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

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Abstract

This paper presents the design and operating principles of a magnetically suspended ceiling actuator when it is used as a planar conveyor system. The presented ceiling actuator consists of a translator which is magnetically suspended under and propelled in the plane below a stationary frame, called the ceiling. Four linear actuators comprise the translator and provide a limited stroke in the xy-plane. Because permanent magnets and iron are employed inside the linear actuators, a passive attraction force is created between the translator and ceiling which provides fail-safe operation. The linear actuators are optimized with the objective to minimize the ohmic losses when the translator is accelerated. Furthermore, it is shown that depending on the level of acceleration, the minimum dissipated power is obtained at different airgap lengths.

1 Introduction

Magnetically suspending a planar actuator underneath a stationary frame or ceiling, reduces the use of ground floor space and provides an alternative for xy-positioning systems that are operated in a deep vacuum. In [1] a structure for the magnetically suspended planar actuator, called the ceiling actuator, is presented. It consists of four linear actuators (forcers) which provide single-sided magnetic suspension and magnetic propulsion over a limited stroke in the xy-plane. Several actuator topologies for the forcers were compared and it was concluded that a three-phase excited slotted linear permanent magnet (PM) actuator achieves the highest acceleration.

In this paper, the design of the linear PM actuator is optimized with a different objective. The same structure as presented in [1] is used, however, in this paper the coils are fixed to the suspended translator instead of the PM array. Additionally, the influence of the airgap on the performance of the ceiling actuator is discussed.

2 Basic operation and control

The ceiling actuator under consideration is shown in Figs. 1 and 2. Four three-phase excited linear PM actuators are used to control the active magnetic bearing in six degrees-of-freedom and move the translator over a stroke of 100x100 mm in the xy-plane. As shown in Fig. 2, the three-phase coils and the salient iron yoke of the four actuators are attached to the translator, while the PM array is fixed to the ceiling. To achieve planar actuation, two linear actuators are placed perpendicularly with respect to the other two.

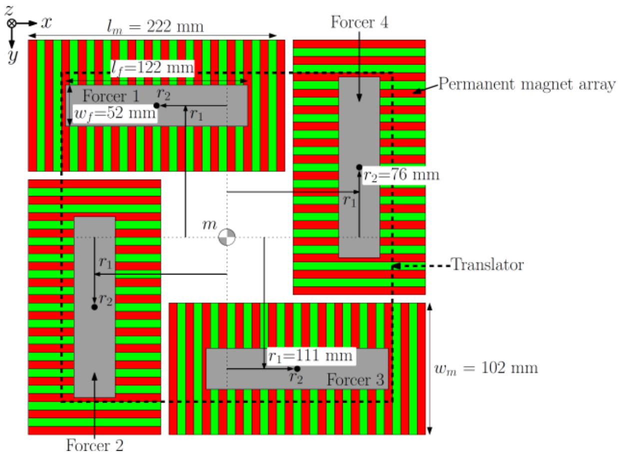

Figure 1: Bottom view of the ceiling actuator.

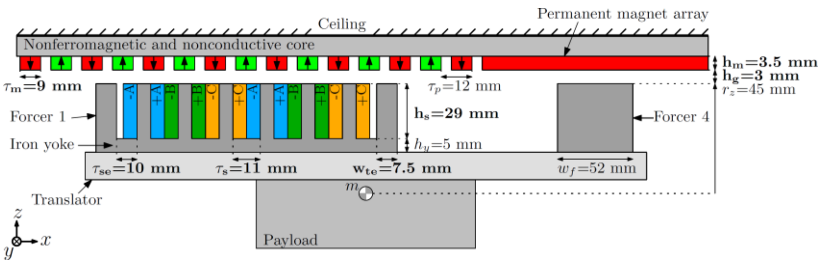

Figure 2: Side view of the ceiling actuator and a cross-section of the linear PM motor.

By decomposition of the three-phase currents in the dq0-reference frame, the propulsion force in each forcer is controlled with the quadrature-axis current and the electromagnetic normal force is controlled with the direct-axis current. Addionally, a passive normal force, F_{z0}, between the translator and ceiling is created due to the reluctance force between the PMs and the iron yoke. When this attractive force is larger than the weight of the translator and the payload attached to it, fail-safe operation is guaranteed in case of power failures. Finally, from the balance of forces and torques, the required direct- and quadrature-axis current for each forcer are solved in order to control the ceiling actuator in six degrees-of-freedoms.

3 Optimization

The design of the linear PM actuators is optimized with the objective to minimize the total ohmic losses of the ceiling actuator when the translator is accelerated with 10 ms^{-2} in the xy-plane. For the optimization, a parameter sweep is performed using a semi-analytical model of the linear actuators. This model calculates the two-dimensional magnetic fields based on Fourier analysis [2]. It accounts for the slotting and finite length of the iron yoke, which was ignored in [1]. In Fig. 2, the optimization variables and their optimal values are indicated in bold. The optimization contraints, PM properties, and the performance of the optimized ceiling actuator are listed in Table 1.

Table1: Optimization constraints, PM properties and results.

Optimizaton constraints			**Properties permanent magnets**	
Tooth flux density	$B_{tooth} < 1.5$ T		Remanence	$B_{rem} = 1.2$ T
Force ripple	$F_{ripple} < 3$ %		Rel. Permeability	$\mu_r = 1.04$
Fail-safety	$m \cdot g < 4 \cdot F_{z0}$		**Properties opt. ceiling actuator**	
Mass load	$m_{load} = 5$ kg		Total moving mass	m = 11.7 kg
			Pas. normal force	$4 \cdot F_{z0} = 413$ N
			Power (a=10 ms^{-2})	$P_{10} = 223$ W

4 Variable airgap

In electrical machines, the airgap is normally minimized to improve the motor constant and, hence, the performance. The performance of the magnetically suspended ceiling actuator, however, also depends on the passive normal force. In Fig. 3 the total dissipated ohmic losses are shown as a function of the acceleration and the airgap length. These results are obtained from an analytical model of the optimized ceiling actuator when it is fully controlled in six degrees-of-freedom and the translator is accelerated with the same value in both the x- and y-direction. For low acceleration levels, the losses are minimized when the translator is suspended with an airgap of 5 mm underneath the magnets. At this airgap length, the passive normal force nearly equals the weight of the suspended platform, resulting in a low power dissipation. When the translator is highly accelerated (> 10 ms^{-2}), however, the dissipated ohmic losses necessary to accelerate the platform and to compensate the developed torque, become dominant. Reducing the ohmic losses in this case, is achieved by decreasing the airgap length to 3 mm, for instance, and, hence, improving the motor constant.

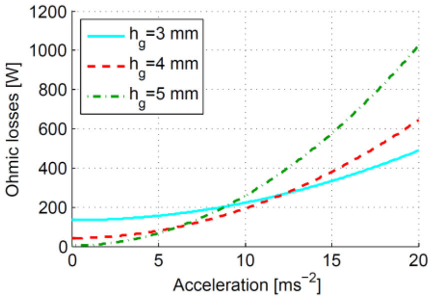

Figure 3: Total ohmic losses in the ceiling actuator as a function of the acceleration and the airgap length.

5 Conclusions

An optimized design for a linear PM actuator is presented which minimizes the ohmic losses in a magnetically suspended ceiling actuator and offers fail-safe operation. In terms of the ohmic losses, it is shown that the ceiling actuator should be operated with a large airgap for low accelerations, while a reduced airgap length is desirable for high accelerations.

References:

[1] T.T. Overboom, et al. Topology comparison for magnetically suspended ceiling actuator. *Proc. IEEE IEMDC*, 3: 1984-1988, 2011.

[2] B.L.J. Gysen, et al. General formulation of the electromagnetic field distribution in machines and devices using fourier analysis. *IEEE Trans. on Magnetics*, 46(1): 39-52, 2010.