with control over six degrees-of-freedoms (6 DOFs)
- Magnetic propulsion of the moving platform over a stroke of 100 mm in the xy-plane
- A passive attraction force, \( F_{z,0} \) for fail-safe operation (mg < 4 \( F_{z,0} \))

Design and operating principles of a magnetically suspended ceiling actuator with fail-safe operation

1. Introduction

Design objective
- Min. ohmic losses for acceleration of 10 ms\(^{-2}\) in xy-plane

Design constraints
- Tooth flux density: < 1.5 T
- Force ripple: < 3 %
- Mass load: 5 kg
- Geometry: see Fig. 2 (not bold)

Optimized design: see Fig. 2 (bold)
Results:
- \( F_{z,0} = 413 \) N
- \( P = 223 \) W for \( \alpha_{xy} = 10 \) ms\(^{-2}\)

2. Basic structure ceiling actuator

Combination of four linear actuators (forcers)
- Forcers 1 & 3: propulsion force \( F_x \)
  - normal force \( F_z \)
- Forcers 2 & 4: propulsion force \( F_y \)
  - normal force \( F_z \)
- Slotted iron yoke for high force density
- Permanent magnets + iron yoke = Passive attraction force, \( F_{z,0} \)

3. Control & model single forcer

Position independent force model
Control by decomposition of three-phase currents in dq-reference frame
- Propulsion force: \( F_{x,y} = k_f I_q \)
- Normal force: \( F_z = k_I I_d + F_{z,0} \)
- \( k_f \) = motor constant

Position dependent torque model
Control also by dq-decomposition
- Torque about axis perpendicular to structure of forcers: \( T_y = k_j I_q \)
- \( k_j \) & \( k_q \) = torque constants
- \( T_0 \) = "cogging" torque

2D harmonic magnetic field model [1]
- Calculation of passive force, motor constant and torque constants
- Includes slotting and finite length of iron yoke

4. Optimization

Control magnetically suspended translator in 6 DOFS
- Sum of forces & torques gives: \( w = \Gamma I + \Gamma_0 \)
- \( w \) = wrench vector containing desired forces and torque
- \( \Gamma \) = linear mapping of current vector \( I \) onto \( w \)
- \( \Gamma_0 \) = contains \( F_{z,0} \) and \( T_0 \)
- Direct wrench control:
  \[ \Gamma = \Gamma^{-1} (w - \Gamma_0) \]
  \( \Gamma^{-1} \) = Moore-Penrose pseudoinverse for minimized ohmic losses

Ohmic losses during magnetic suspension and propulsion
\[
P = \frac{R_{mot}}{2 k_f^2 (h_y)} \left( (mg - 4 F_{z,0} h_y)^2 + m^2 \sigma_{z,y}^2 + \sigma_{z,y}^2 \right)
\]

Operation with variable air gap
- Passive force, \( F_{z,0} \) and motor constant, \( k_y \), change with air gap

Selection air gap
- Low acceleration \( \Rightarrow \) Large air gap
  \( (4F_{z,0} \leq mg) \)
- High acceleration \( \Rightarrow \) Small air gap
  \( (mg \leq 4F_{z,0}) \)

5. Planar actuation with variable air gap

Figure 1. 3D impression of the ceiling actuator.
Figure 2. Side (left figure) and bottom (right figure) view of the proposed ceiling actuator.
Figure 3. Propulsion force, normal force (top figure) and torque components (bottom figure) as a function of the position.
Figure 4. Ohmic losses as a function of acceleration and air gap length.

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