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Miniaturisation of electrical machines

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Abstract

Purpose – Approaches for a miniaturisation of electrical machines that are based on an electromagnetic principle have to overcome numerous challenges. Some of these are only a result of the rules of growth (or shrinkage), some are a result of the micro technological fabrication processes. This paper aims to give an overview of the current state of the art including various examples of linear and rotating micro actuators that have been realised.

Design/methodology/approach – The paper presents details of further miniaturisation by using thin film technology for depositing and structuring soft magnetic and hard magnetic material as well as copper for conductors and insulation.

Findings – There are numerous limitations for the miniaturisation with respect to material properties, friction/guidance, etc. and this paper illustrates ways to overcome these limitations.

Originality/value – The paper presents a compact overview on the achievements gained in 12 years of research within a collaborative research centre of the German DFG.

Keywords Actuators, Electric motors

Paper type Research paper

1. Introduction

Electrical machines are currently built by industry with ratings between 2 gigawatts and some milliwatts, all being based on the same electromagnetic principle and similar designs, e.g. with windings located in slots of a magnetic core. A further miniaturisation has to face numerous challenges:

- According to the laws of growth, friction plays a dominating role.
- Geometries in the range of some μm cannot be created by punching laminations and inserting coils made from wire, but require to use micro fabrication techniques.
- The properties of microtechnically manufactured material might differ significantly from the properties of conventional material.
- The time constants of the windings drop to the range of some μs, forcing the switching frequency of the supply into the megahertz range.

In the following sections, the state of the art in electromagnetic micro motors is described that has been achieved throughout the last ten years in the DFG's collaborative research centre 516 Design and Manufacturing of Active Microsystems.

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2. Electromagnetic design

2.1 Magnetic properties of NiFe layers

The design of microtechnologically fabricated motors is closely linked to the fabrication processes for a number of reasons (Gehrking, 2009): As mentioned before, the material properties can vary significantly with the details of the galvanisation process and even more with the geometry to be fabricated. For example, it was found that the relative permeability of NiFe layers is significantly higher in horizontal direction, i.e. parallel to the wafer, than in vertical direction.

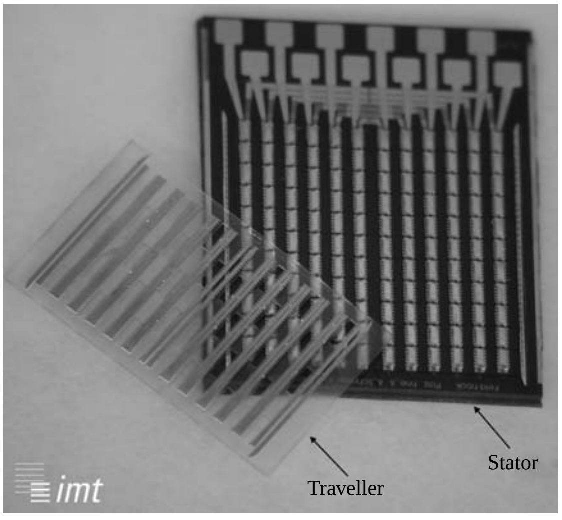
Consequently, a motor should preferably be designed with the flux looping in parallel to the wafer. A possible layout of a linear micro switched reluctance motor with horizontal flux is shown in Figure 1. In the following, this layout will be called horizontal motor.

In addition, it had to be experienced that NiFe layers of 5 μm thickness have a relative permeability of approximately 500, but 50 μm layers have only a relative permeability of approximately 50 (Figure 2).

2.2 Driving force

The non-linear behaviour of the NiFe layer leads to consequences that are completely different from the behaviour of conventional motors and actuators: Usually, an increase of the active area in the air-gap between stator and traveller would lead to an increase of the driving force by the same factor, e.g. doubling the height of the active part would double the force. Taking the dependency of permeability and layer height into account, an increase of height can even lead to a reduction of force (Figure 3).

In addition, the geometrical details like the radius of edges or the aspect ratio influences the force to be generated by a motor and needs to be taken into account as well, when designing a micro motor. On the other hand, the small active length (i.e. small layer height)



Source: Demmig *et al.* (2006)

Figure 1.
Basic principle of a linear micro switched reluctance motor with horizontal flux

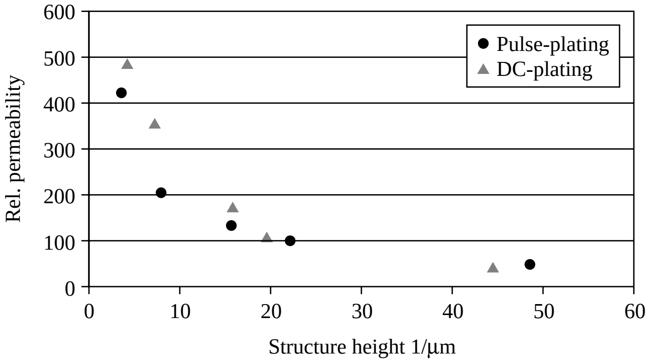


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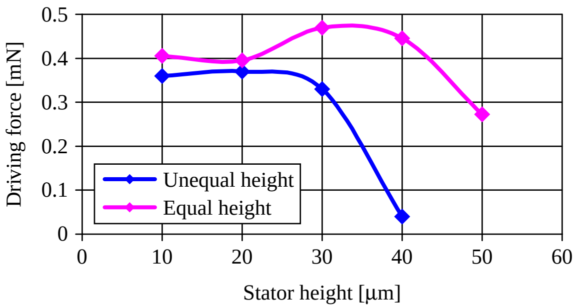
Figure 2.
Measured relative permeability as a function of the layer height



Source: Demmig *et al.* (2006)

Figure 3.
Force of the horizontal motor as a function of the layer height

of the horizontal motor does not allow a fairly accurate prediction of the operating characteristics by analytical calculations or 2D finite element method (FEM), but requires to use 3D FEM with a mesh width below 1 μm (Figure 4). In order to limit the maximum number of elements, all existing symmetries have to be used. Figure 5 shows that the prediction accuracy that can be achieved is quite satisfying.

2.3 Power supply

An important thing to consider at the interface between a micro actuator and its supply is that the inductance of a winding decreases on miniaturisation, but its resistance increases. Consequently, a winding's time constant $T = L/R$ decreases.

Today's power electronic supplies of motor windings are commonly using pulse width modulation or comparable strategies, i.e. the constant DC voltage of the general supply is switched on and off quickly in order to impress a variable DC current or a given current vs time into the winding. In order to limit the parasitic ripple current that is superimposed to the desired current, this method requires a switching frequency, which is significantly higher than the inverse of the winding's time constant.

Consequently, the supply of a micro actuator must have a switching frequency in the megahertz range due to the low time constant mentioned above.

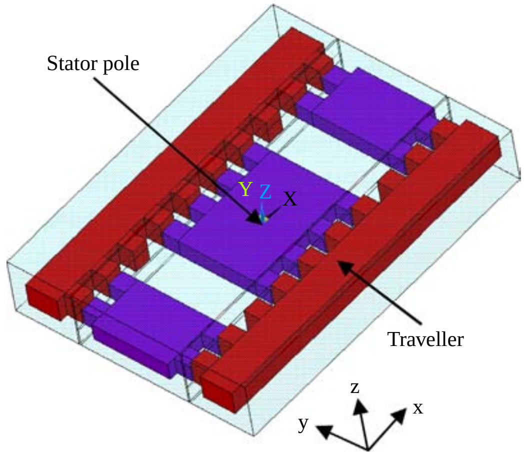


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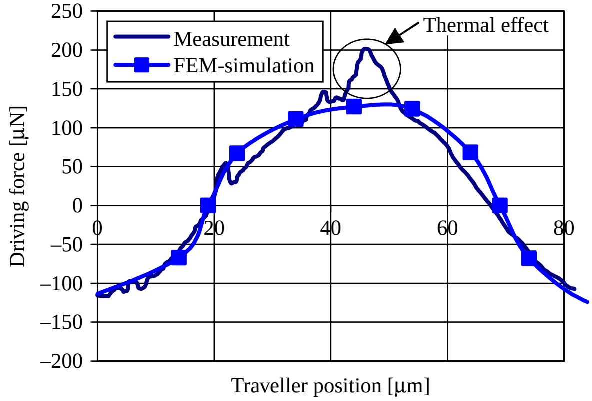
Figure 4.
3D FEM model of the horizontal motor



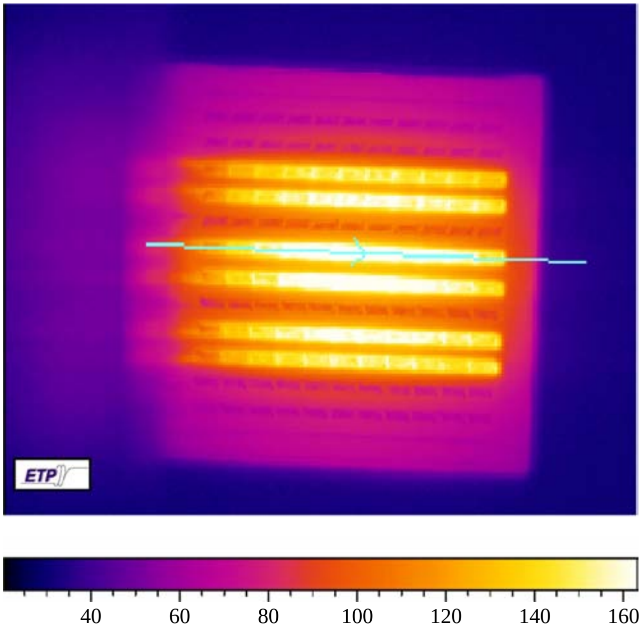
Source: Demmig *et al.* (2006)

Figure 5.
Comparison of measured and predicted force of the horizontal motor as a function of the traveller position

2.4 Current density and temperature

But not all consequences of the laws of growth are causing additional challenges: in conventional motors, e.g. the current density in the windings is limited to values in the range of 3-12 A/mm^2. Using high temperature superconductors, the current density can reach 300 to 500 A/mm^2 – but this is, of course, not a very economical alternative.

But as the volume of the winding (and any other object) is proportional to the cube and its surface is proportional to the square of its dimensions, the permissible loss density may be increased significantly, when miniaturising actuators. Figure 6 shows the temperature distribution in the horizontal motor, when all phases are fed with their full current.



Source: Demmig *et al.* (2006)

Figure 6.
Temperature distribution in the horizontal motor

3. Bearings and guidance

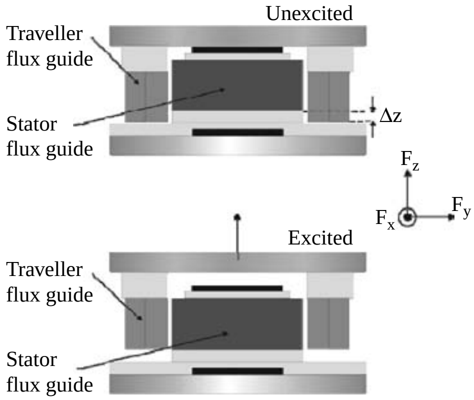
Different approaches have been made in order to deal with the friction that becomes a dominating effect especially on miniaturisation of linear motors due to Maxwell's normal forces, which attract stator and traveller.

The first approach was the use of roller bearings made from ruby balls with a diameter of 200 μm (Seidemann *et al.*, 2003). It was successfully tested with different types of actuators. Nevertheless, the assembly of the ruby balls is difficult and the friction coefficient varies over the length of the actuator.

A purely tribological guidance showed to be feasibly for actuators without ferromagnetic flux guide or for actuators like the horizontal motor, which are magnetically designed having two air-gaps in series, so that Maxwell's normal forces originating from the two air-gaps compensate each other.

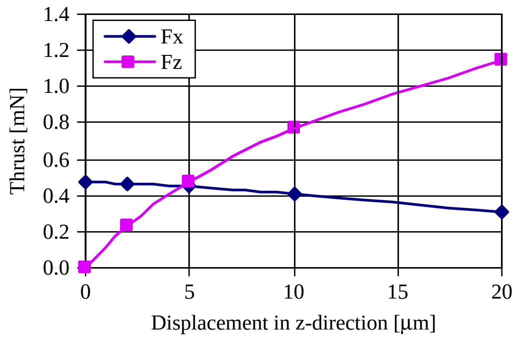
But as Figure 7 shows, the general design of the horizontal motor allows to integrate a passive magnetic guidance in vertical direction: without current, the vertical position of the ferromagnetic part of the traveller is lower than the vertical position of the stator. When current flows, a part of the flux generated by the stator winding will enter the traveller from above, thus leading to a Maxwell force in vertical direction that is able to lift the traveller.

Figure 8 shows simulation results of the force in vertical direction as a function of the vertical displacement between stator and traveller and its influence on the force in horizontal direction that moves the traveller. It can be seen that the force in horizontal direction decreases only slowly with increasing vertical displacement, whereas the lifting force increases significantly.



Source: Gehrking *et al.* (2006)

Figure 7.
Principle of the passive magnetic guidance of the horizontal motor



Source: Gehrking *et al.* (2006)

Figure 8.
Forces in vertical and in horizontal direction as a function of the vertical displacement of the traveller

Nevertheless, a guidance in crosswise direction is required as well. In an ideal case, the sum of all normal forces in the air-gaps of the horizontal motor should add to zero, but small differences will always exist. But as the forces to be expected in crosswise direction are relatively low, they can be taken by a tribological guidance made from diamond like carbon (DLC).

4. Prototypes

4.1 General

In order to demonstrate the state of technology that has been achieved, different prototypes of micro actuators have been built and tested. As the integration of miniaturised and accurate sensors into such actuator is a challenge in itself, it was not possible to realise a closed-loop control. Thus, it was chosen to design and operate the prototypes as stepper motors.

In general, there are three types of conventional stepper motors:

(1) Permanent magnet (PM) motors with a PM in the traveller or rotor and a multiphase winding in the stator, comparable to the general layout of conventional synchronous motors.

(2) Variable reluctance (VR) motors with a ferromagnetic traveller or rotor with teeth only and a multiphase winding in the stator, which must have ferromagnetic teeth as well.
(3) Hybrid motors, which combine the two types above having ferromagnetic teeth in stator and traveller/rotor and in addition a PM in either stator or traveller/rotor.

Even though, for conventional stepper motors, hybrid motors show the best performance, it had to be experienced that their miniaturisation is most difficult due to the complexity of the large number of microtechnological manufacturing steps required.

As shown in the following subsections, the other two motor types have been built and tested successfully in various versions. Owing to the properties of the microtechnologically fabricated NiFe described in Section 2.1, it is preferable to use either a VR principle with the flux looping in parallel to the wafer or to use a PM principle without any ferromagnetic material.

4.2 Linear micro actuators

The horizontal motor mentioned above is a VR stepper motor that has been built and successfully tested in various versions. Figure 1 shows its general layout. The ferromagnetic parts of stator and traveller have teeth with a pitch of 100 μm. The height of the ferromagnetic layer is 30 μm.

The stator winding has six phases and consists of 3D meander coils (Figure 9) looping around the ferromagnetic poles. Each of the phases consists of two rows of poles. This leads to a step with of 16.7 μm in full step mode. With microstepping a step with of close to 1 μm can be achieved. Nevertheless, this design has the disadvantage that it is not possible to build a planar micro actuator based on it, because planar actuators require a horizontal air-gap between stator and traveller.

Amongst the different alternatives of linear actuators with a horizontal air-gap and consequently a vertical flux across the air-gap, it has shown to be preferable to use a PM design without any ferromagnetic material. The stator consists of a multiphase winding only and the traveller of PM material that can be microtechnologically fabricated as well. Even though the amount of magnetic material required increases without ferromagnetic flux guide in the stator, this design has the advantage that no attracting Maxwell forces are existing between stator and traveller, which would lead to a significant increase of the friction.

4.3 Rotating micro actuators

The dimensions of the rotating motors, which have been built, go down to a diameter of only 1 mm. In general, two motor types turned out to be preferable that are quite similar to those of the linear actuators.

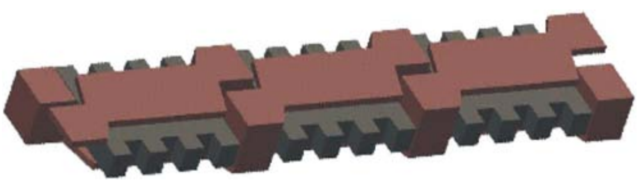


Figure 9. 3D meander coils of the horizontal motor

Figure 10 shows a rotating VR motor comparable to conventional switched reluctance motors. The six phases of the stator winding are distributed on 12 teeth. The exterior rotor has teeth on its inner diameter.

As alternative, rotating PM actuators with different diameters down to 1 mm have been built and tested (Figure 11). Like in the linear PM actuators, the PM's flux penetrates in vertical direction through the stator winding. As no attracting Maxwell forces between rotor and stator exist, the actuators could be realised with only a tribological layer between rotor and stator instead of a bearing. The wear of this DLC layer is so low that even some days of continuous operation are possible without problems.

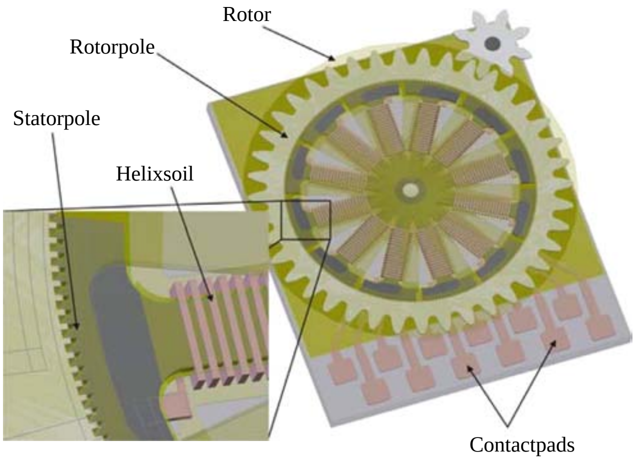


Figure 10.
Rotating micro variable reluctance actuator

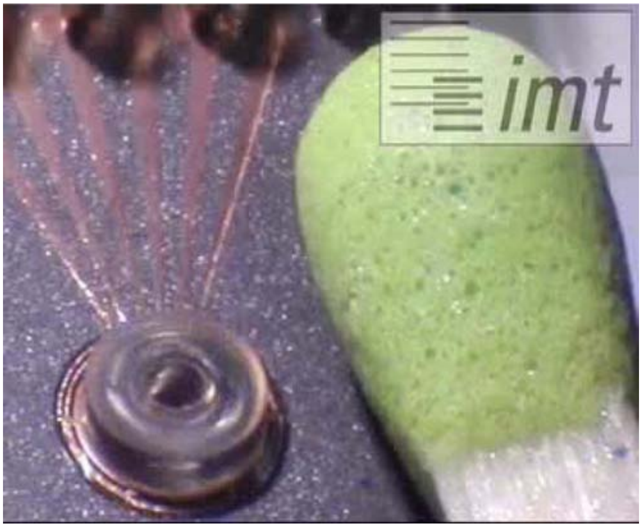


Figure 11.
Rotating PM synchronous motor

5. Conclusion

It has been demonstrated that it is today feasible to build electromagnetic motors and actuators by using purely microtechnological manufacturing techniques with satisfying operating characteristics. Nevertheless, the properties of microtechnologically fabricated ferromagnetic material provide some limitations that need to be taken into account when designing such actuators. Additional restrictions and chances due to the laws of growth like a high friction, a very low time constant of the windings, or a very high permissible current density must be taken into account as well.

References

Demmig, S., Gehrking, R., Feldmann, M., Büttgenbach, S. and Ponick, B. (2006), "Specific design rules for micro linear motors", *SPEEDAM, Sicily*, pp. 16-27-31.

Gehrking, R. (2009), "Entwurf von Aktivteilen elektromagnetischer Mikrolinearmotoren unterschiedlicher Wirkprinzipien", *Fortschritt-Berichte VDI*, Reihe 21, Nr. 384.

Gehrking, R., Demmig, S., Ponick, B., Feldmann, M. and Büttgenbach, S. (2006), *A Micro Linear Motor with Integrated Passive Magnetic Guidance*, IECON, Paris, pp. 1245-50.

Seidemann, V., Edler, J., Büttgenbach, S. and Stölting, H.-D. (2003), "Linear variable reluctance (VR) micro motor with horizontal flux guide: concept, simulation, fabrication and test", *Proceeding of the Transducers, Boston, MA, USA*.

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Bernd Ponick received his Diploma in Electrical Engineering in 1990 and his doctorate degree in the field of electrical machines in 1994, both from the University of Hannover. After nine years in the Siemens large motor factory as Design Engineer for large variable speed motors, Manager for Electrical Design Department and Technical Director, he is, since 2003, Professor for Electrical Machines and Drive Systems and Director of the Institute for Drive Systems and Power Electronics at Leibniz Universität Hannover. Bernd Ponick can be contacted at: ponick@ial.uni-hannover.de