Decoupling and Adjustment of Forces in an Electromagnetic Guiding System with six Degrees of Freedom

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1 Introduction

Nowadays, non-contact linear guides are proposed for applications in various technical systems. First of all, the matter of rail mounted high-speed passenger transportation by maglev trains is well-known. Furthermore, the employment of magnetic levitation techniques in slower transportation facilities is discussed. For these applications, a smooth and silent operation of non-contact guides is a major benefit. This paper describes the derivation of an adjustment directive for the non-linear and coupled forces of a high comfort elevator guiding system based on so called electromagnetic ω-actuators.

2 Description of the Guiding System

There are several feedback control strategies for the magnetic suspension of a vehicle containing six degrees of freedom (DOF; Six DOF without regarding the vehicle's velocity in riding direction as a seventh DOF.). The direct control of every single DOF, the so-called DOF-control, is one possibility.
This paper presents the adjustment of a vehicle's spatial position by utilising four electromagnetic ω("omega")-actuators, e.g. introduced in (Morishita & Akashi 2001) and (Schmülling, Appunn & Hameyer 2008).

2.1 The ω-actuator

The benefit of the ω-actuator compared to standard actuators (Wang, Jin & Liu 2009) as often deployed in high speed maglev trains (Löser 2008) is the supply of forces in three directions instead of one. One of these actuators is presented in Figure 1. It consists of a three-legged iron yoke, equipped with permanent magnets on the outer pole surfaces of the lateral legs and coils around them. The operation of this actuator is based on the superposition of the permanent magnets' fluxes with the electrically excited fluxes. The analytical calculation of the actuator's magnetic fluxes is based on the method of the magnetic equivalent circuit (MEC), which works similarly to an electrical equivalent network. During operation, three actuating forces occur in the air gaps of the actuator. These forces are equivalent to the magnetic flux in the respective air gap. Every single

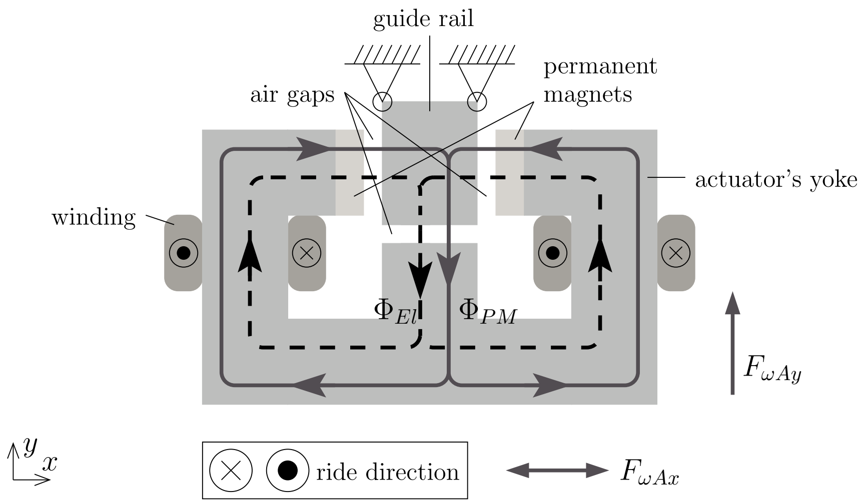

Figure 1: Cross-section of one ω-actuator.

air gap flux depends on the current of both coils and the length of every single air gap. This means e.g. readjusting the current in one coil influences all three forces. Therefore, the forces of an ω-actuator are coupled.

2.2 The Guiding Topology

The actuators can be mounted on opposite edges of a vehicle's forepart and backside. That means, four ω-actuators are mounted on one vehicle. In combination with two guide rails located on opposite sides of the chassis, the complete guiding system is formed. Taking into account, that the ω-actuator does not possess an offset force in one direction, which is able to compensate the gravity, this kind of actuator is predestined for the guiding of vertical transportation vehicles. As an example, an elevator guiding system is introduced and presented in Figure 2. The Figure shows the elevator car between two guide rails. The required guding forces are depicted as well. These forces have to be adjusted by the ω-actuators, which are placed on the roof and beneath the floor of the elevator car. Figure 3. presents the arrangement of one actuator and the guide rail. If the elevator car is a rigid body there are five DOF to adjust: The two remaining translatory DOF x and y as well as the three rotary DOF α, β, and γ as shown in Figure 2. Due to the light-metal construction of an elevator car, a deformation of the chassis caused by the electromagnetic forces is expected. For a compensation, the torsion forces around the vertical z-axis also have to be adjusted why the torsion angle χ is introduced, which characterises the angular displacement between roof and floor. The position vector of the elevator car is defined as follows:

$$\mathbf{q} = (x\ y\ \alpha\ \beta\ \gamma\ \chi)^T \tag{1}$$

To adjust these six quantities and move the elevator car to a central position ($\mathbf{q} = \mathbf{0}$) an adjustment variable for each DOF must be obtained. Therefore, it is essential to transform the local forces in each air gap to global forces which

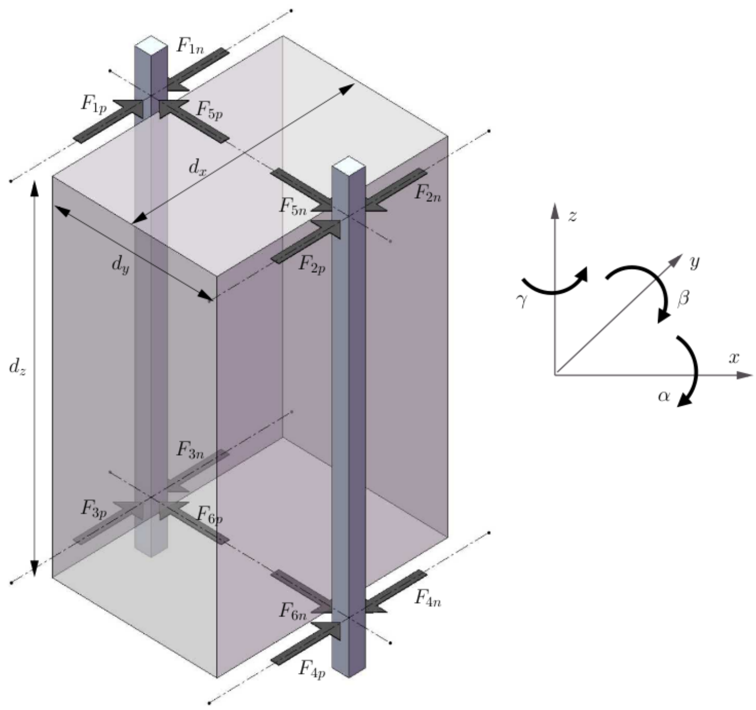

Figure 2: Elevator car with all actuating forces.

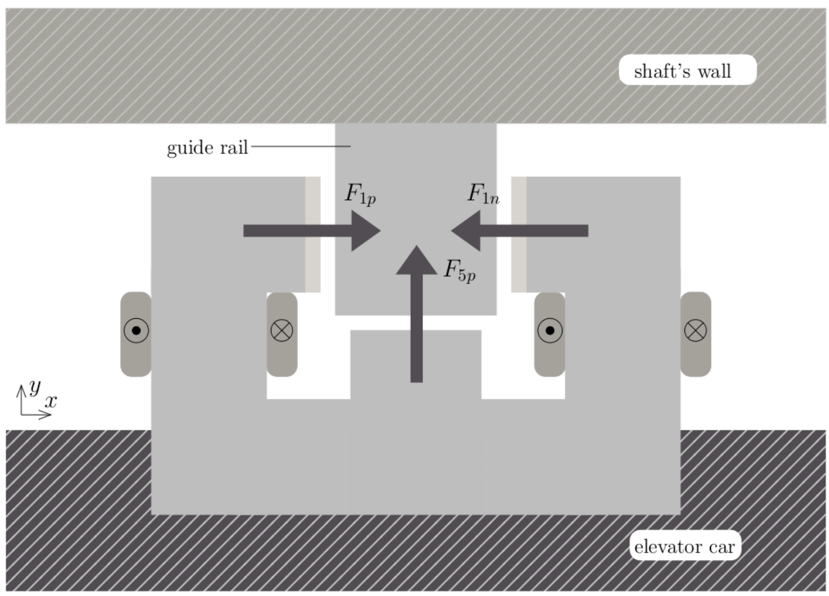

Figure 3: Arrangement of one ω-actuator on the roof of the elevator car.

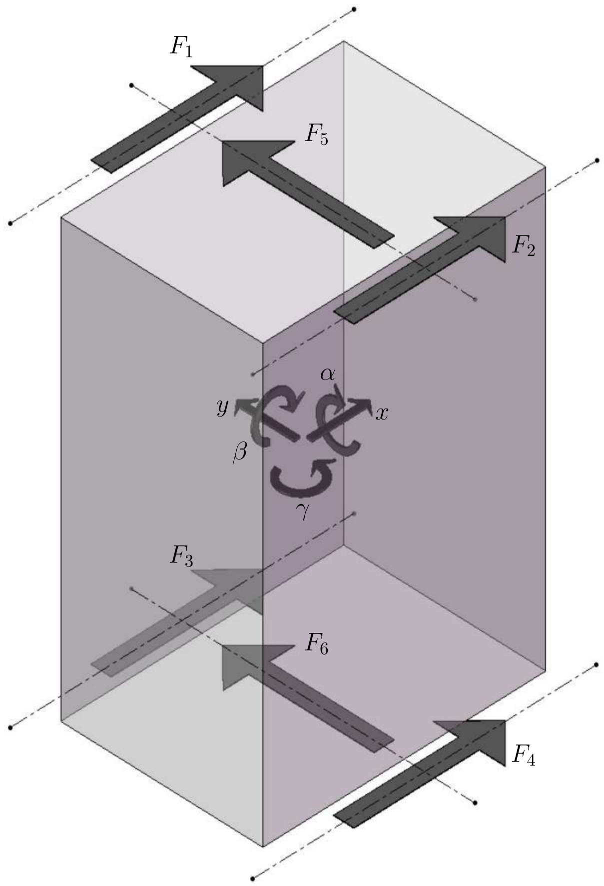

Figure 4: Elevator car with six remaining adjustment forces.

only interfere with one of the DOF. It is as well necessary to decouple the forces. This means, a unique adjustment directive for each global force is required.

3 Force Transformation

In a first step, the aligned forces of the guiding system are combined (q.v. Figures 2 and 4):

$$\begin{aligned} F_1 &= F_{1p} - F_{1n} \\ F_2 &= F_{2p} - F_{2n} \\ F_3 &= F_{3p} - F_{3n} \\ F_4 &= F_{4p} - F_{4n} \\ F_5 &= F_{5p} - F_{5n} \\ F_6 &= F_{6p} - F_{6n} \end{aligned} \tag{2}$$

Each of the six remaining forces is a difference of two quadratic equations and has to be linearised (Schmülling et al. 2008) to apply a state control (Appunn, Schmülling & Hameyer 2010) to the system. One force equation is now a linear combination of the coils' currents and the air gap lengths. To describe the correlation between the local forces and the global forces and torques, which are able to directly affect every single DOF as a part of the global positioning vector $\mathbf{q}$, the force transformation is obtained:

$$\underbrace{\begin{pmatrix} F_x \\ F_y \\ M_\alpha \\ M_\beta \\ M_\gamma \\ M_\chi \end{pmatrix}}_{\mathbf{F_{global}}} = \underbrace{\begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & -d_z/2 & 0 & 0 & d_z/2 & 0 \\ d_z/2 & 0 & d_z/2 & -d_z/2 & 0 & -d_z/2 \\ -d_y/2 & 0 & d_y/2 & -d_y/2 & 0 & d_y/2 \\ -d_y/2 & 0 & d_y/2 & d_y/2 & 0 & -d_y/2 \end{bmatrix}}_{\mathbf{T_{force}}} \underbrace{\begin{pmatrix} F_1 \\ F_5 \\ F_2 \\ F_3 \\ F_6 \\ F_4 \end{pmatrix}}_{\mathbf{F_{local}}} \tag{3}$$

In this transformation, $\mathbf{F_{global}}$ is the vector of the global forces and torques, $\mathbf{F_{local}}$ is the vector of the local forces between actuators and guide rails, and $\mathbf{T_{force}}$ is the force transformation matrix. d_z is the height and d_y the width of the elevator car, which can also be seen in Figure 2. By changing the currents, the local forces are adjusted. Thus, global currents are required to ensure a direct control of the global forces. By merging several equations a current transformation matrix $\mathbf{T}$ occurs:

$$\underbrace{\begin{pmatrix} I_x \\ I_y \\ I_\alpha \\ I_\beta \\ I_\gamma \\ I_\chi \end{pmatrix}}_{\mathbf{I_{global}}} = \underbrace{\begin{bmatrix} 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \\ -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \end{bmatrix}}_{\mathbf{T}} \underbrace{\begin{pmatrix} I_{1l} \\ I_{1r} \\ I_{2l} \\ I_{2r} \\ I_{3l} \\ I_{3r} \\ I_{4l} \\ I_{4r} \end{pmatrix}}_{\mathbf{I_{local}}} \tag{4}$$

Here, $\mathbf{I_{global}}$ is the vector of the global currents and $\mathbf{I_{local}}$ is the vector of the real currents in the actuators' coils. Herewith, the virtual global currents are calculated, which represent adjustment variables for the global forces. However, the inverse operation is not possible since the equation system is over-determined: Eight currents in eight coils have to operate six global currents. An augmentation of the equation system is required to calculate the real currents in the actuators' coils by known global currents.
In a first step, it has to be identified what the system's over-determination means physically. The answer is: Additional to their ability of affecting the six global DOF the actuators are able to excite forces, which

1. compensate each other or
2. deform (uncompress) the elevator car.

Thus, these currents do not support the force/torque balance of the elevator car, but stress the components of the elevator's chassis and consume additional energy. For this, it has to be ensured that these global currents are set to zero.

As further contraints two current equations are introduced:

$$\begin{aligned} I_{h1} &= 0 = I_{1l} + I_{1r} + I_{2l} + I_{2r} + I_{3l} + I_{3r} + I_{4l} + I_{4r} \\ I_{h2} &= 0 = I_{1l} + I_{1r} + I_{2l} + I_{2r} - I_{3l} - I_{3r} - I_{4l} - I_{4r} \end{aligned} \tag{5}$$

As presented, two global variables with auxiliary information are introduced: I_{h1} and I_{h2}. In this variables additional state information is stored during transformation and recalled during the inverse transformation. Finally, the transformation matrix $\mathbf{T_{aug}}$ for implementing the feedback control is formed:

$$\underbrace{\begin{pmatrix} I_x \\ I_y \\ I_\alpha \\ I_\beta \\ I_\gamma \\ I_\chi \\ I_{h1} \\ I_{h2} \end{pmatrix}}_{\mathbf{I_{aug}}} = \underbrace{\begin{bmatrix} 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \\ -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \end{bmatrix}}_{\mathbf{T_{aug}}} \underbrace{\begin{pmatrix} I_{1l} \\ I_{1r} \\ I_{2l} \\ I_{2r} \\ I_{3l} \\ I_{3r} \\ I_{4l} \\ I_{4r} \end{pmatrix}}_{\mathbf{I_{local}}} \tag{6}$$

By utilizing the transformations presented to adjust the local forces, global state space controllers can be drived. The subsequent section describes measuremet results of the elevator guding system operated by six parallel state controllers, one for each DOF.

4 Measurements

In several measuremts, the functionality of the entire guiding system is investigated. During operation, the system is excited by external force impulses on the elevator car's chassis in several directions. As an example, the force impact in x-direction on the floor of the elevator car is presented. Fig. 5 shows the excitation response of all DOF. As displayed, all six DOF show an impact response and a fast disturbance compensation. However, that all DOF controllers show a reaction is a reasonable result. On the one hand, the force impulse was not exerted to the barycenter of the elevator car. Due to this, all spatial DOF are excited as well. Furthermore, the actuators moved out of their desired position. This produces additional magnetic forces to the actuators and herewith to the elevator car's chassis, which leads to a deformation (torsion) of the elevator car. After $t \leq 1\,\mathrm{s}$ all DOF deviations are compensated and the elevator car is back in its desired position.

5 Conclusion

In a first section, the assembling of the ω-actuator is presented. The functionality of the actuator is described and its qualification in guiding systems for vertical transportation vehicles is accentuated. The problem of mutual influences between every single actuator force is declared. A current change in one coil leads to a change of each actuator force. Thereafter, an elevator guiding

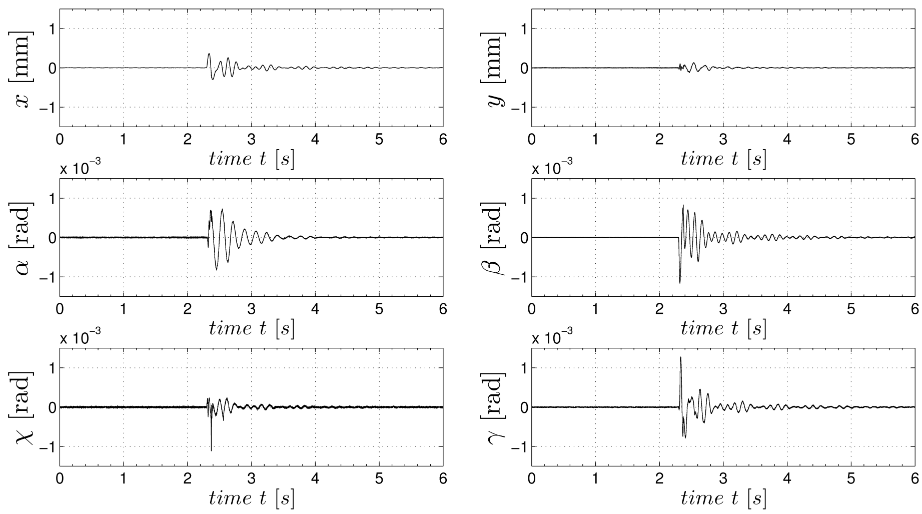

Figure 5: The six measured DOF exited with an impulse in x-direction on the floor of the elevatorr's chassis.

system composed of four of these actuators is introduced. The spatial position of the elevator car within its shaft is defined by position vector $\mathbf{q}$. To ensure a clear design of a feedback control for this six DOF problem, a transformation from local adjustment variables to virtual global currents is presented. This transformation has to be augmented to avoid the over-determination of the system and to allow a reciprocal transformation. The complete derivation of the augmented transformation matrix is presented as well. The result is a practical approach for an easy control design of systems levitated by ω-actuators. Finally, the manageability of this procedure is proven by a running magnetically guided elevator car in a testing facility.

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