Contactless Linear Electromechanical Actuator: Experimental Verification of the Improved Design

Anton LEBEDEV†, Dipali THAKKAR‡, Dick LARO‡, Elena LOMONOVA† and Andre VANDENPUT†

† EPE Group, Department of Electrical Engineering, Eindhoven University of Technology, The Netherlands

‡AM Group, Department of Mechanical, Maritime and Materials Engineering, Delft University of Technology, The Netherlands

Tel: +31 40 2473571 – Fax: +31 40 2434364 – e-mail: a.lebedev@tue.nl

Abstract This paper describes ways to overcome the major applicability limitations of a novel linear electromechanical actuator. Guidelines for selecting a proper soft magnetic material for a magnetic system of the actuator are presented. Conventional laminated electric steel and a soft magnetic composite material are compared based on the measured dynamic performance (up to 1000 Hz) and manufacturability. A serious cross-coupling between two actuation directions of the actuator is identified and investigated. Improvements to the design are described. Experimental verification of the improved design is carried out by the two scientific groups. First measurement results show a significant (3 to 7 times) reduction of the cross-coupling.

Keywords : Design, Linear actuator, Magnetic suspension

1. Introduction

In recent years the move towards high precision positioning systems is being made. In order to design such intelligent mechatronics systems a multidisciplinary approach must be applied. Besides an advanced control strategy, an accurate electromechanical design should be performed. Much attention has to be paid to the selection of magnetic materials, used in the system, as they have a great impact on the magnetostatic characteristics as well as on the dynamic behavior and, in its turn, on the control system.

An example of a six degree-of-freedom (6 DoF) high precision positioning system is described in [1]. This system is intended for optical disc mastering applications. It should provide contactless propulsion of a mover in one long stroke sliding direction (1 DoF) and contactless suspension in other directions (5 DoF). The system is modular and utilizes three identical linear actuators (IU-shaped modules), each providing an actuation in two DoF.

Development of the IU–module is thoroughly described in [2]. In this paper the authors outline some major limitations of the actuator, propose ways to overcome those limitations and present measurement results for an improved IU–module.

1.1. IU–module operation principle

An IU–module is a complex electromechanical system combining features of an active magnetic bearing (suspended mass in the order of 0.3 kg) and a linear Lorentz actuator (long stroke range – 50 mm). Schematic layout of the IU–module is shown in Fig. 1. Permanent magnets create a bias magnetic flux through the mover, causing its levitation, which is unstable due to the Earnshaw's theorem. Suspension coils introduce a difference in the flux density distribution in the air gaps above and below the mover. That enables controlling the *z*–force (suspension force) acting on the mover. Thus, suspension force is a difference in reluctance forces acting upward and downward. An interaction of the total flux (created by the permanent magnets and suspension coils) passing through the air gap between the stator and the mover with currents in the propulsion coils produces the Lorenz force acting in the *x*–direction. It allows controlling the *x*–component (propulsion force) acting on the mover.

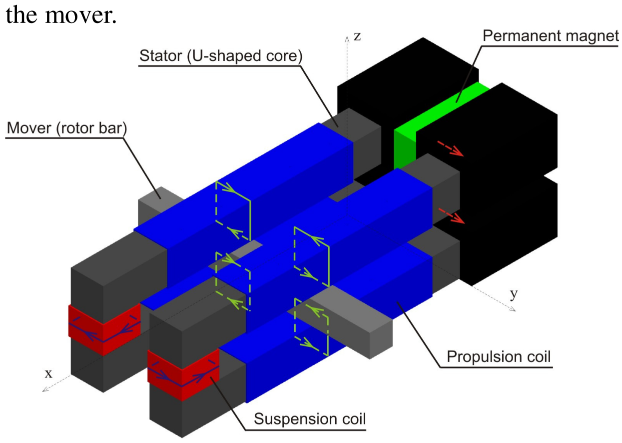

Figure 1: The three dimensional schematic layout of an IU–shaped actuator. The specified directions of magnetization of the permanent magnets and currents in the suspension and propulsion coils correspond to the case when the total force on the mover has positive *x*- and *z*-components.

2. Limitations of the Actuator

Several prototypes have been built during the design flow of the IU–module to validate the design choices. An IU–module prototype is shown in Fig. 2. Measurements of the static and dynamic behavior of the actuator have been conducted [3]. Measured performance is in a close agreement with modeling results and satisfies requirements of the 6 DoF positioning system that it was intended for. However, an extension of the IU–module applicability to other systems requires some improvements.

First of all, to increase the stability of a control system, the bandwidth of the actuator should be improved. In a contactless magnetically levitated and propelled actuator, the main source of the phase lag between the control current and resulting force is the hysteresis of the iron materials. Thus, a soft magnetic material with the lowest phase lag should be selected for the IU–module.

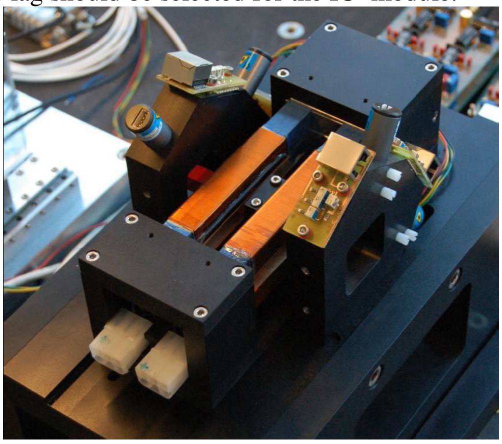

Figure 2: The IU–module prototype.

The second limitation of the actuator is due to a combination of the suspension and propulsion in one module. It introduces an interaction between the magnetic fluxes created by different field sources (two permanent magnets and six coils) through the common magnetic system. As an example, Fig. 3 illustrates an influence of the propulsion current i_x on the suspension force F_z at different x- and z-positions of the mover.

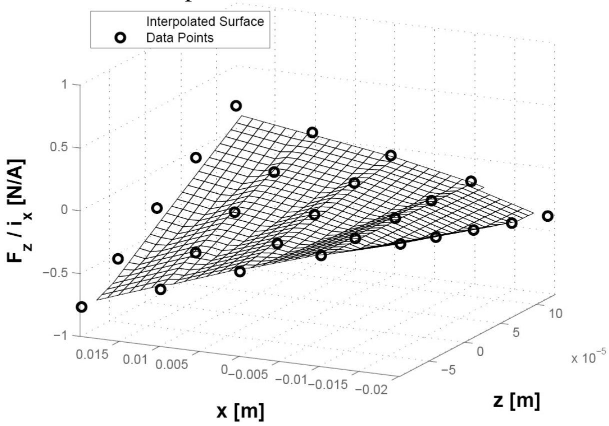

Figure 3: Influence of the propulsion current on the suspension force. Cross-coupling effect.

Measurements show that at certain positions of the mover, a coupling coefficient $\Delta F_z/\Delta i_x$ goes up to 0.75 N/A (worst case, when the mover is close to the permanent magnets and 0.1 mm below the middle of the air gap). It means that the magnetic flux created by the propulsion current e.g. of 2 A increases or decreases the suspension force by 2·0.75=1.5 N. The cross-coupling should be significantly reduced to allow separate control of the suspension and propulsion of the IU–module.

3. Soft Magnetic Material Selection

Magnetic system of the IU-module is loaded with a bias field created by the permanent magnets and switching DC fields created by the suspension and propulsion coils. Those switching fields induce eddy currents in the magnetic system, causing a phase lag between the control currents and the required electromagnetic forces. A conventional way of limiting the eddy currents is the application of laminated electrical steels. However, in recent years, viable alternative - soft magnetic composite (SMC) materials have become commercially available. They provide relatively high saturation flux densities, isotropic properties and low eddy current losses. In the paper, a dynamic behavior of a commonly used electric steel M270-35A is compared to that of an SMC material Somaloy 700 based on the magnitude of the generated forces and phase lag between the control current and the generated force. To compare the two types of materials, the IU-module can be substituted for a simple C-shaped actuator with equal parameters of the magnetic system. This substitution allows faster and easier modeling, manufacturing, assembly and measurements.

Various modeling techniques are available for the analysis of non-laminated C-shaped actuators, e.g. [4]. However, investigation of laminated structures requires a more complicated modeling and is more time consuming.

Fig. 4 shows a prototype of a C-shaped actuator for dynamic force measurements. Measurement results (Fig. 5) show comparable dynamic behavior of the materials at frequencies up to 1000 Hz with an advantage of electric steel. It provides higher electromagnetic force and lower phase lag (4 degrees difference at 400 Hz) than the SMC material. Peaks above 450 Hz are due to mechanical resonances in the prototype. Laminated electric steel is selected as a primary material for the magnetic system of the IU–module. However, it should be noted that the difference in the performance is not significant and the SMC material can be utilized in case of a minor redesign (increase in the dimensions) of the magnetic system.

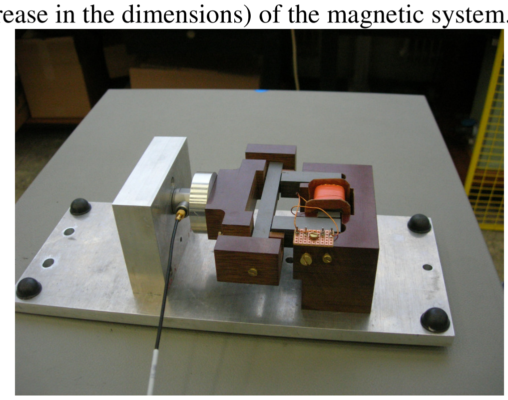

Figure 4: C-shaped actuator prototype.

Another important issue in selecting a proper soft magnetic material for the use in an actuator is manufacturability and ease of prototyping. From this perspective, SMC materials have definite advantages over laminated electric steels. Blocks of SMC can be cut into complicated 3D shapes using an electric discharge machining process. In contrast to that, laminations should be first cut and then carefully glued together piece by piece. Accurate alignment of sheets is important also. Nonaligned laminations introduce extra air gaps between adjacent blocks and form uneven surfaces of the bars. This leads to a reduction in the electromagnetic force and complicated manufacturing of the coils. Grinding the glued laminated bars (as one of the ways to improve the nonalignment) introduces short circuits between laminations which in its turn increase the phase lag. An example of the frequency response measured on the IU–module, stator of which is made of laminated blocks planed by grinding, is shown in Fig. 6. The two curves correspond to two materials of the mover: laminated electric steel (not grinded) and SMC. The results show a significant increase in the phase lag (up to 10 degrees) if compared with the C-core results. An augmentation of the gain with frequency is a result of a slight increase of the current at higher frequencies. An advantage in the performance of electric steel is barely noticeable in Fig. 6 due to the scale of influence of the grinding process.

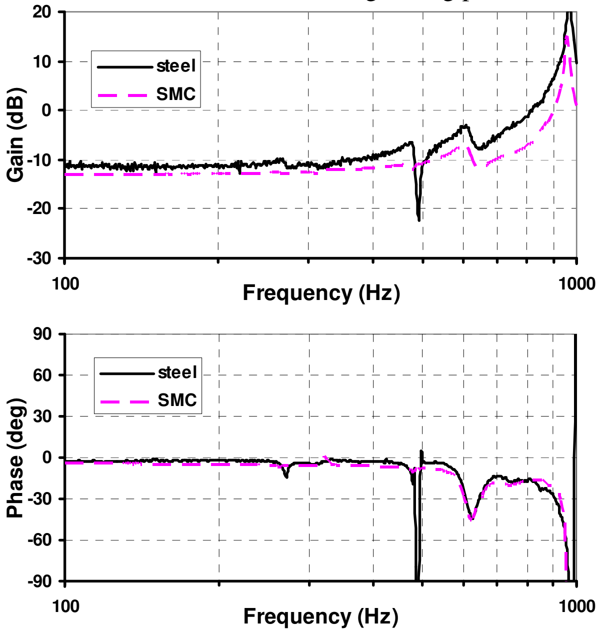

Figure 5: A current-to-force frequency response of the C-shaped actuator.

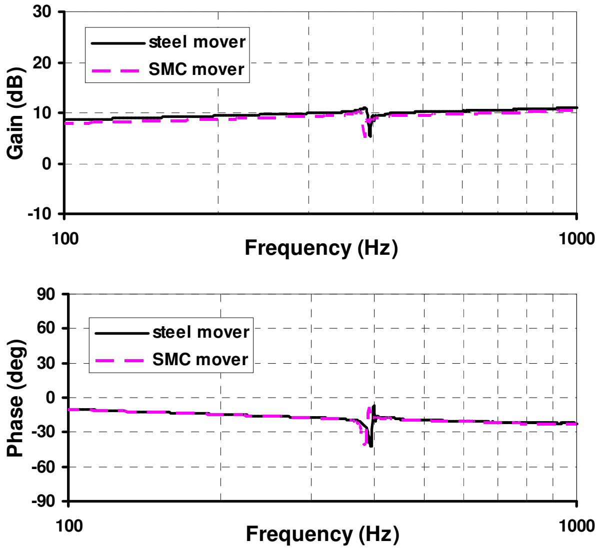

Figure 6: A current-to-force frequency response of the IU-module suspension.

4. Cross-coupling reduction

The principal cause of the cross-coupling effect in the IU-module is a combination of the suspension and propulsion in one actuator. To control the horizontal position (the *x*–position) of the mover the propulsion coils are placed on the same U–shaped cores as the suspension coils. Being excited, the propulsion coils distort the distribution of the magneto motive force (MMF) in the stator bars. Considering Fig. 1, a long propulsion coil can be virtually divided into two main parts: one is to the left of the mover (closer to the suspension coils) and one is to the right of the mover (closer to the permanent magnets). The MMF of the right part adds up to the dominant MMF of the permanent magnets without a noticeable influence on the bias flux. However, the MMF of the left part is in the same order as the MMF of the suspension coil and, thus, an interference of the propulsion magnetic flux with the suspension force is significant.

The nature of the propulsion force (Lorenz force) suggests that only a part of a propulsion coil is used in the process of the electromechanical energy conversion. The length of this part is generally defined by the width of the mover (in the *x*-direction) with an addition of the fringing flux paths. This fact gave rise to an idea of splitting the propulsion coils into segments [5]. In this paper the authors present intermediate measurement results verifying the concept of segmented coils.

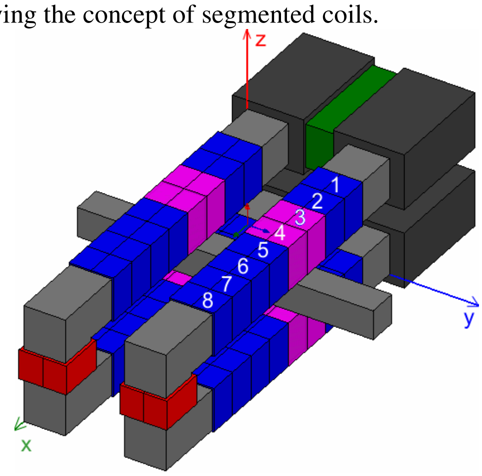

Figure 7: The three dimensional schematic layout of an IU–shaped actuator with segmented propulsion coils.

Schematic layout of an IU–module with segmented propulsion coils is depicted in Fig. 7. Depending on the *x*-position of the mover, only those segments participating in the electromechanical energy conversion (highlighted (pink) segment numbers 3 and 4 in Fig. 7) will be energized to produce the required propulsion force. Energizing small segments instead of the full coils reduces dissipation and, consequently, leads to a less thermally loaded actuator. This is especially important for high precision positioning applications, where thermal expansion can be crucial for the positioning accuracy. Reduced dissipation also allows increasing the current density which in its turn increases the propulsion force.

The IU–module prototype has been modified to perform the measurements with the segmented coils (Fig. 8). Suspension and propulsion forces are measured dependent on the suspension current i_z at i_x=0.5 A (Fig. 9) and on the propulsion current i_x at i_z=0.5 A (Fig. 10). Results in Figs. 9, 10 correspond to the middle position of the mover in the *x*-direction (segments 4 and 5 are energized); *z*-position is 0.1 mm below the middle of the air gap. The cross-coupling coefficient $\Delta F_z/\Delta i_x$ between the propulsion and suspension direction in Fig. 9 is only 0.078 and there is no influence of the suspension current on the propulsion force (Fig. 10). The measurements have been carried out for different *x*- and *z*-positions of the mover in the air gap with different sets of segments energized. Results (Fig. 11) show significant (3 to 7 times, depending on the position of the mover) reduction in the cross-coupling coefficient between the propulsion and suspension directions.

To further minimize the cross-coupling effect, the length of the segments can be reduced. However, this will also complicate the production of the coils and power electronics circuitry.

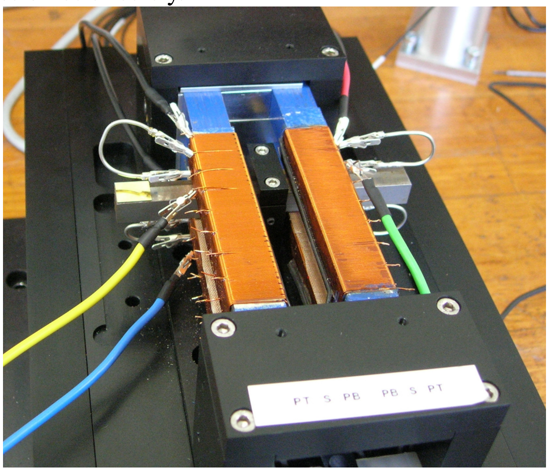

Figure 8: The IU–module prototype with segmented propulsion coils.

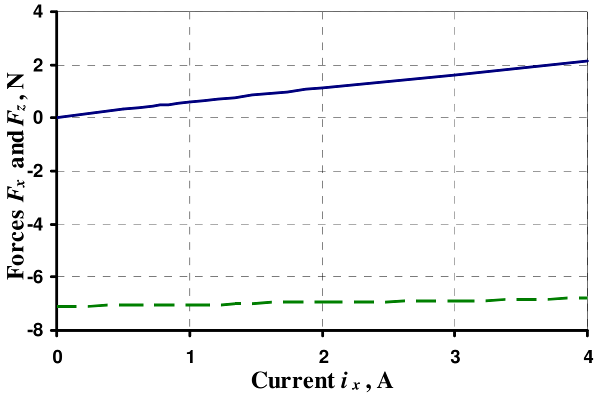

Figure 9: Measured suspension (dashed) and propulsion forces dependent on the propulsion current.

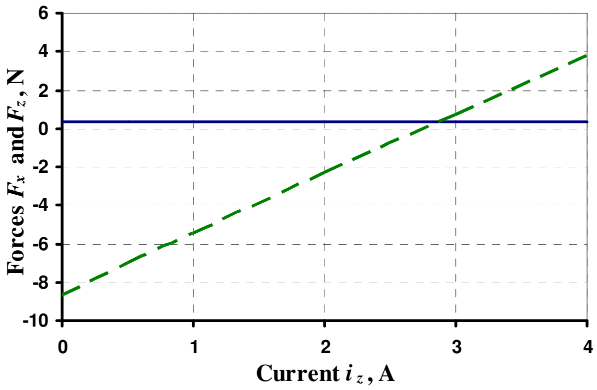

Figure 10: Measured suspension (dashed) and propulsion forces dependent on the suspension current.

5. Conclusions

In the paper the two major limitations (of the electromagnetic origin) of the novel linear electromechanical actuator with active magnetic suspension (IU–module) are investigated. Firstly, selection of a proper soft magnetic material for the magnetic system of the actuator is carried out. The laminated electrical steel shows a better dynamic performance when compared to the SMC material at frequencies up to 1000 Hz, however loosing in manufacturability.

A significant cross-coupling effect between the two actuation directions of the IU–module has been identified. It imposes limitations on the separate control of the propulsion and suspension. The propulsion coils have been segmented in order to improve the performance of the actuator. Preliminary verification of the improved design (the concept of segmented coils) shows a significant reduction in the cross-coupling, increasing the stability of the control system. A thorough investigation of the concept will be further carried out by the AM Group, TU Delft.

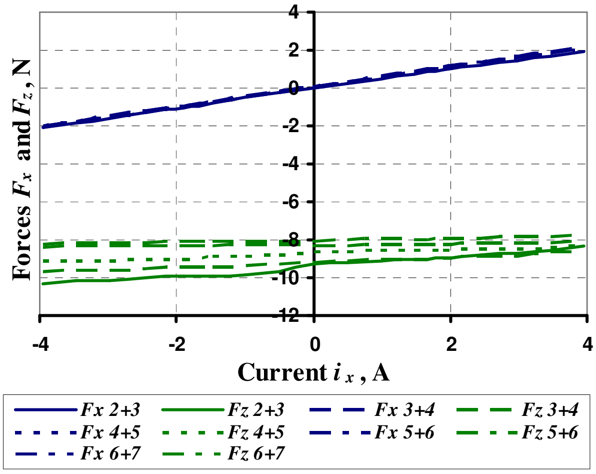

Figure 11: Measured suspension and propulsion forces dependent on the propulsion current at different *x*-positions of the mover (numbers of the energized segments are indicated).

References

[1] A.V. Lebedev, E.A. Lomonova, P.G. van Leuven, J. Steinberg, D.A.H. Laro, "Analysis and initial synthesis of a novel linear actuator with active magnetic suspension", IEEE IAS Proceedings, USA, October 2004, pp. 1-8.

[2] A.V. Lebedev, E.A. Lomonova, D.A.H. Laro, A.J.A. Vandenput, "Optimal Design Strategy for a Novel Linear Electromechanical Actuator", IEEJ Transactions, Industry Applications, 10D09, Vol.126, No.10, 2006, pp. 1330-1335.

[3] J. Wesselingh, D. Thakkar, D. Laro, J. Spronck, A. Lebedev, J. van Eijk, "Characterization of a contactless multi degree of freedom electromagnetic actuator", submitted to Sensors and Actuators A, Physical Journal.

[4] Lei Zhu, Carl R. Knospe, and Eric H. Maslen, "Frequency Domain Modeling of Non-laminated C-shaped Magnetic Actuators", Ninth International Symposium on Magnetic Bearings, August 2004, pp. 1-6.

[5] A. Molenaar, "A Novel Planar Magnetic Bearing and Motor Configuration Applied in a Positioning Stage", Ph.D. thesis, Dept. of Mechanical Eng., TUDelft (2000).