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Modelling and control of tunable magnet actuators

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Abstract

High-precision disturbance rejection systems that exploit the low stiffness of electromagnetic actuators are susceptible to positioning errors stemming from excessive heat dissipation and thermal expansion under sustained actuation loads. Conventional vibration isolators and gravity compensators utilise permanent magnets to compensate for static forces, generating a position-dependent magnetic flux bias between the stator and the mover. This static compensation force can be varied by displacing either the mover or the magnets. Displacement of the mover is often not admissible and moving the magnets can substantially restrict bandwidth and complicate the mechanical design. As an alternative, recent research has sought to control the bias flux by altering the magnetisation level of the low coercivity magnets *in-situ*. Due to the nonlinear variation in magnetic flux during magnetisation pulses, a secondary actuator is required to maintain control over force; however, introducing two actuators is often infeasible due to space restrictions. Combining a traditional reluctance actuator and the Tunable Magnet Actuator in a single stator-core design allows to share the biasing flux, resulting in a much more compact design. This paper presents a magnetic equivalent circuit-based modelling approach to describe such a combined actuator, with which the ability to generate a smooth increase in force is demonstrated. Lastly, a tuning algorithm using the least possible energy for magnetising the Tunable magnet is experimentally validated.

Actuator, design method, mechatronic, modelling

1. Introduction

Magnetic actuators have an extensive history of use in high-precision machines. They offer an ability to track precise and fast motions with no direct contact, and thus with no friction and particle generation. However, as the limits in throughput of high-precision machines are pushed, thermal dissipation from actuated stages with higher actuation forces becomes a source of positioning errors due to thermal expansion [1]. This is a particular cause for concern in gravity-compensating stages with quasi-statically varying normal and torsional loading conditions.

A new form of reluctance actuator incorporating a Low Coercive Force (LCF) magnet within the stator core that can be tuned between remnant magnetisation states may provide an energy-efficient solution for sustained actuation forces. In [2] such an actuator is combined with a Lorentz coil actuator for gravity compensation of quasi-statically varying loads. Another concept of a Tunable Magnet (TM) actuator is further explored in a design where High Coercive Force (HCF) NdFeB magnets are integrated to give bi-directional and linear control of the actuation force through control of the magnetisations states [3].

Here we show that the topology described in [3] can be furthered to include an additional reluctance force to compensate for unwanted dynamics during magnetisation pulses, resulting in a compact design that removes the need for separate parallel actuators as in [2].

2. Lumped model

The duration and energy of magnetisation pulses depend on the voltage across the magnetising coil and the initial magnetisation state of the magnet. In a lumped parameter approximation of the TM actuator, the voltage V and current i in the electric circuit is given by (1), and the magnetomotive force (MMF) $\mathcal{F}$ across and magnetic flux ϕ through equivalent magnet circuit components by (2).

$$V = iR + d\lambda/dt, \qquad \lambda = N\phi, \tag{1}$$

$$\mathcal{F} = \phi\mathcal{R} + \gamma, \qquad \gamma = Ni, \tag{2}$$

where λ and γ are respectively the flux- and current coupling coefficients, R is the electrical resistance, $\mathcal{R}$ is the reluctance of magnetic bodies, and N is the number of turns of the coil. The inductive field H, flux density B and $\mathcal{R}$ are dependent on the length l and cross-sectional area A of the lumped bodies,

Magnetomotive force (MMF): $\mathcal{F} = Hl$ (3)

Flux: $\phi = BA$ (4)

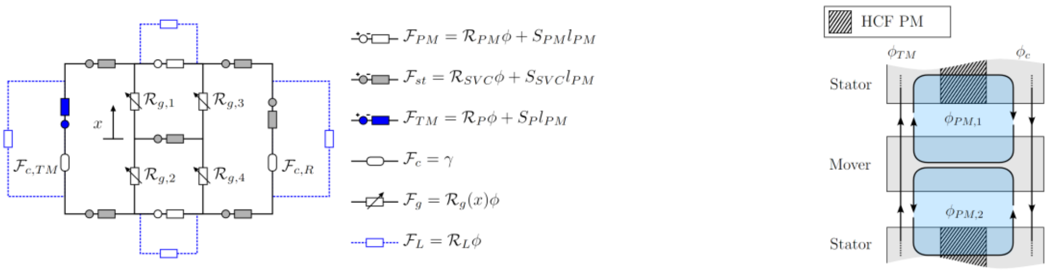
Reluctance: $\mathcal{R} = l/\mu A$ (5)

The permeability μ is equal to the derivative dB/dH. From (1) it is apparent that the inductance L of the coil depends on μ (6).

$$\frac{d\lambda}{dt} = NA\frac{dB}{dt} = \frac{N^2A}{l}\frac{dB}{dH}\frac{di}{dt} = L(\mu)\frac{di}{dt} \tag{6}$$

Due to magnetic hysteresis, the value of μ in the TM can change by two orders of magnitude during magnetisation, causing proportional variations in the inductance of the magnetising coil. This nonlinearity is considered through the implementation of a Preisach model, while the comparatively anhysteretic B-H relation of laminated steel segments is determined from a single-value curve (SVC). As in [4], Eddy current effects in the steel are added to the output of the SVC. The resulting nonlinear field problem is solved through a method of fixed-point iterations described in [5] wherein the B-H relation is linearly approximated as a series combination of a reluctance and an MMF-source (7) as shown in Figure 1a. In the HCF magnets these terms are assumed to be constant. The subscripts: PM, SVC and P, in Figure 1, denote the method of estimation for the HCF magnets, the laminated steel and the TM, respectively.

$$\mathcal{F}_m = H_m l_m = \phi_m\mathcal{R}_m + S_m l_m \tag{7}$$



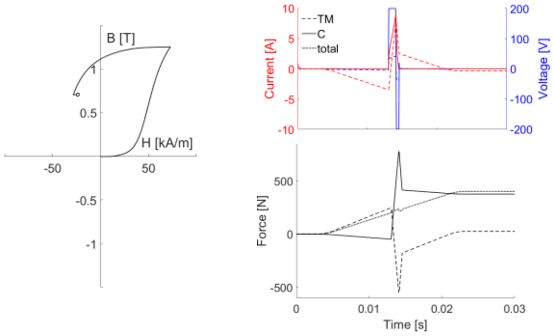
(a) (b)

Figure 1. (a) An equivalent magnetic circuit of the actuator, where ferromagnetic elements are a series equivalent of a reluctance and an MMF-source. $\mathcal{R}_{g,1-4}$ are the air-gap reluctances, and $\mathcal{F}_{c,TM}$ and $\mathcal{F}_{c,R}$ are MMFs of the magnetising and non-magnetising coils, respectively. (a) Illustration of the flux paths of the TM ϕ_{TM}, the non-magnetising coil ϕ_c, and the bias-flux of the NdFeB magnets $\phi_{PM,1}$ and $\phi_{PM,2}$.

2. Tunable magnetisation and dynamic reluctance forces

A problem with the magnetisation process is that it requires some overshoot of the reference signal. This is shown in Figure 2a of the results of the lumped parameter model when the remnant magnetisation state of the TM is tuned from 0 T to 0.7 T, requiring a transient magnetisation pulse to 1.2 T. This results in a spike in the actuation force at 13 ms in Figure 2b (*solid line*).

To compensate for this spike, an additional coil shown in Figure 1a is added to induce a field $\mathcal{F}_{c,R}$ that generates a reluctance force without magnetising the TM. To achieve this, HCF magnets are placed between the two coils, producing flux biases to the magnetic flux through the magnetising coil ϕ_{TM} and non-magnetising coils ϕ_c, while roughly isolating the two circuits, as illustrated by the schematic in Figure 1b.



(a) (b)

Figure 2. Transient change in electric currents, magnetic flux and forces during a step change in the actuation force

The dashed lines in **Figure 1**Figure 2b show how the additional inductor contributes to an actuation force that increases relatively smoothly over a 20 ms duration (*dotted line*). The current in both coils subsides to roughly zero when the force is constant again at 23 ms, thus mitigating continued joule heating.

Due to the superposition of the flux from the HCF PMs ϕ_{PM} with the controlled flux paths ϕ_{TM} and ϕ_c, the actuation force on the mover, when centred, is linearly dependent on these control inputs based on Maxwell's stress tensor:

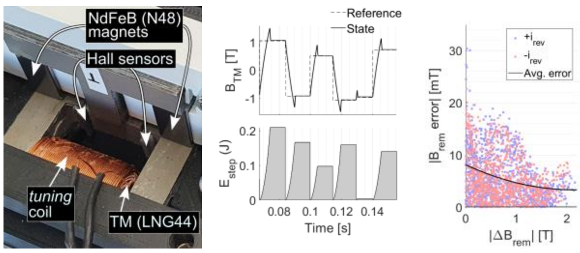
$$F_{a,x=0} = \frac{4}{\mu_0}\phi_{PM}\left(\frac{\phi_{TM}}{A_{TM}} + \frac{\phi_c}{A_c}\right), \tag{8}$$

where μ_0 is the permeability of air.

3. Magnetisation state tuning

A control algorithm was devised for a demonstrator that includes an Alnico 5 (LNG44) magnet (Figure 3a). The algorithm uses the modelled method in Figure 2b, whereby a magnet is tuned with two consecutive maximum voltage pulses, thus expending the least possible amount of energy.

The algorithm estimates the timing of magnetising pulses using look-up tables of linearised hysteretic reversal curves. The magnetisation state is manipulated in a range of -1 T to +1 T within a Root Mean Squared Error (RMSE) of 7.2 mT [7]. As shown in Figure 3c the steady-state flux density error reduces for consecutive states with a larger difference in flux density $|\Delta B_{rem}|$. Reversal curves become steeper when the magnetisation states are further apart, causing the inductance to increase and the rate of magnetisation to reduce. Thus reducing the error resulting from sampling delay. The lab setup and control algorithm is further detailed in [7].



(a) (b) (c)

Figure 3. (a) Test setup for remnant magnetisation state tuning (b) Measurements of flux density (B_{TM}) and calculated accumulation of joule heating (E_{step}) during 6 random tuning steps. (c) Error across 2000 remnant magnetisation states initiated by either positive or negative current pulses ($+i_{rev}$ and $+i_{rev}$, respectively)

4. Conclusion

A model is proposed as a basis for studying the energy efficiency of Tunable Magnet Actuators. This model is used to demonstrate the feasibility of compactly designing such actuators with the ability to exert a smoothly varying force. Furthermore, a tuning method is experimentally validated for changing the magnetisation state of the Tunable magnet with two magnetising pulses, within an RMSE of 7.2 mT.

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