

Electromagnetic Actuators – Current Developments and examples

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Abstract:

The range of applications for actuators covers all technical areas. Actuators can be found as system component in nearly every controlled system to move or steer particular parts to control the overall process of the system. Such actuators operate on various basic principles. However, in this paper only actuators operated by the electromagnetic field are considered. Such devices are for example rotating electrical machines, lifting magnets, active magnetic bearings for high-speed rotary applications, magnetic levitation devices for traction applications and many more. Although large electromagnetic devices, such as a large motor fits into this definition of an actuator, in this paper however only small electromagnetic devices are discussed. It is intended to give a general overview over the development of such small actuators. Models and methods to determine the operational behaviour of such devices are discussed. Such computer models enable an improvement of the actuator's function towards a desired behaviour, objective to technical and/or economical constraints. Real applications, such as the Penny-Motor as an ultra flat electromagnetic micromotor, illustrate the approach and demonstrate the general and large range of applications for electromechanical actuators.

Introduction

The ongoing trend towards the miniaturisation of systems and the trend of system integration force the development engineers to construct smaller and smaller devices. Due to the recent developments and ongoing research in the field of hard- and soft-magnetic material delivered materials with improved material properties (Fig. 1). Therefore, extremely small electric motors with very compact electromagnetic circuits can be developed (Fig. 3, 7, 8). Simultaneously developments in the area of the system technology and their processes enable actuator constructions at the on-chip level. Micro-pumps can perform the crucial task of on-chip cooling of processors operated by high clock-frequencies. Devices with geometrical dimensions in the range of some micrometer based on the principles of the electrostatic field can already be found on the market and have gained technical reasonable maturity. Such micro electro-mechanical systems (MEMS) are applied e.g. as RF switches operate in GSM applications, MEMS relays (Fig. 2) etc.

In contrast to such electrostatic applications in the geometrical micrometer range, devices operated by the electromagnetic field are larger. A theoretical estimation of the favoured torque ranges of the mentioned electrostatic and

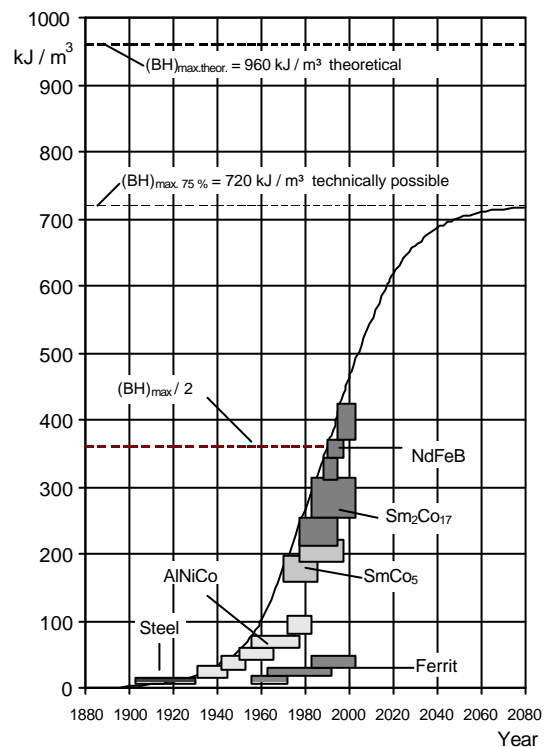


Fig. 1. Development of permanent magnet material. (source VACUUMSCHMELZE)

electromagnetic actuation principles draws this line between both at $1\mu\text{Nm}$ [9]. Actuators working on the electromagnetic principle can be found in outer dimensions in the range of some millimetre. A reason for this is that for those

small dimensions the energy stored in the electromagnetic field is significantly smaller when compared to that of the electric field. However, the voltage exciting the electric field is large when a high value for the field energy has

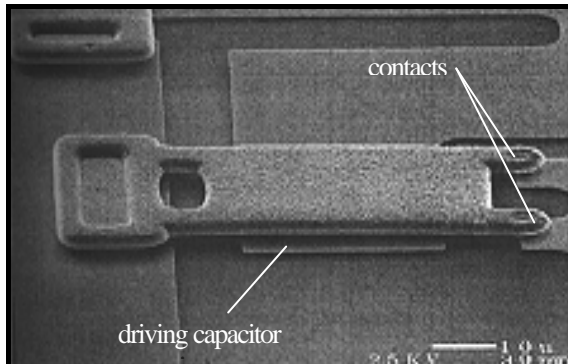


Fig. 2: MEMS relays (total length < 0,1 mm source: ESAT/MICAS KULeuven).

to be realised to have large forces for actuation and this can be one of the constraints in the design.

Nowadays, applications of small electromagnetic actuators can be found in various fields. Novel types of such devices are usually implemented in systems out of the innovative industries, such as the automotive industry, computer periphery device manufacturer, audio / video device production and the medical instrumentation industry. For such devices in general particular properties regarding the quality, life-time, safety of use, radiated audible noise and reliability are prerequisites. To ensure such requirements and to simultaneously decrease the time to market, computer models serve during the development as tools for the design engineer. A second reason to apply computer simulations is the usually complicated geometry of the electromagnetic actuators. To exploit the entire properties of the material used in the construction of an actuator sufficiently accurate material models are required. Regarding the increasing frequency operating the machines to receive high speeds [5], particular attention must be paid on the correct and accurate material models. With further miniaturisation of the electromagnetic devices special modellisation techniques are required to simulate the device on the crystal level.

Electromagnetic actuators

Janocha [1] defines an actuator as the connecting link between information processing system components of a controlling system and

a technical or non-technical process. Following this definition actuators are the technical elements, which adjust and control e.g. a flow of energy. Their input is a power-less electrical signal and their output an electrical power or mechanical energy, which is commonly a torque for motors or a thrust for translational movements.

Magnetic models computing the forces

To basically generate a mechanical energy by an electromagnetic actuator a force must be produced by a magnetic field. Forces can be observed e.g. on current carrying conductors exposed to a magnetic field. Such a force is called Lorentz-force. Other forces can be generated by a varying reluctivity of the magnetic circuit along its path of movement; they are called reluctance forces. Both principles are applied to actuator designs. The magnetic field for the first mentioned principle can be excited by permanent magnet material or by windings, which are formed out of various coils [2, 3, 4].

Usually both, Lorentz- and reluctance force effects are superposed. Therefore, the determination of the change of the active air gap along the relative movement of the rotor and stator geometry is important for an accurate force / torque calculation. It is evident, that complicated geometries require advanced numerical methods to determine the air gap forces accurately.

For this purpose, three- and two-dimensional numerical models to compute the magnetic field of the actuator can be applied. The design of

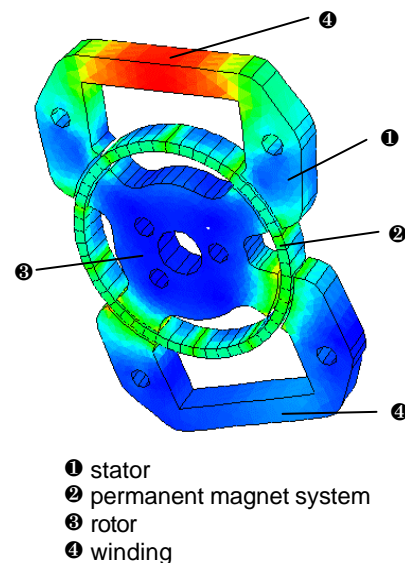


Fig. 3: Magnetic field solution of a small electromagnetic stepper motor. (software Magnet 5.4)

electromagnetic actuators by using the finite element method (FEM) is discussed in this paper. Fig. 3 illustrates the solution of the computation of the magnetic field of a small stepper motor. To rotate the permanent magnet system, which is constructed to the rotor, the two stator-windings are excited by a particular sequence of stator currents. The magnetic field is plotted for the situation of an excited upper winding. The colours indicate the level and the flux density distribution.

Thermal models

Regarding the trend of minimisation thermal aspects of a design have to be considered as well. Actuators are very often installed very close to sources of thermal heat or are exposed to high ambient temperatures. The automotive industry e.g. demands for actuators, which can operate in a range of -40° up to $+180^{\circ}$ C of the ambient temperature without losing their performance. Due to the temperature dependent properties of the materials, e.g. resistance of the winding material or the magnetic properties of the permanent magnet material used in the devices, the physical behaviour of the actuator is varying as well.

To form the entire model of the actuator, next to the copper losses, the magnetisation and eddy current losses in the ferromagnetic material have to be considered to represent further heat sources for the thermal model. Regarding the demanded high rotational speeds and therefore high frequencies operating the motors, those losses become very important.

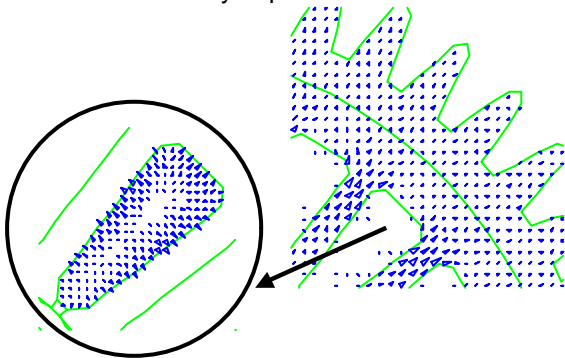


Fig. 4: Detail of the thermal field solution of a heat flow in a slot of an electrical machine. (in-house software Olympos2D)

Due to system integration heat flows dissipated from the power electronic components, which might be fixed to the housing of the actuator represent further heat sources in the thermal model. For the modelling of thermal fields the

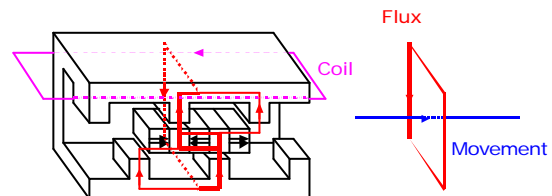
use of finite element models in three or two dimensions is appropriate as well. With the help of a thermal model of the device under study the appropriate cooling conditions can be evaluated (Fig. 4). The coupling of both, magnetic and thermal FEM model is possible and yields a numerical iteration to obtain the desired solution [6, 7].

Electric circuit models

Typically, power electronic circuits operate actuators. Regarding the time, these circuits usually do not deliver a constant energy flow to the device. Furthermore, actuators must not operate continuously. Therefore, duty cycles determine the thermal equilibrium of the device and have to be considered in the overall model. The behaviour of the actuator depends on the power electronic as well. In the case induced currents or voltages have to be computed in two-dimensional FEM magnetic models external winding circuits have to be defined. Such circuits couple the FEM model to a linear network of reactances, capacities, voltage sources and resistances [8]. In these circuits the properties of the power electronic components can be considered.

Finite element models

To build up a FEM model, in a pre-process the device's geometrical shape is approximated by finite elements. In two-dimensional models the standard elements are commonly triangles and in the three-dimensional case tetrahedron elements can be used. This type of elements is very flexible and capable to approximate very well even complicated geometrical shapes (Fig. 5). In this step of modelling the device, material and boundary conditions have to be defined.



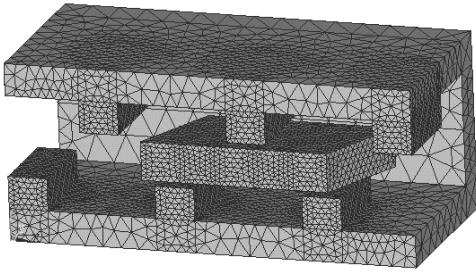


Fig. 5: (top) Geometry, direction of movement, expected flux path and (below) the associated 3D FEM discretisation of a linear transversal flux (TF) motor. The surrounding discretised air is not plotted. (software Magnet5.4)

On the finite element a function is applied to represent the desired potential describing discretised Maxwell equations. This system of equations has to be solved in a process to be evaluated during the last step of analysis, the post-process. Outgoing from the computed potential solution, the interesting field values, such as field strength and magnetic flux density can be calculated for all places inside the model. From the obtained field values e.g. the forces and other physical quantities, such as the induced currents and voltages can be derived. Computer models enable a thorough study of actuators without the requirement of expensive prototyping. Prototyping is of course required at the end of the design procedure to verify simulated results or if required, to improve the device's numerical model. Various different geometrical variants of an actuator concept can be studied and the particular properties can be compared. Figure 6 shows another variant of a concept of a linear TF actuator with its associated force characteristic.

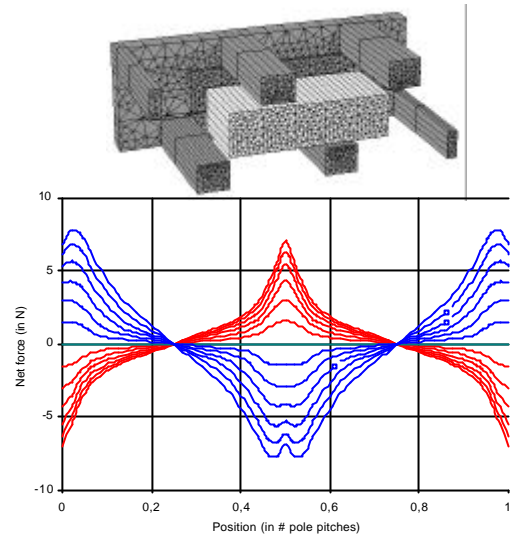


Fig. 6: 3D FEM models of a variant of a TF linear motor with the associated force vs. position characteristic.

With the computer models the appropriate choice of material can be controlled and studied. For example, the utilisation of the materials used can be evaluated and the geometry may be varied by keeping an identical actuator behaviour. Fig. 7 shows the flux density distribution inside a rotating TF actuator.

Penny-Motors

Designed to provide an output torque of more than 100 μNm , the high-end Penny-Motor as a member of an ultra flat micromotor family has a diameter of 12,8 mm and a height of 1,4 mm (Fig. 8). Important application fields for these innovative drives are e.g. datacom, medicine, automobiles, automation.

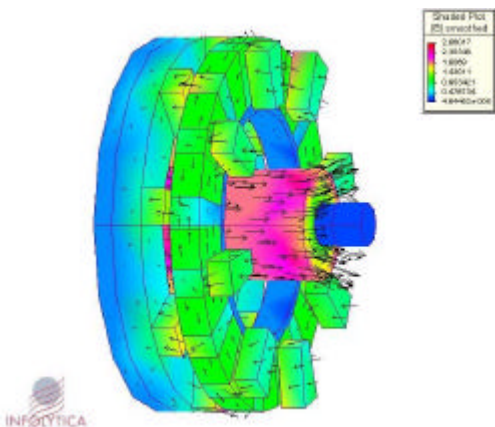


Fig. 7: Computed flux density distribution inside a rotating TF machine. Some parts of the machine are made invisible to show the inner yoke of the motor. (software Magnet6)

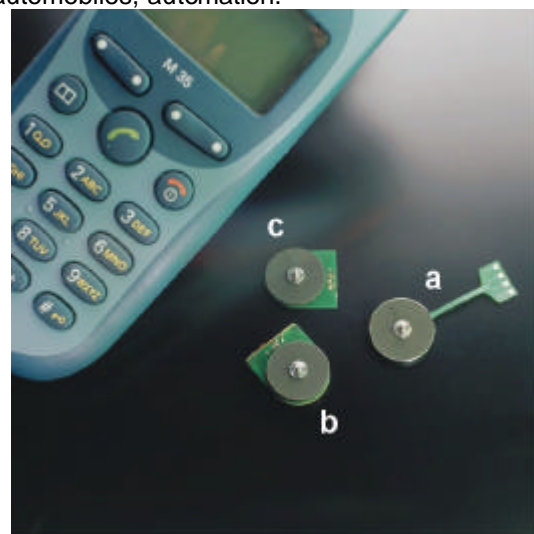


Fig. 8: Three members of the Penny-Motor family: a) HE type for high torque; b) YL type for low price; c) EC type for electronic commutation.

Besides the maximum torque and the ultra-flat shape essential design parameters of the Penny-Motors were a construction that allows easy assembly and the suitability for massproduction. This is the reason why all of the casing may be produced by means of already industrially well proven punching and bending techniques.

Core center of the penny motor is a three-strand disk shaped coil produced by lithographical methods and a merely 400 μm thick magnet-ring made of rare-earth material consisting of eight segments, which correspond to four poles-pairs. Both coil and magnet-ring decisively determine the performance of the motor and may be optimally produced by a combination of precision and microtechnical methods.

The integrated miniature ball bearing is as an option magnetically pre-stressed and therefore practically free of slackness. In addition, the revolving magnetic back-iron minimizes the influence of eddy currents with the known positive effects on the motor's efficiency (Fig. 9).

Magnetic circuit of the Penny-Motor

The main goal of dimensioning the magnetic core, was to achieve a maximum torque without rendering the assembly too costly. The operating point of the Penny-Motor was calculated and optimized by parameter variations. The calculation includes an approximation of the stray materials, such as rare-earth permanent magnet material NdFeB (Fig. 1). Different types of soft magnetic materials were studied as well.

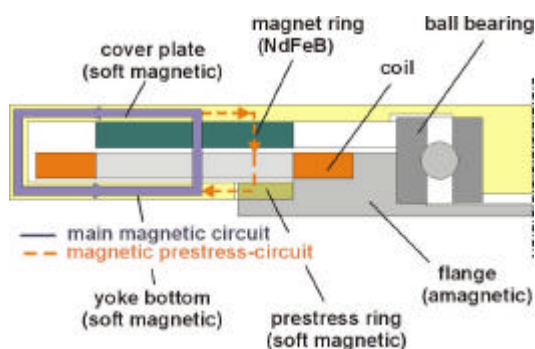


Fig. 9: Magnetic circuit of the HE Penny-Motor.

To obtain a better knowledge on the magnetic field, a commercial FEM tool was used to examine the different motor types. Verified by experiments the magnetic flux density within the air-gap of the high-end motor shows significantly more than 0,5 T. As illustrated in Fig. 9, the soft magnetic components lead the magnetic flux essentially through the ferromagnetic housing of the motor. These soft -

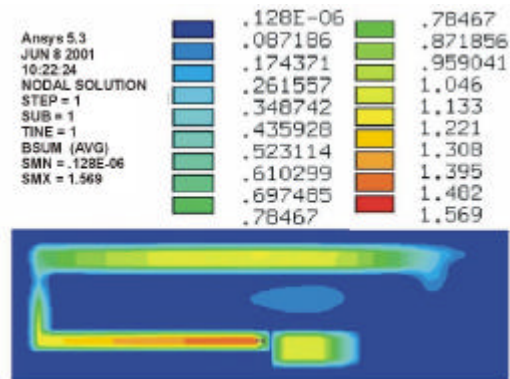


Fig. 10: Function of the non rotating pre-stress ring within the magnetic circuit of the Penny-Motor. (software ANSYS)

magnetic parts of the motor are optimized for a saturation of 1,6 T. This design ensures that the bearing in the inner area is not affected by magnetic fields. Fig. 10 shows the effect of the pre-stress ring. In this configuration the ring causes a well defined magnetic force of about 0,3 N on the ball bearing. Depending on the geometry of the pre-stress ring this force can be varied in the wide range of 0 N up to more than 5 N.

Magnetizing miniaturized NdFeB magnets

An innovative method was applied to produce the required NdFeB magnet-rings including the magnetization procedure is to employ enhanced micro moulding techniques and an already patented magnetizing method as described in [10, 11]. A disadvantage of the type of compound magnets which could not be solved yet is the relatively low energy product and the high magnetization energy required to entirely magnetize the material when compared to the uncompounded anisotropic NdFeB-material.

In the case of applying the anisotropic NdFeB-material the magnet-rings should be constructed of a single ring guaranteeing for its geometry of being within close tolerances. In spite of the lower magnetization energy, when compared to the compounded grades of NdFeB, the anisotropic material requires a minimum magnetic field of e.g. 2400 kA/m for 100% saturation. To ensure a uniform, magnetization within the complete magnet segment area, in practice magnetic fields up to 4000 kA/m and more were applied to the magnets during the magnetization procedure.

Because of the small magnet segments and the required high magnetic field, a specially adapted magnetization tool was developed [11]. To save time and costs a commercial FEM code (Fig. 11) was employed to deliver simulation results of the magnetic field excited by high currents. This represented a solid basis for the final design of the magnetization tool.

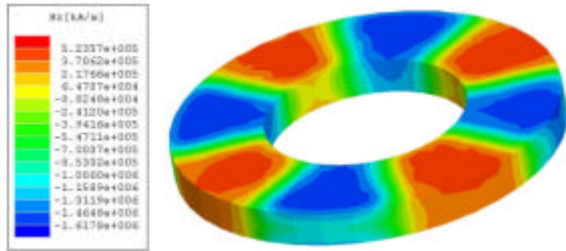


Fig. 11: 3D profile of a magnetic field caused by a current of approximately 5000 A through a special shaped copper conductor within the magnet ring. (software MAXWELL3D)

Penny-Motor bearings

Various bearing configurations have been considered under technical, economical and under availability aspects. For a ball bearing it can be shown that deep grooved radial ball bearings in the dimensions of the bore of 1 mm, outer diameter 3 mm, width 1 mm and the precision class of ISO P4 / ABEC 7 represent a standard bearing with features already close to the requirements for the Penny-Motor. A critical feature of the Penny-Motor assembly is the amount of angular misalignment within the bearings. Referring to a ball bearing, the angular misalignment is defined as the degree to which the outer ring in a diagonal way can be displaced versus the inner ring. For the Penny-Motor this displacement results in a corresponding lateral displacement of the rotor disc. The relationship can be determined by the tangent of the lateral displacement $d = r \cdot \tan \mathbf{b}$ (Fig. 12).

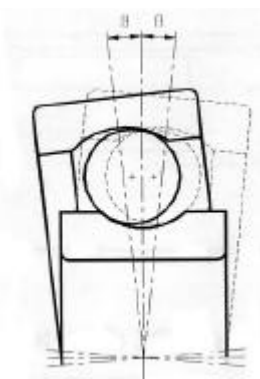


Fig. 12: Angular misalignment of a ball bearing.

The magnitude of the angular misalignment is a function of the internal geometry of the bearing, radial slackness influenced by the assembly and cross raceway curvatures. An analysis has been performed to determine the degree of angular mis-

alignment that can be expected in the Penny-Motor bearings as a function of the radial slackness tolerance. Varying the radial slackness from 1 to 10 μm and assuming unpreloaded bearings with a standard curvature of 57% the angular misalignment lies within a range of approximately 0,5° to 1,5°.

This seems not to be the optimum for the Penny-Motors and that is the reason why also high quality standard ball bearings are not matching the motor's requirements. Therefore, an extensive development of the ball bearing focussing on the Penny-Motor has been performed. The use of tighter raceway curvatures can reduce the displacement by more than 50%. Other important optimization parameters are the tolerances of the inner and outer ring diameter of the bearings and of the corresponding motor components. This tolerances causes during the final assembly complex and significant deformations with an extensive influence on the resulting radial slackness of the bearing (Fig. 13). Employing a high-end measuring machine with an automated classification and sorting routine allows the assignment of well suited parts of the bearing system for the final assembly to guarantee high quality bearings with a minimized angular misalignment.

Conclusion

Computer simulation is a powerful assistant in the field of micro actuator R&D. Decisively for success is often the combination of simulating electric, electromagnetic, thermal and mechanic phenomena's. It is not compelling to solve this tasks with only one flexible but complex tool. In many cases of practical relevance a combination of highly specialized simulation tools leads to qualified results.

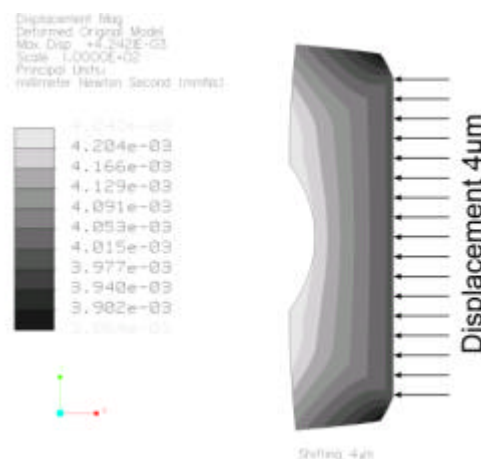


Fig. 13: Influence of mechanical assembly on the internal geometry of a miniature ball bearing. (software ProMechanica)

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