Proposals for the use of Magnetic Guideways for Vertical Transportation Systems

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1. Introduction

Nowadays, more and more high-rise buildings are constructed in Asia and in other parts of the world. These buildings make high demands on their passenger transportation systems, since the height, and with it the number of storeys, obtains new maxima every year. Examples are the Taipei Financial Center in Taiwan, the Petronas Towers in Malaysia, and the Burj Dubai in the United Arab Emirates, which is still under construction. In this sense, conventional elevators with mechanical guiding systems come to their application limitations due to the very high requirements of these buildings. An improvement of the operational behaviour of such high elevator systems can be achieved using wear and lubricant free electromagnetic guides instead of slide or roller guides.

The presented work deals with different proposals for the electromagnetic guiding of vertical transportation systems. Benefits and disadvantages of the investigated guideway topologies are presented and discussed. It is also respond to the technique of ropeless elevators as an application example for active magnetic guideways.

2. Vertical Electromagnetic Guiding

One benefit of electromagnetic guideways is the wear-free operation. In addition, these guideways have no consumption of lubricants, a further advantage compared to mechanical guideways. Due to the frictionless operation, the elevator can be operated at a higher speed when compared to conventional systems. However, the main advantage is the opportunity to control the ride comfort by adjusting the damping rate of the guiding system. The ride comfort depends on vibration and noise caused by misalignment and misconnection of the guide rail. This topic and the opportunity to improve the convenience are presented in literature, for example in [1] and [2]. The active control of the damping rate requires a closed loop system.

Electromagnetic guiding of an elevator car requests high demands to the guiding topology and the control system. Compared to magnetic levitation systems for horizontal applications they possess no rated force in a defined direction. The displacement of the elevator car from its designated position can occur in every direction. The non-guided elevator is assumed to behave like a rigid body. It is fixed in one degree of freedom (DOF) by its propulsion device, a rope for example. This is the DOF in vertical z direction. The other five degrees of freedom are the translatory movements in x and y direction and the rotary movements α, β, and γ about the axes of a Cartesian coordinate system.

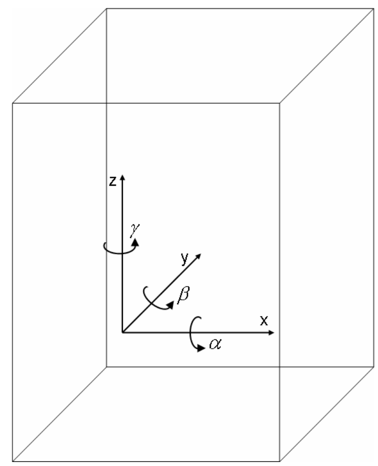

Figure 1: The six degrees of freedom of a rigid body.

These five DOFs need to be controlled by the electromagnetic guides. Fig. 1 shows an elevator car with all six degrees of freedom.

3. Application Example: Ropeless Elevators

A novel concept in elevator construction determines the location of the elevator drive not at the top of the shaft, but directly attached to the elevator car. These ropeless elevator systems driven by linear motors are an opportunity to optimise the passenger traffic in very high buildings. Due to the ropeless handling, it is possible to operate more than one elevator car in a single shaft. This provides the implementation of new passenger transportation strategies to modern buildings [3]. A further limitation of conventional elevators is the maximum rope length. This can be a problem e. g. in deep mining applications [4]. Elevators driven by linear motors make high demands on the guiding technology. Compared to conventional systems linear motors generate normal forces. These forces have to be compensated in addition to the forces produced by the load or passengers. For these requirements, a controllable active damping is more suitable than mechanical guides.

The development of a linear synchronous motor for an elevator system is described in [5]. A test bench, which was built to verify the operation of the ropeless elevator, is shown in Fig. 2. This system is to be improved by implementation of non-contact electromagnetic guideways.

For the placement of guiding systems in a shaft of a ropeless elevator different topologies exist, since there are

Figure 2: Ropeless elevator test bench.

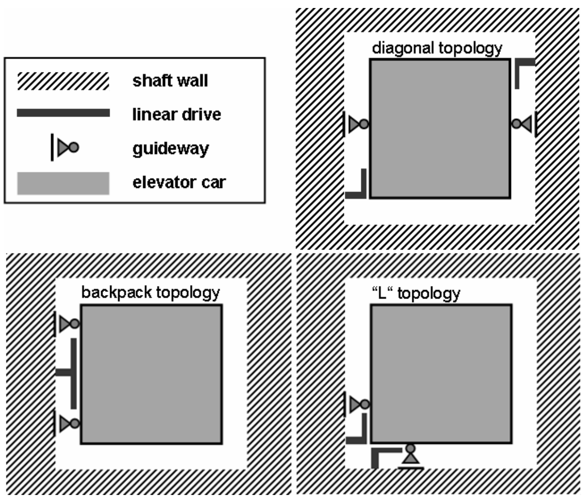

Figure 3: Top views of several elevator topologies.

a number of opportunities to arrange the separate guideways on the shaft's wall. Each possible construction subjects to different basic conditions. These conditions depend on used material, shaft architecture, and drive.

Three placement possibilities are presented in Fig. 3. The backpack topology, for example, can be used if only one shaft wall is made of concrete and the others are e. g. made of glass. This would be an opportunity to realise superior architectural elevator designs. One disadvantage of the backpack topology compared to the diagonal topology is the higher lateral force on guideways. Therefore, the test bench elevator is built in diagonal topology. Here, the employed guiding possesses a standard topology.

4. Guiding Topologies

This section collects an overview of different types of actuators, which can be employed in a vertical active magnetic guiding system. Benefits and disadvantages of these actuators are discussed. A further subsection explains the methodology of the actuator design with the help of an explicit example. Several opportunities for guideway packaging are discussed in a third subsection.

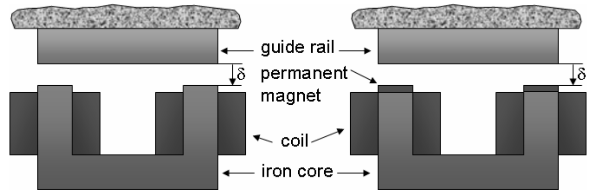

Figure 4: U-shaped actuators without and with permanent magnets.

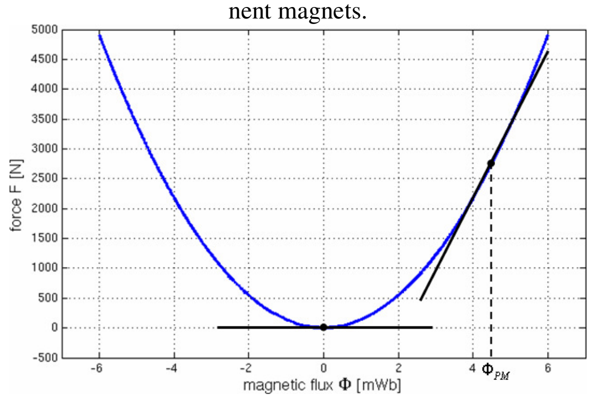

Figure 5: Force F in dependence on magnetic flux Φ.

4.1. Potential Actuators

For one guideway, different electromagnetic actuators can be used. Simple actuators, only capable of producing an attractive force in one direction, are one possibility. These u-shaped actuators (UA) are common actuators employed in electromagnetic levitation vehicles [7]. The simple design is affected by its u-shaped yoke wound by its electric excitation coil. The pole faces can additionally be equipped by permanent magnets. Fig. 4 presents the entire body of a UA with and without permanent magnets. If permanent magnets are assembled depends on the basic conditions. The disadvantage of the magnet material is the increment of the magnetic air gap width δ. This yields a raise in leakage flux. On the other hand the permanent magnets are able to compensate a static offset force. Here, the employment of the magnets tends to lower energy consumption. Finally, the permanent magnets are of basic necessity for the adjustment of a feedback control. A controller is designed by linearisation of the differential equations of the entire system. The magnetic force F of one pole face depends on the magnetic flux Φ as follows:

$$F = \frac{\Phi^2}{2 \cdot A \cdot \mu_0} \tag{1}$$

Here, A is the surface area of one pole face and μ_0 the permeability of vacuum. The characteristic of the force F represents a parabola and is shown in Fig. 5. It can be seen that a linearisation around the working point of a flux $\Phi = 0\ Wb$ is not possible. In this case, the slope of the linearised force F_{LIN} is zero. By using permanent magnets an offset force is prepared, which relocates the working point to the flux Φ_{PM}. Around this point a linearisation is possible. If permanent magnets are not used, an offset current is required to relocate the working point to the linear range of the parabola. However, this approach can not be recommended due to the higher energy consumption.

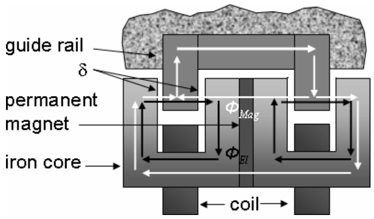

Figure 6: E-shaped actuator.

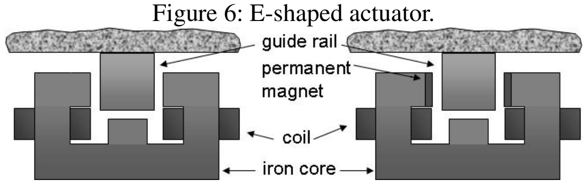

Figure 7: Three-armed actuators without and with permanent magnets.

Other types of actuator are able to produce forces in more than one direction. An example is the e-shaped actuator (EA) presented in Fig. 6. Due to its ability to produce a force in two directions it can substitute two UAs. The EA in Fig. 6 consists of two u-shaped yokes and one permanent magnet in between. The two yokes feature two coils in series connection. The flux in the air gaps consist of a permanent magnet component Φ_{Mag} and an electric excited component Φ_{El}. By adjusting Φ_{El} the permanent magnet flux can be increased in one air gap and decreased in the other one at the same time. Thus, positive and negative forces can be produced on the same action line. In Fig. 6, this action line is in horizontal direction. One benefit of this type of actuator is the savings in space compared to two UAs. A disadvantage is the necessity of a u-shaped guide rail. This construction is more complex when compared to the guide rail of a UA and therefore more expensive.

The next system development step is an actuator, which is able to substitute a complete mechanical guide. It has to produce forces in three directions. In Fig. 7 such an actuator concept can be seen. It consists of a three-armed yoke with coils at the two lateral arms. For this reason it is called three-armed actuator (TAA). Additionally, it is provided with permanent magnets at the lateral air gaps. The force production at a current $I = 0\,A$ (and in a central position) is zero in horizontal direction. The excitation of the actuator with the electrical circuit yields an increment of the flux in one air gap and a decrement in the other one. Similar to the EA positive and negative forces in horizontal direction can be produced. The third direction is controlled by the middle arm. This attractive force in vertical direction depends on the superposition of the fluxes in the lateral arms. Thus, a mathematical decoupling of the forces is required to design an adequate control system. The design of a control system for an elevator car guided by TAAs is described in [2]. The TAA without permanent magnet is not meaningful by reason of the linearisation of the working point described above.

4.2. Actuator Design

The layout of electromagnetic actuators consists of two steps:

1. Analytical design of the magnetic circuit.
2. Verification of the design by numerical simulation.

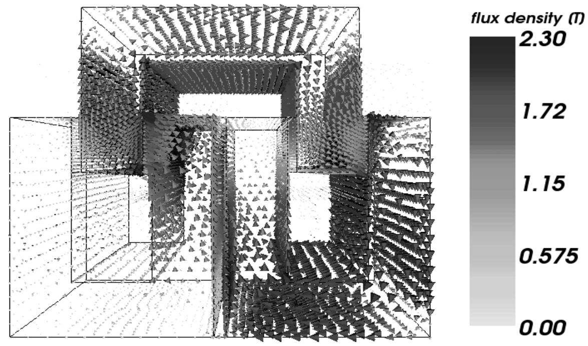

Figure 8: Solution of a finite-element analysis of an EA.

This section deals with an exemplary design of a UA.

The required parameters have to be ascertained. Those are maximum force F_{Max} and the needed time constant τ. With the saturation flux density B_{Max} of the yoke resolving (1) yields to a minimum yoke face area of A_{min}. Applying the saturation flux density B_{Max} yields the required force F_{Max}. The flux density B_{Max} depends on the excitation variables as follows:

$$B_{Max} = \frac{\Theta + 2 \cdot H_C \cdot h_{PM}}{2 \cdot \frac{H_C \cdot h_{PM}}{B_R} + 2 \cdot \frac{\delta}{\mu_0}} \qquad (2)$$

Here, Θ is the magnetomotive force (MMF) of both coils, H_C the coercivity of the magnet material, B_R the remanent flux density of the magnet material, and h_{PM} the height of the magnet. H_C and B_R are known values depending on the used material.

The actuator is designed to produce the maximum force by excitation with a maximum electrical MMF of Θ_{Max} and a force of zero by excitation with $-\Theta_{Max}$. This leads to the condition

$$\Theta_{Max} = 2 \cdot H_C \cdot h_{PM}, \qquad (3)$$

due to the fact that magnetic and electrical excitation respectively yield half the maximum flux density $B_{Max}/2$. With (2) and (3) the magnet height h_{PM} and the MMF Θ_{Max} is calculated.

The time constant τ depends on the air gap width δ and on the number of turns per coil N since these values assign the windings' inductivity L and resistance R. By adjustment of the variable N the required time constant can be accomplished.

Due to flux leakage in the magnetic circuit the analytical layout has to be reviewed carefully. For this reason, a numerical computation of the layout is performed. The calculation tool iMOOSE [6] provides the computation of electromagnetic forces as well as the calculation of inductivities. An illustration of the magnetic flux density distribution in an EA is presented in Fig. 8.

4.3. Packaging

The actuator packaging describes the form of installation arrangement of the entire guideway system. Here, several types of packaging for ropeless elevators in diagonal topology are presented.

The first package studied consists of three u-shaped actuators with permanent magnet excitation arranged around a guide rail in the elevator shaft. To control one degree of freedom by means of these UAs, it is necessary

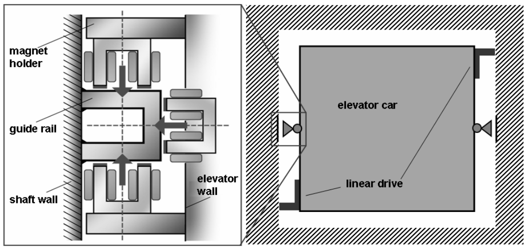

Figure 9: Diagonal elevator topology with UA-guiding.

to couple at least two oppositely mounted actuators. These coupled actuators are positioned along an action line of one positioning force. Twelve actuators in four packages establish the entire guiding system. Two packages are arranged at the top and two further packages are arranged at the bottom of the elevator car. The construction of the actuator packages and their mounting on the elevator car is presented in Fig. 9. Opposite actuators can be driven by one rectifier around the defined working point (q.v. 4.1). In this case, the two actuators are reverse connected to the power electronics. However, in this form an actuator package depends on one and a half rectifier. Therefore, the entire guideway system, which is composed of four packages, requires a total of six rectifiers.

To verify the feasibility of this actuator packaging a dynamic simulation of the entire guideway system is performed. The entire elevator model contains the dynamic moving equations of the elevator car and the dynamic electromagnetic equations of all twelve actuators. For simulating, these equations are implemented in MATLAB/Simulink. To control the guideway system a multi variable state control is established. In principle, every single actuator can be controlled separately. For this reason, the control algorithm calculates the local manipulated variable from the local air gap heights. Due to large tolerances in high elevator shafts this method is unfavourable, since an independent control of solid-coupled actuators leads to unstable operation conditions. Therefore, a control of the degrees of freedom, the so called DOF-control is applied [7], [8]. At this juncture, the decoupling of the actuators does not occur mechanically, but it occurs in the control loop system. Local measurement values are transformed into global values. This concept observes the absolute position of the elevator car in the shaft, described by the six predefined DOFs. The entire series of simulation shows that the employed electromagnetic guideway system for ropeless elevators is able to substitute common guides. All performed test cases show a stable operation.

An improvement of this system can be achieved by substitution of the two fronting UAs in one package with one EA. This yields savings in space in the shaft and provides a larger passenger area.

A third opportunity is the substitution of one package with one TAA [2]. Benefit of this method is the simple design of the guide rail. This will be a high expense factor of elevator systems in very high buildings. The disadvantage of this solution is the higher requirement of power electronics. A package with one single TAA requires two rectifiers, which causes to eight rectifiers for the entire guideway system. Due to this higher effort of power electronics and a more complex control system the application of these actuators need not necessarily to be reasonable.

5. Conclusion

Several proposals of the construction of electromagnetic guideways in elevator shafts are discussed. All analysed actuators and packages are able to guide elevator cars in shafts with an adjustable convenience. However, the advantages and disadvantages of the different actuators and packages are described.

It is derived that the adoption of permanent magnets in electromagnetic actuators is reasonable although they are expensive. Considering this, three types of actuators are presented and discussed. Furthermore, fundamental design rules for the dimensioning of actuators are established. These design rules include both an analytical layout and a finite-element analysis of the apparatus processed. On the basis of a dynamic simulation the feasibility of three guideway topologies obtained. Benefits and handicaps of these topologies are discussed.

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