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A note on electromagnetic gravity compensation actuators based on soft electro-permanent magnets for adjustable reluctance force

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Abstract

Electrodynamic drives or so-called voice coils are preferably used for positioning tasks with high resolution in combination with a large range of motion. In case of vertical lifting, the gravitational force should be compensated without using the drive itself, which would otherwise result in unwanted heat generation. This is especially important in vacuum applications in which the heat of the drive coil cannot be dissipated by convection. Additionally, the self-heating leads to undesirable changes in the dimensions of components which can adversely affect accuracy in the case of precision devices. In this paper the combination of an electromagnet having an adapted force-displacement characteristic together with a permanent magnet (PM) of low coercivity is investigated. The PM generates the necessary magnetic field without power loss. The coil is used for magnetization or demagnetization of the PM, which results in an infinitely adjustable magnetic force. The magnetic circuit has been optimized by finite element parameter studies. A test rig has been built to verify the design experimentally. Finally, an algorithm for influencing the gravity compensating magnetic force by current impulses is proposed.

Keywords: vertical lifting, gravity compensation, electromagnet, adapted force-displacement characteristic, infinitely adjustable magnetisation

1. Introduction

A gravity compensation can be realized e.g. by mass pieces in conjunction with levers. However, the electric drive would again have to perform the residual compensation, if the load changes. Additionally the position dynamic decreases due to higher inertia. Furthermore adding counterweights and levers can lead to extra parasitic eigenfrequencies.

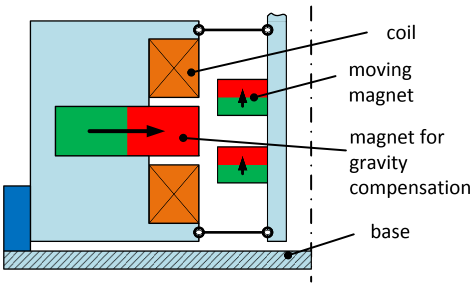

Figure 1 Integrated magnetic gravity compensator (half section).

A different possibility of passive gravity compensation is the usage of forces between several PM or PM and ferromagnetic parts [1]. Figure 1 shows a principle of a magnetic gravity compensator (MGC) integrated into a voice coil actuator. The realised force-position-characteristic is linear. The exact compensation is only possible for one force which has to be mechanically adjusted during assembly. Load deviations during operation have to be balanced by the drive. Because of the drawbacks of existing systems a passive non-integrated compensation system should be developed which delivers a force that is

a) adjustable during operation and
b) as constant as possible over a certain displacement (e.g. low stiffness).

This paper shows a concept addressing these points and its experimental verification.

2. Concepts of adjustable magnetic gravity compensation

2.1. Electro-permanent magnets

The idea of the MGC is based on electro-permanent magnets (EPM) [2]. A passive adjustable MGC has to contain at least one PM whose magnetisation condition can be altered by a momentary magnetic field generated by a coil. This effect was already used by [2] to realise a switchable magnetic force. The device consists of a coil wound around two PM in parallel. One of these has a high coercivity, the other one has a low coercivity and comparable remanent magnetisation. The applied field from the coil is just strong enough to reverse the remanent magnetisation of the PM having low coercivity. Switching the magnetisation direction the two permanent magnetic fields either add up or compensate each other.

This concept only works well for switching applications. A precisely adjustable arbitrary force is difficult to realise.

2.1. Polarized electromagnet with adapted characteristic

A possibility to realise a MGC with the desired features is shown in figure 2. Inspired by the EPM the proposed system is a polarised electromagnet where the coil is used to magnetise the PM to the desired level by a momentary current feed.

Usually the force of electromagnets decreases quadratically with increasing displacement. Using a specific shape for the armature and its counterpart leads to nearly constant forces within a certain displacement range [3]. Each partial flux between center pole and armature (see flux lines in figure 2, note the magnified area) provides a specific portion of the force-displacement characteristic, both in size and in direction. The dimensions of the magnetic circuit and the geometric details of the air gap region (diameter and axial position of the edges relative to each other) were determined by a parametric FE analysis study. Due to its low coercivity and high remanence AlNiCo was chosen for the PM-material.

3. Concepts of variable force setting

If the weight force changes, the remanent magnetisation of the PM needs to be adjusted by the coil. As a consequence of the nonlinearity between the required magnetising current and the resulting remanent force, a considerable set of characteristic curves is needed for the determination of the magnetising current.

Another, considerably easier, way for adjusting the force is a three step algorithm. At first the PM is magnetised above saturation, secondly a current of reversed polarity demagnetises the PM completely and in the last step the PM is magnetised to the desired level using only one characteristic curve.

4. Experimental validation

The aim of the experimental validation is to compare force-displacement-characteristic between the experimental setup and the results of FE analysis and to analyse reproducibility of the magnetisation algorithm for desired operating points.

Figure 2 shows a schematic of the experimental measurement setup. The adjustment accuracy of the armature position by the hand-operated lifting table is 5 micrometers; the force sensor has an accuracy class of 0.2% for 100 N full scale. The magnetisation current is provided by a programmable current source. Since all parts of the magnetic circuit are electric conductors, eddy currents have to be taken into account by sufficiently long duration of magnetisation (half sine of one second).

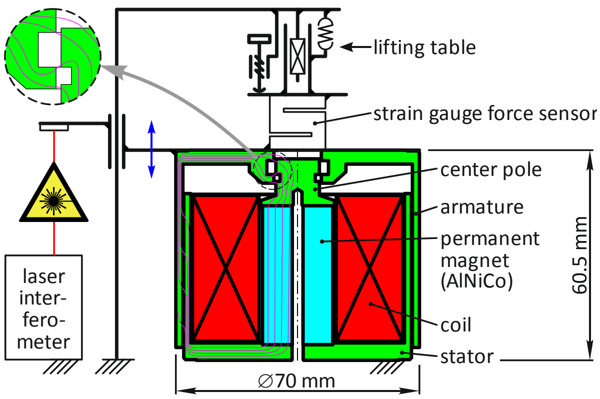

Figure 2 Experimental setup; depicted armature position: z = 0 mm.

The demagnetisation-magnetisation-process was carried out repeatedly leading to the same force-displacement characteristics within bounds of measurement accuracy.

Figure 3 shows the measured characteristic between compensation force and magnetising current for the experimental setup. The demagnetisation point was determined by experiment and mirrored along the vertical axis.

Figure 4 shows the measured force-displacement-characteristic for different magnetisation currents. The FE simulation was carried out with a fully magnetised PM. The measured result for maximum magnetisation current corresponds with the FE analysis with the expected accuracy.

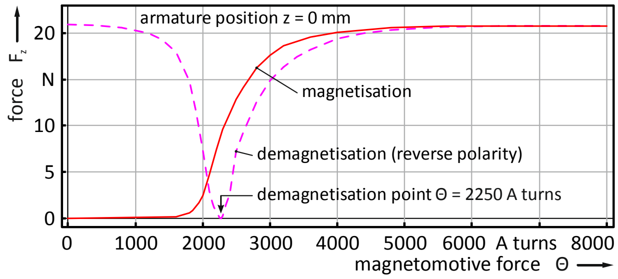

Figure 3 Magnetisation and demagnetisation characteristics.

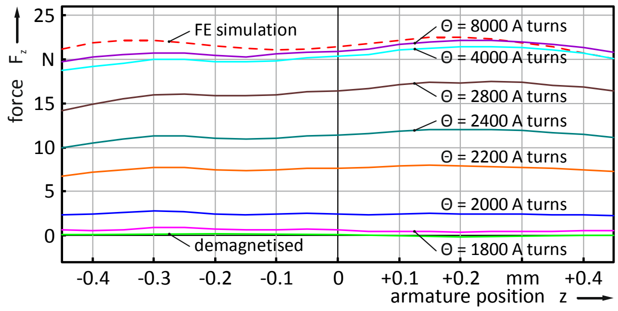

Figure 4 Force-displacement-characteristics.

The coil contains no temperature sensor. Therefore, the temperature increase during the three-step magnetization process described above can only be estimated: A cycle consisting of 8000 A turns magnetisation, 2250 A turns demagnetization and worst case 8000 A turns magnetisation leads to a heat energy of 434 J. When thermal transfer is neglected, the coil temperature increases 1.9 K.

5. Summary

In this paper a MGC with variable adjustable force is presented. The geometry of the magnetic circuit was determined by FE parameter studies. Specifically, this concerned the details of the armature and its counterpart to achieve a nearly constant force over the required displacement.

The force-displacement characteristics were confirmed by an experimental validation. The proposed three-step method for setting a new operating point provides repeatable results. However, the proper demagnetisation field strength must be determined for each produced MGC due to material and geometry tolerances. It has also been demonstrated that there is no demagnetisation effect for the AlNiCo-PM due to strokes beyond the specified range and its resulting large air gap.

The design still has considerable reserves with regard to the heating of the coil. The coil and therefore the whole actuator can be built significantly smaller due to a very low duty cycle. Scaling the actuator's geometry for a different force range is only possible if the detail geometry of armature and center pole are redesigned by FE parameter studies.

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