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Application of a Permanent Magnet Biased E-Core Reluctance Actuator in a Magnetically Suspended Ceiling Actuator

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In the paper a novel actuator is presented for a magnetically suspended ceiling actuator. The actuator consists of several stator segments which contain the coils and the magnets. The armature, therefore, has a totally passive design. Because of its salient structure, a translational force can be produced for motion of the armature. The magnets create a passive attraction force for failsafe operation, which can be controlled for magnetically suspending the armature. Decoupling of the attraction and translational force, however, is complex, because they are strongly coupled. Therefore, position and current dependent force models are created based on curve fitting of inductances. It is shown that using these models, decoupling of the attraction and translational force in the ceiling actuator is possible.

Index Terms—Magnetic levitation, reluctance machines.

I. INTRODUCTION

A permanent magnet biased E-core reluctance actuator (PMECRA), as shown in Fig. 1, is investigated for application in a magnetically suspended ceiling actuator. In the figure, part of the ceiling actuator is shown, which contains three stator segments. The structure of each stator segment is similar to a design of a reluctance actuator, which is used for valve actuation inside a combustion engine [1]. In the ceiling actuator the armature has a salient structure in order to create a translational force. Because the magnets and the coils are embedded inside the stator of the ceiling actuator, the armature has a simple and fully passive construction.

In the ceiling actuator, a passive upward attraction force is required to prevent the armature from falling down in case of a power failure. Therefore, unlike a magnetically suspended planar actuator [2], in the ceiling actuator iron has to be employed into the structure in order to create passive upward attraction force between the iron and the magnets. The main challenge, though, is to actively reduce this passive attraction force to stably suspend the armature and also to create a translation force to provide motion of the platform. Both forces, however, are strongly coupled.

In this paper, first the basic operating principles of the pm biased e-core actuator are explained. Next, position dependent models for both the attraction and translational force are derived, which also describe the force dependency on the current. Finally, based on these models, it is shown that the forces can be decoupled by appropriately commutating currents inside the three stator segments from Fig. 1.

II. OPERATING PRINCIPLES

The operating principle of the PMECRA can be explained by considering a single stator segment, as is shown in Fig. 2. In the absence of any current inside the coil, the magnet creates a passive attraction force, F_z , between the stator and the armature.

Fig. 1. Ceiling actuator containing three permanent magnet biased E-core actuators.

Fig. 2. Dimension and operating principles of a single permanent magnet biased E-core actuator.

By imposing a negative DC current through the coil, a coil flux, ϕ_c , is created which opposes the magnet flux, ϕ_m and the attraction force is reduced, as shown in Fig. 3. The figure shows the attraction force as a function of the current density when the stator is aligned with the armature teeth. Similar to a reluctance actuator, the attraction force has a quadratic dependency on the current. However, in this case the graph is biased because of the magnet. The attraction force can be fully diminished for a certain current, though operating the current beyond this point is undesirable, because the same attraction force can be obtained with smaller amplitude of the current and, hence, with lower power losses.

Because of the salient structure of the armature, a translational component of the reluctance force is produced when the stator and armature teeth are unaligned. By appropriately commutating AC currents in each stator segment from Fig. 1, a net

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Fig. 3. Force-current characteristic of the pm biased E-core actuator for different airgap lengths.

TABLE I
DESIGN FOR THE PERMANENT MAGNET BIASED
E-CORE RELUCTANCE ACTUATOR

Description	Parameter	Value
Slot pitch	τ	10 [mm]
Width second airgap	w_s	4 [mm]
Slot height	h_s	10 [mm]
Coil height	h_c	25 [mm]
Tooth tip height	h_t	12.5 [mm]
Magnet height	h_m	12.5 [mm]
Core height	h_b	10 [mm]
Length of segment	L	50 [mm]
Remanent flux density	B_{rem}	1.3 [T]
Coercivity	H_c	-0.985x106 [A m ⁻¹]
Relative permeability magnet	$\mu_{r,m}$	1.05
Relative permeability iron	$\mu_{r,i}$	∞

translational force, F_x , can be controlled. For the ceiling actuator the segments in Fig. 1 are shifted by $x = 6\tau + (2/3)\tau$ from each other. Inherently, in this actuator the translational force is much lower than the attraction force.

The translational and attraction force inside the actuator can be calculated by modeling the magnet as a coil with an equivalent current or magneto motive force (MMF), $i_m = -h_m H_c$. In the analysis of the forces no saturation inside the actuator is assumed. Therefore, F_z and F_x can be described through the change of magnetic energy in a linear and doubly excited system [3]

$$F_z = \frac{1}{2} i_c^2 \frac{dL_c}{dz} + i_c i_m \frac{dM}{dz} + \frac{1}{2} i_m^2 \frac{dL_m}{dz}, \quad (1)$$

$$F_x = \frac{1}{2} i_c^2 \frac{dL_c}{dx} + i_c i_m \frac{dM}{dx} + \frac{1}{2} i_m^2 \frac{dL_m}{dx}, \quad (2)$$

where L_c is the self inductance of the coil, L_m is the self inductance of the coil equivalent of the magnet, M is the mutual inductance between both coils and i_c is the coil current. Both forces are calculated on the armature, where the relative displacement of the armature to the stator is x in the translation direction and $z = -h_g$ in the normal direction.

In Table I, dimensions are given for a design of the structure which is shown in Fig. 2. Throughout the paper, this design will be used. The design achieves a passive elevation force of $F_{z0} = 207$ N (airgap length is 1 mm), which can be reduced to zero when the DC current density is equal to -7 A mm⁻².

Fig. 4. Magnetic equivalent circuit of a permanent magnet biased E-core actuator.

III. RELUCTANCE MODEL

For the analysis of the PMECRA, a magnetic equivalent circuit (MEC) or reluctance model is created [4]. In Fig. 4 the reluctance model is shown when the stator and armature teeth are aligned. The reluctances are calculated according to [5]

$$R_{g1}(z) = \frac{1}{\mu_0 \left(\frac{\tau L}{z} + 0.52(L + \tau) + 0.308z \right)} \quad (3)$$

$$R_{g2} = \frac{1}{\mu_0 \left(\frac{h_c L}{w_g} + 1.04(L + h_t) + 0.616w_g \right)} \quad (4)$$

$$R_m = \frac{h_m}{\mu_{r,m} \mu_0 L (3\tau - 2w_g)} \quad (5)$$

$$R_l = \frac{2\tau}{\mu_0 h_c L} \quad (6)$$

The inductances per turn are obtained from the reluctance model and from Fig. 3 it can be concluded that the attraction force calculated with this model shows good agreement with FEM prediction obtained from FLUX 2D. The reluctance model, however, becomes inaccurate when the stator and armature teeth are unaligned and calculating the translational force is not possible. Therefore, the model is only sufficient for the design of the actuator.

IV. CURVE FITTING INDUCTANCE

To calculate the translational and attraction force, expressions for L_c , L_m and M as function of x and h_g have to be determined. The position dependency of the inductances per turn is analyzed in FEM-package FLUX 2D and shown in Fig. 5. For different positions of the armature in x , the inductances in Fig. 5(b) show a sinusoidal behavior with an offset. Therefore, each inductance as function of x is approximated with the following function

$$L(x, z) = \hat{L}_0(z) + \hat{L}_1(z) \cos\left(\frac{\pi}{\tau} x\right) + \hat{L}_3(z) \cos\left(\frac{3\pi}{\tau} x\right) \quad (7)$$

where $\hat{L}_0(z)$, $\hat{L}_1(z)$ and $\hat{L}_3(z)$ are the z -dependent amplitudes of the different harmonics. Because the inductances are inversely proportional to the z -position of the armature, as

Fig. 5. Inductances per turn obtained from FEM and curve fitting as function of (a) the airgap length ($x = 0$) and (b) the translational position of the armature ($h_g = 1$ mm).

is shown in Fig. 5(a), the amplitude of each harmonic, i , is described by

$$\hat{L}_i(z) = a_i z^{-3} + b_i z^{-2} + c_i z^{-1} + d_i \quad (8)$$

where the coefficients a_i , b_i , c_i and d_i have to be obtained for each harmonic of the inductance. For translational positions of the armature which are equal to $x = 0$, $\tau/3$ and τ , the following should hold:

$$L(x = 0, z) = \hat{L}_0(z) + \hat{L}_1(z) + \hat{L}_3(z) \quad (9)$$

$$L(x = \tau/3, z) = \hat{L}_0(z) + \frac{1}{2}\hat{L}_1(z) - \hat{L}_3(z) \quad (10)$$

$$L(x = \tau, z) = \hat{L}_0(z) - \hat{L}_1(z) - \hat{L}_3(z). \quad (11)$$

From this set of equations the amplitude of each harmonic can be expressed by the total inductance at the different positions in x . For the three positions of the armature in x , the total inductance is calculated with FEM when the z -position of the armature is ranged from $z = -h_g = -0.4$ to -3 mm. Through curve fitting on the results from FEM, the coefficients in (8) are obtained for the three inductances, L_c , L_m and M , respectively. The fitted models described by (7) and (8) show good agreement with the FEM predictions, as shown in Fig. 5(a) and (b).

The models for the inductances are used to calculate the attraction and translational force according to (1) and (2). In Fig. 6, the attraction force as function of the airgap length is

Fig. 6. Attraction force as function of the airgap length ($x = 0$).

Fig. 7. x -dependency of the attraction force, F_z , and the translation force, F_x ($h_g = 1$ mm).

shown for different values of the coil current when $x = 0$. The force as function of x when the airgap length is fixed to 1 mm, is shown in Fig. 7. Both the attraction and translational forces calculated by the fitted model show good agreement with the result obtained from FEM.

V. COMMUTATION

With the obtained models, the force produced by each stator segment in Fig. 1 can be calculated. Because only part of the complete ceiling actuator is analyzed, torques created on the armature are ignored. As is discussed in Section II, an AC current is injected into the coils of each stator segments in order to create a net translational force. The attraction force, however, is mainly controlled by a DC current, which is the same in every stator

Fig. 8. Force profiles of ceiling actuator containing three PMECRA's with (a) the attraction force and (b) the translational force ($I_{DC} = -625$ A.turns, $h_g = 1$ mm).

segment. Therefore, the following currents for the different segments are proposed

$$i_c = I_{DC} + I_{AC} \sin\left(\frac{\pi}{\tau} \left(x - k\frac{2\tau}{3}\right)\right) \quad (12)$$

where $k = 0, 1, -1$ for stator segment *A*, *B* and *C*, respectively. In Fig. 8 the translational and attraction force calculated with the models obtained with curve fitting and FEM are shown when $I_{DC} = -625$ A.turns and $I_{AC} = 0$ and $I_{AC} = -750$ A.turns. In the figure, it is clearly shown that the attraction force is increased due to the AC current, which indicates the coupling of the translational and attraction force. Both forces suffers from a large ripple, which is created by cogging force and higher harmonics which are not compensated by the current proposed in (8).

In order to decouple the translational and attraction force and to get a constant force profile, I_{DC} and I_{AC} need to be adjusted as the armature is moved along the stator. Using the description for the inductances in (7) and (8), the total translational and attraction force of the three stator segments together are solved for I_{DC} and I_{AC} . Because the force has a non-linear dependency on

Fig. 9. Set points for I_{DC} and I_{AC} when $F_x = 15$ N and $F_z = 200$ N ($h_g = 1$ mm).

the current, a set of four solutions for I_{DC} and I_{AC} as function of the armature position and force set points, is obtained. From this set, the combination with lowest amplitude of the currents and, therefore, the lowest power losses, is chosen. For a given force set point with $F_x = 15$ N and $F_z = 200$ N and an airgap length of 1 mm, the values for I_{DC} and I_{AC} as function of x are shown in Fig. 9. The profiles for I_{DC} and I_{AC} have a dominant third harmonic, which is not included in (12). When the armature is moved along the stator, the total amplitude of both currents need to be adjusted by 8% and 21%, compared to the average value, respectively.

This model-based commutation will be used inside a position feedback controller and is assumed to have sufficient decoupling to allow the use of separate single-input-single-output (SISO) controllers for the position of the mover in x and z [2]. In future work, measurements on a prototype will be carried out to experimentally verify this assumption.

VI. CONCLUSION

In this paper, it is shown that a permanent magnet biased E-core reluctance actuator can be applied in a magnetically suspended ceiling actuator. For the topology, position and current dependent models for the attraction and translational force are obtained by curve fitting of the inductances. By appropriately commutating the currents, it is shown that the translational and attraction force can be decoupled and independently controlled.

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