Design of a High Power Density Electromagnetic Actuator for a Portable Braille Display

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Keywords

Actuators, Design, Device applications, Simulation, Linear drives, Magnetic Devices, Permanent magnet motors.

Abstract

Refreshable Braille displays are generally large and expensive. This paper presents the design of a small and inexpensive linear electromagnetic actuator, which allows a considerable reduction in size and cost of refreshable Braille displays. The actuator concept is optimised with electromagnetic finite element simulations, which are verified with measurements on a prototype.

Introduction

The Braille alphabet is a tactile representation of the regular alphabet and blind people all over the world use this system to read. An example of the sentence 'hello world' is given in Fig. 1. The objective is to develop a portable and inexpensive refreshable Braille display to disclose computer use to visually impaired people.

Refreshable Braille displays have been developed before (e.g. [1]), but they are bulky and expensive. Existing refreshable Braille displays consist of 20 to 80 Braille cells allowing one line of text to be shown at a time. The fingertips slide over the pins of the Braille cells, just as in "paper Braille". Small displays contain only a single or a few Braille cells with pins pushing into the fingertips. They are not as successful as larger displays, probably because the human skin is more sensitive to lateral movement than to orthogonal pressure [2].

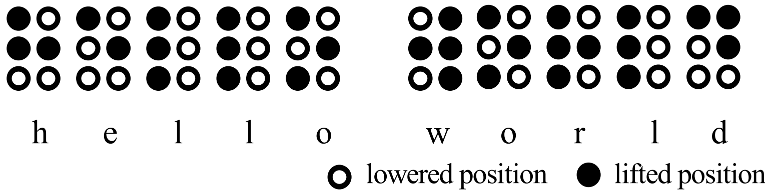

Fig. 1: The Braille alphabet: example.

The refreshable Braille cell presented here consists of 8 pins in a 2 by 4 matrix, allowing eight-dot computer Braille (the lowest row contains status pins). Each pin has two stable positions, a set or lifted position and a reset or lowered position, actuated by a linear electromagnetic actuator.

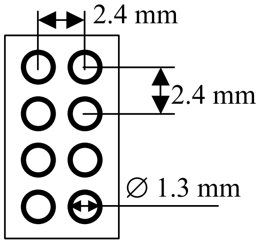

Fig. 2: Dimensions of a computer Braille cell.

Design concept

The sensation of moving over a line of Braille characters without the need of a long and bulky linear display can be achieved with a rotating ring [3][4]. A ring on which Braille cells are located rotates inside a housing (Fig. 3). Only a single part of the ring can be 'read' in a window ('3 character display'), the remaining part of the ring is covered by the housing. The rotating ring concept also permits infinite text lines, increased reading speed because the hand has not to return to the beginning of the line any more [4].

The pin position of the Braille cells that are covered by the housing is unimportant. When the ring rotates, a new cell will enter the window. Just before this point, the Braille-cell pins have to be set: all pins take a predetermined position according to a particular letter of the Braille alphabet (Fig. 1). Once a Braille cell is located in the window, pins should retain their position. After leaving the window, pins can be cleared. Their position is not important any more.

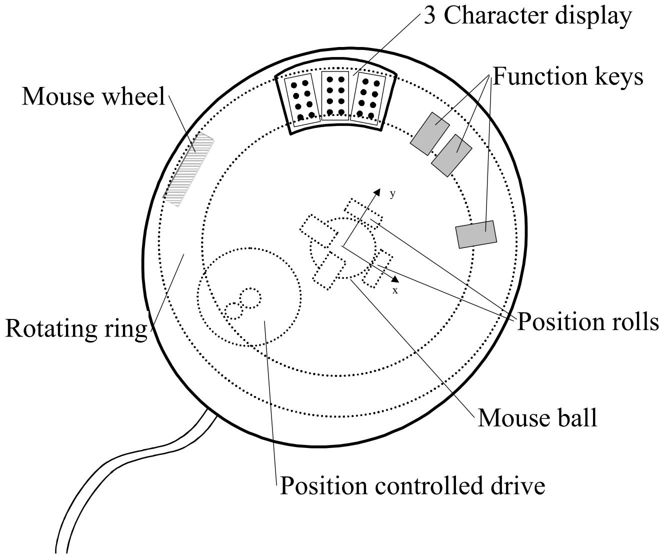

Fig. 3: Design concept of a Braille mouse.

This design concept permits to split up functions: if every pin, attached to the rotating ring, is bi stable, the actuation of the pins to change their position can be achieved separately from the rotating ring, i.e. fixed inside the housing. For this activation, less actuators are required when compared to classic refreshable Braille displays: eight actuators are sufficient whereas about 600 actuators are required for a regular large linear display.

The objective is therefore to create a rotating ring with bistable pins. A holding force of 0.1 N was aimed at, as it is for piëzo-electric actuators in regular Braille displays. The distance between two pins, which is 2.4 mm (Fig. 2), restricts the diameter of the plunger-pins. The vertical displacement of the pins should be at least 0.8 mm.

Creating stable positions

Because pins can be activated separately form from the rotating ring, permanent magnets can be used to create the lifted and the lowered stable position. Different topologies of the pin and ring assembly are studied. Fig. 4 shows two main concepts.

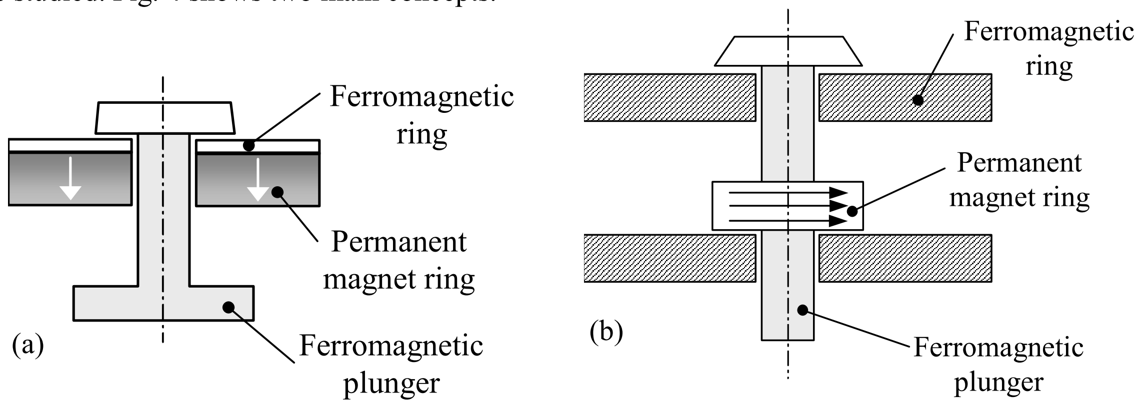

Fig. 4: (a) Concept 1: holding mechanism with permanent magnet material attached to the stator and (b) Concept 2: holding mechanism with permanent magnet material attached to the plunger.

In the mechanism drawn in Fig. 4a, the plungers and a top layer of the ring are constructed of soft magnetic material. The main part of the rotating ring consists of permanent magnet material which is perforated to hold the pins. When a pin is in the elevated position, magnetic flux lines close through the bottom of the pin and subsequent forces hold the pin in this position.
Fig. 4b shows the dual principle: a small permanent magnet ring is associated to the pin whereas the rotating ring consists of soft magnetic material. Both, the high and the low position are stable.
Small, commercially available magnets – as used in watches – reduce material and production cost significantly. Therefore, the second concept was preferred.

Concept optimisation

This concept is further developed. The rotating ring is in fact a double, perforated ferromagnetic ring, each ring enabling one of the two stable positions. Indeed, the magnetic flux lines close from the permanent magnet on the plunger/pin through the soft magnetic stator in order to achieve an optimal flux line distribution. Along those flux lines, the vertical component of Maxwell's attraction force is the force holding the pin in the desired position. The horizontal components compensate each other.
The topology of ring and plungers is optimised in order to achieve the specified holding force of 0.1 N. Two extreme topologies are proposed in Fig. 5. In model A flux lines go down and close through the combination of stator and pin (see also Fig. 6). In model B flux lines lie in the plane of the magnet. Obviously the vertical force is zero in this position but the force will increase quickly when the pin/magnet moves.

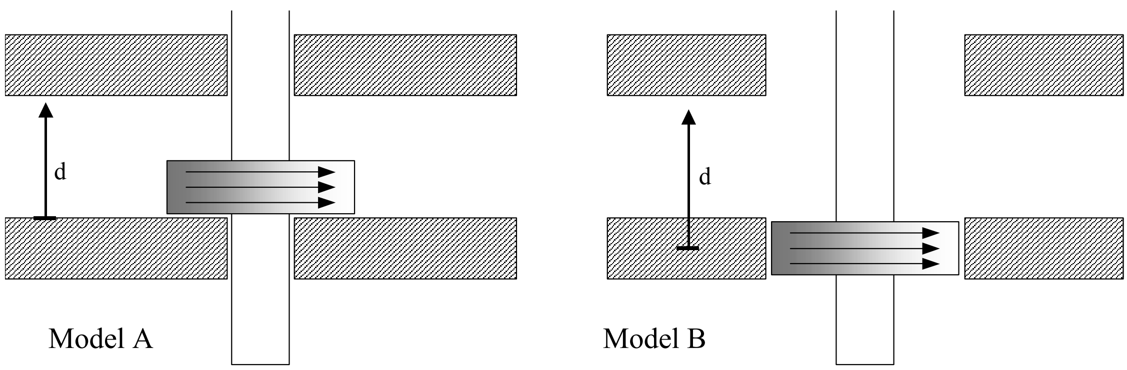

Fig. 5: Two topologies for the second concept.

Finite element simulations

Simulations with static electromagnetic solvers based on the finite element method are performed to calculate the magnetic field and the resulting forces.
Due to the cylindrical geometry of the pin, an axisymmetrical solver seemed preferable, but the transverse direction of magnetisation of the available permanent magnets (as indicated in Fig. 5) excluded this option.
For this reason the geometry of a single pin is modelled in a X-Y cartesian coordinate system (Fig. 6). The calculated results are based on unit problem depth. Postprocessing on the solution of the magnetic field is performed in order to obtain the forces acting on the plungers. The enhanced Maxwell stress tensor method [5] is used to calculate the vertical forces acting on a single pin.
Simulations on this model led to the optimisation of the geometry. The solution of the optimised 2D model is compared with a three-dimensional solution (Fig. 9) of the optimised geometry.

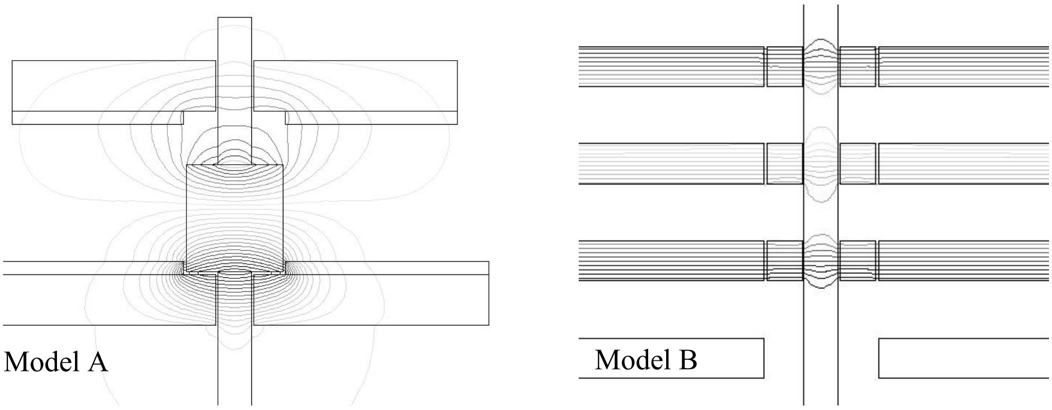

Fig. 6: Magnetic flux lines for model A and model B with three magnets on the plunger.

For both topologies force per unit problem depth is calculated as a function of the position of the pin (d, Fig. 5) with one to three magnets associated to the pin (Fig. 6). The multiplication factor (equivalent depth) to obtain the force is 1.49 mm.
Fig. 7 illustrates the different behaviour for the two proposed topologies (Fig. 5) with a different number of magnets on the calculated pin. In both cases, 0.1 N is just reached with only one magnet on the plunger. The course of the force, however, is different.
Model A yields the highest holding force for the ultimate position. The curve of model B on the other hand shows that approximately the same maximum force is attained, but for an earlier position. In the end position the holding force is zero, but due to stray forces this position will never be reached. However, if the pin would drift away from this position, the holding force will increase rapidly keeping the pin close to the end position. The end points of the holding force characteristic are stable points.

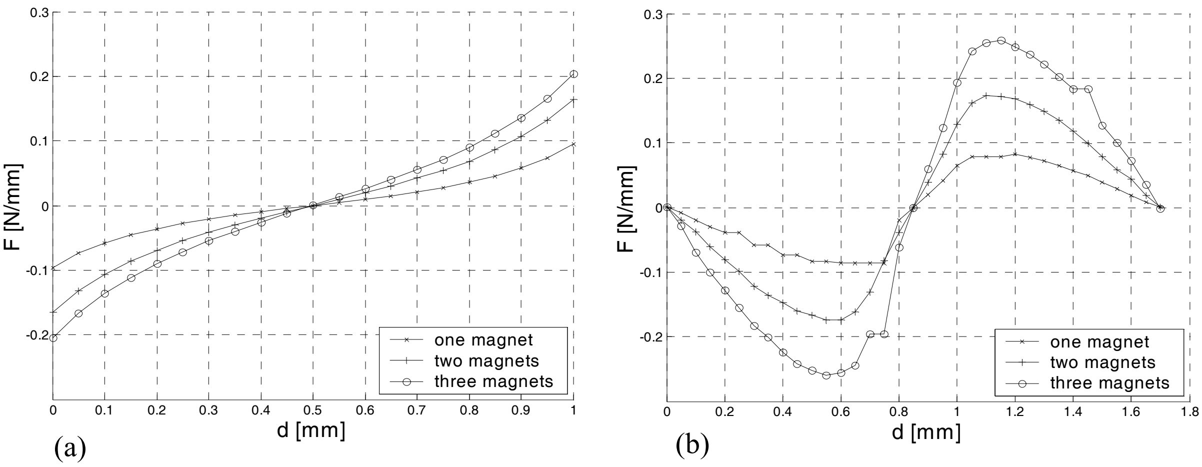

Fig. 7: Force characteristic for model A (a) and model B (b) (see Fig. 5).

The optimal geometry is found in a combination of those two models. A ferromagnetic layer ('collar' on Fig. 9a) is introduced to the stator of model A in order to improve the holding forces.
Fig. 8 shows the holding force characteristic for different number of magnets on a pin and for different heights of the ferromagnetic collar.
For the magnets available (height = 0.7 mm), a collar of 0.3 mm proved to be a good choice. Indeed, the maximum holding force is attained somwhat before the position in view, but does not drop to low values when reaching this position. As a result, drift is minimized and yet the endpoints are stable points in the holding force characteristic.

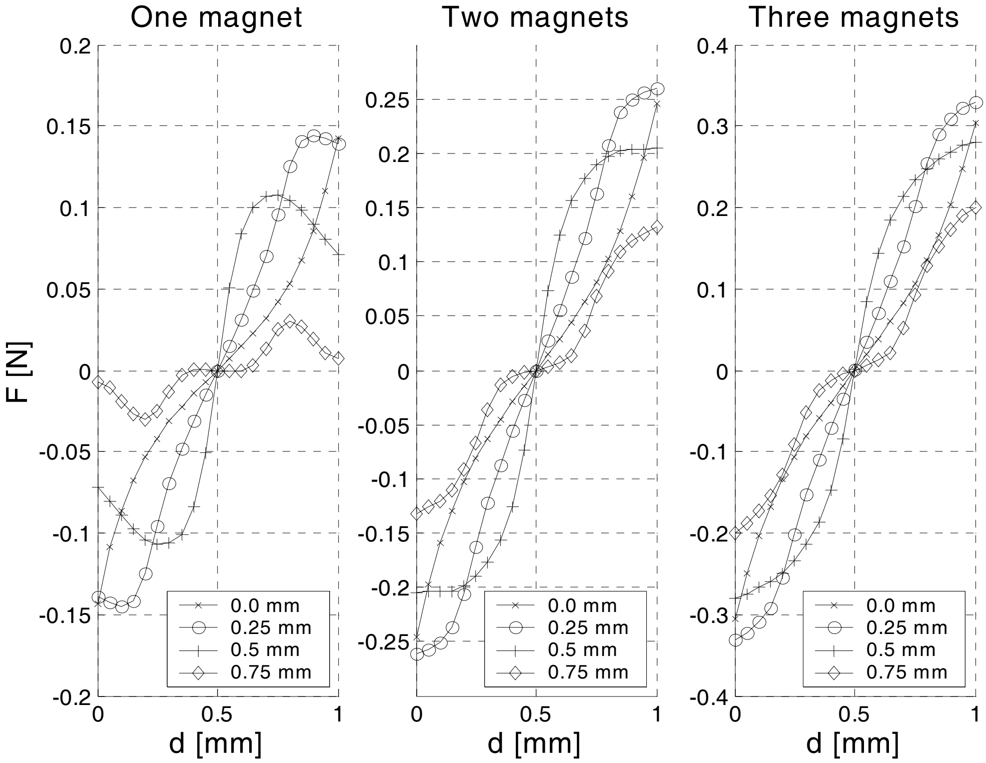

Fig. 8: Influence of the ferromagnetic collar on the force characteristic.

The final simulation results are shown in Fig. 9a. Those results are compared to 3D simulations (Fig. 9b) of the optimised geometry confirming the two-dimensional approximation.

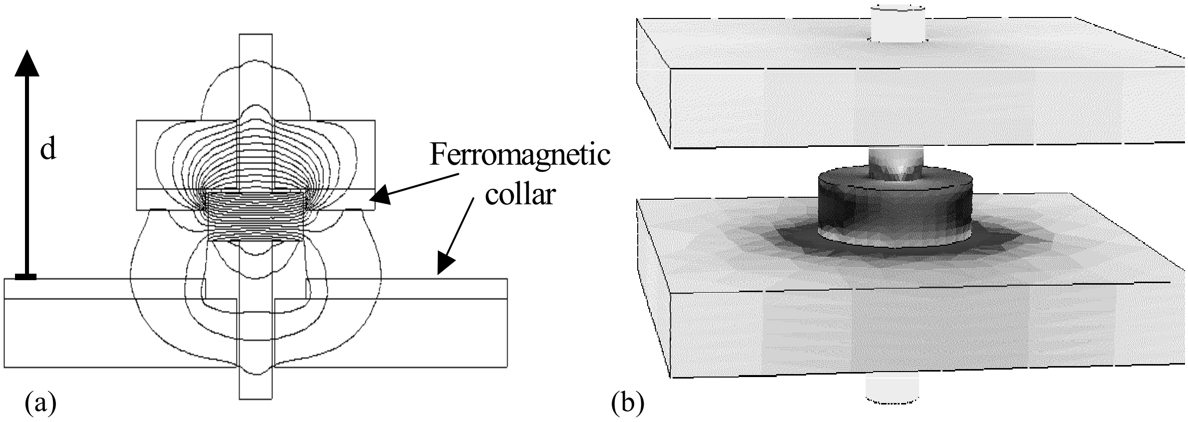

Fig. 9: (a) Magnetic flux lines in a 2D model of one pin and
(b) flux density distribution in a 3D model of one pin.

Influence on neighbouring pins

Particular attention is paid to the influence of a moving pin on its neighbours.
If one pin is moving, the pins closest to the moving pin may experience a force pulling them together with the moving pin. As a consequence, they might undesirably change their position.
A 2D section of the real situation is simulated. Fig. 10a shows the model, Fig. 10b the calculated flux lines.

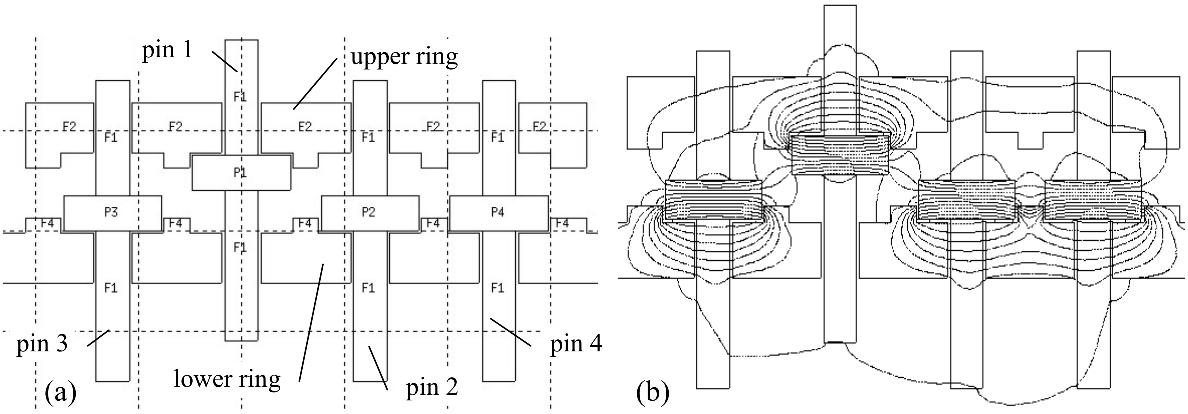

Fig. 10: (a) Two-dimensional model of 4 Braille pins and
(b) magnetic flux lines in the model of (a).

A 2D simulation of the 3D problem is valid here, because the 2D model covers the worst-case situation. Indeed, the attractive force between two neighbouring pins is maximal for the smallest distance between their magnets. However, this minimum distance between the two pins appears only at one point of the cylindrical magnet. In the 2D model on the other hand, this minimum distance is maintained over the whole depth the forces are calculated for. The 2D model is therefore more restrictive compared to the 3D reality.
Fig. 11 provides the results of this force calculation in the case that pin 1 moves, pin 2 occupies the elevated position while pin 3 and 4 are in the lowered position. The graph reveals that pins next to the moving pin experience a minor influence, but their position will not be altered. Pins that are positioned further away do not undergo any influence.

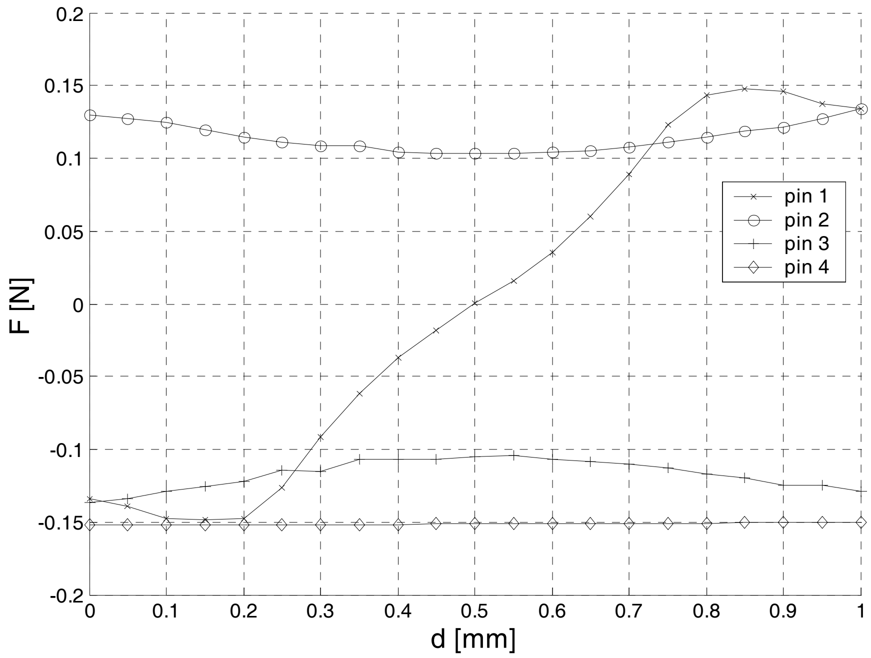

Fig. 11: Force acting on the moving pin and its neighbours in lifted, respectively lowered position.

The minor influence between neighbouring pins increases when the distance between upper and lower ring (Fig. 10a) decreases. This effect is due to the height of the permanent magnets. When upper and lower ring come as close to each other in such a way that the permanent magnets overlap, influence between neighbouring pins will cause problems. Fortunately, the design criteria can be met without those problems.

Verification

Based on the simulation results and the specifications of a Braille cell, all dimensions, e.g. the optimal height for the collar, are determined. A prototype for tests by visually impaired people is built (Fig. 12).

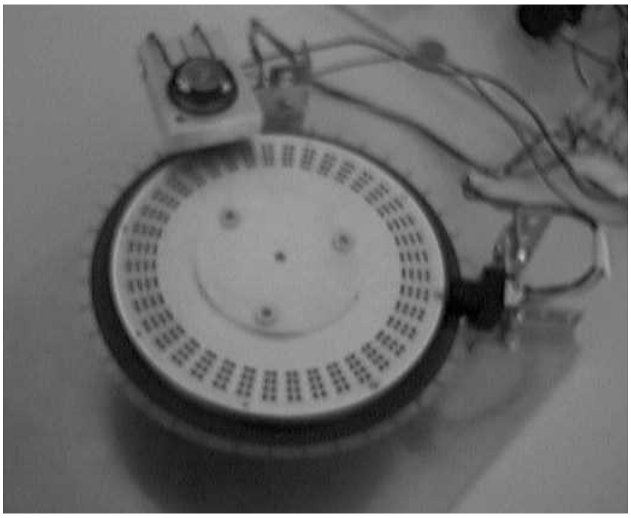

Fig. 12: Prototype of the Braille ring (KULeuven).

Measurements on this prototype are presented in Fig. 13. The upward force is measured as a function of the displacement for different pins starting from their top position. Due to the measurement set-up force measurements terminate when the pin falls down. The graph proves that the specified holding force is obtained for the prototype and that the simulation results are confirmed by the measurements.

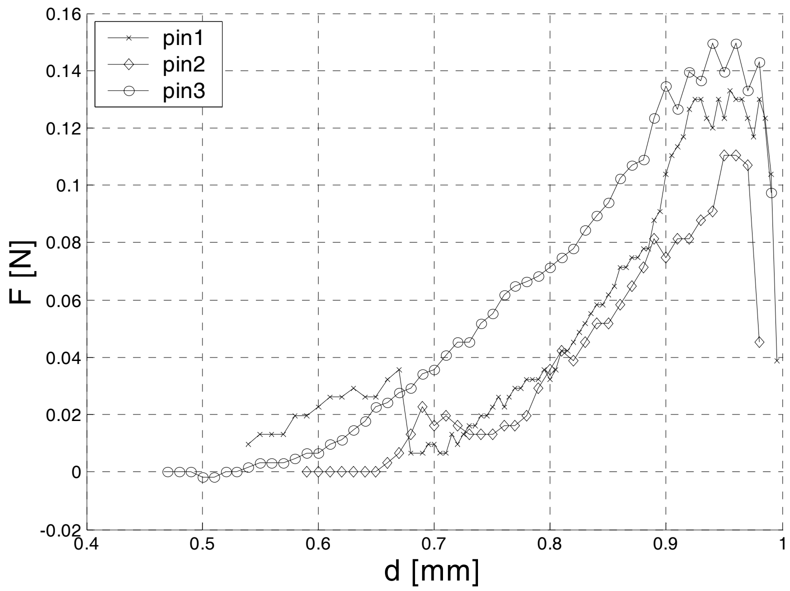

Fig. 13: Force measurements.

Conclusion

A linear magnetic actuator has successfully been designed for a portable Braille display application. Holding forces in small linear actuators are limited by available energy density from permanent magnet materials. The paper illustrates the optimisation of high power density linear actuators in order to obtain maximum output forces by using finite element models.

Acknowledgment

The authors are grateful to the Belgian "Fonds voor Wetenschappelijk Onderzoek Vlaanderen" for its financial support of this work and the Belgian Ministry of Scientific Research for granting the IUAP No. P4/20 on Coupled Problems in Electromagnetic Systems. The research Council of the K.U.Leuven supports the basic numerical research. The authors kindly thank Dr.-Ing. F. Jurisch (VACUUMSCHMELZE) for providing the authors with the permanent magnet rings.

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