BIPOLAR MAGNETIC ACTUATORS AND APPROACHES FOR THEIR DESIGN

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ABSTRACT

Starting from the generic requirements for instrument locking during launch, piezoelectric, magnetic and other actuators have been studied in detail. Bipolar magnetic actuators are considered to have a high potential for such applications with a typically required displacement of 1 to 3 *mm* and forces between 5 and 60 *N*. After functional performance and reliability, the mass of the actuator is the third most important criterion for space applications and leads to the trend of miniaturisation. In this context, the use of permanent magnetic materials as well as different working principles of bipolar magnets have been investigated. Two prototypes of such miniaturised bipolar actuators for locking purposes on satellites are presented, which show a very good force-to-weight ratio and need power only during switching between the two stable actuator rest positions.

1. INTRODUCTION AND MOTIVATION

Miniaturised linear actuators are needed in many space applications for switching between two end positions of a pin or a plunger. Such actuators can be found for instance in multi-purpose locking devices or in valves for satellite propulsion systems. Fig. 1 shows a typical example of a launch lock for an instrument door.

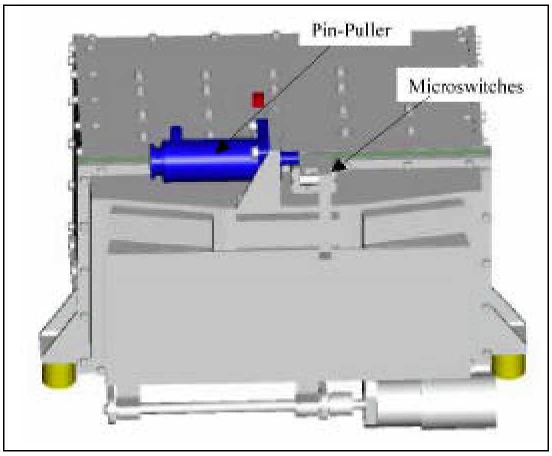

Fig. 1: *Pin-Puller Application – Example 1 (D-CIXS Door Mechanism, Courtesy of RAL/CLRC)*

The locking pin is restraining the closed door at the top, opposite to the hinge line at the bottom. After launch, the pin-puller will be activated allowing the door to rotate [1].

Another example for a potential application is depicted in Fig. 2, where premature deployment of a wire boom due to launch vibrations shall be prevented. A possible solution has been envisaged with a retractable pin, which shall lock the rotation of the wire drum shown inside the mechanism housing on the left side. After release of the locking pin, the wire boom can be deployed from a spinning spacecraft in radial direction. The wire boom shall be used for the study of electric field and plasma phenomena around other planets like Mercury [2].

Fig. 2: *Pin-Puller Application – Example 2 (Wire Boom Deployment Mechanism, Courtesy of SENER)*

In various cases, a solenoid actuator combined with a counteracting spring is applied for pin motion. In most of these devices, one of the end positions can only be maintained if the actuator is continuously powered or if a separate mechanical latch is used in addition. This problem can be overcome with bipolar electromagnetic actuators.

Bipolar electromagnets, containing permanent magnetic materials with a high energy density, allow a considerable reduction in size and mass compared to conventional solenoids. Such actuators show a very attractive set of characteristics:

Their operation is very fast. Relatively large forces (e.g. up to 100 *N*) and strokes (e.g. 1 to 3 *mm*) are achievable in a small volume. However, what makes them really unique is the opportunity to accomplish a bistable working principle, which requires electrical power only during switching. When energised, the electromagnetic flux drives the moving part of the actuator in the desired end position. The additional permanent magnet flux holds or “latches” the moving part in the selected position when electrical current is removed. As there is no mechanical latch, bipolar actuators can be always reset by remote electrical command, which makes them very easy to handle for integration and system testing and which allows multiple lock/release operations in orbit.

At the present stage, only a few bipolar actuators can be found in space applications, e.g. in latching valves. However, also in comparison with non-magnetic actuation principles such as piezoelectric ceramics or shape memory alloys, bipolar electromagnetic actuators have a good chance to fill the gap between micro-mechanical actuators and conventionally sized devices. In particular, for power-critical applications like planetary space probes or landing modules, small bipolar actuators could be very beneficial.

2. REQUIREMENTS FOR LOCKING ACTUATORS

Some typical requirements for actuators in locking applications are summarised in Table 1.

Table 1: *Typical requirements for locking actuators*

Technical feature	Required value
Displacement	*1 ... 3 mm*
Holding force Switching force	*5 ... 60 N* *2 ... 25 N*
Diameter Length	*10 ... 25 mm* *15 ... 40 mm*
Mass	*20 ... 80 g*
Energy consumption	*only during switching*

Independent from the physical principle utilised in the actual drive, an actuator system is usually made of several subsystems necessary for function fulfilment (Fig. 3).

When the suitability of an actuator for a particular task like instrument locking during launch is evaluated, the specific impact caused by these subsystems must be taken into account. Beside additional mass and volume, energy demand and overall efficiency are crucial factors for spacecraft and must be already considered during the conceptual design phase.

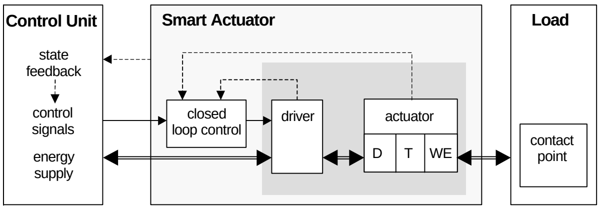

Fig. 3: *Generic structure of an actuator (D – Drive, T – Transmission, WE – Working element)*

3. REVIEW OF LINEAR ACTUATOR WORKING PRINCIPLES

Physical effects and resulting actuator principles suited for the design of linear direct drives with limited stroke are compared in Table 2 and discussed in detail in [3]. Typical values for force-displacement and force-velocity characteristics of different actuator principles are shown in Fig. 4.

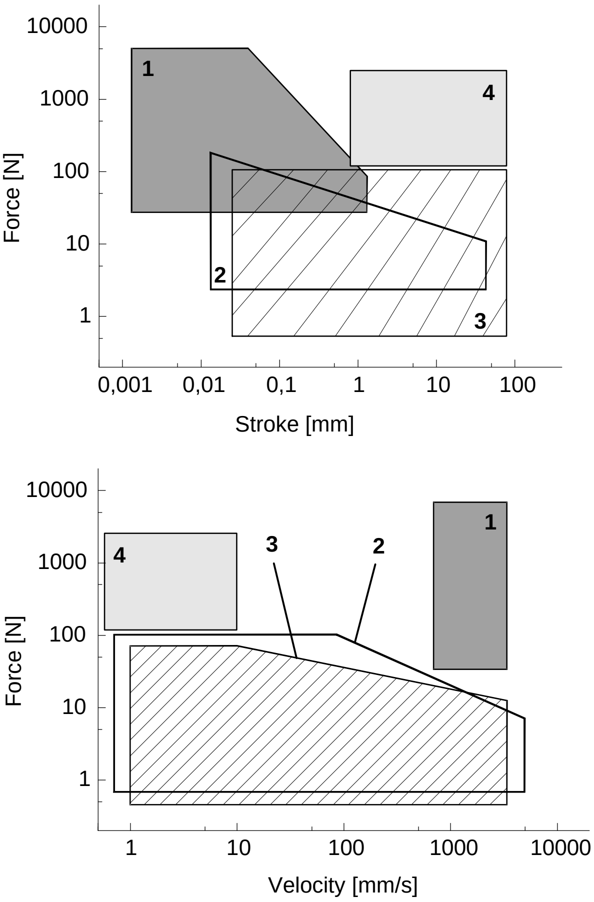

Fig. 4: *Comparison of force-displacement and force-velocity characteristics; 1-Piezoelectric actuator, 2-Electromagnetic actuator, 3-Stepper motor (with gearbox), 4-Paraffin actuator*

***Table 2:** Comparison of actuator principles*

Characteristics	**Permanent magnetic**	**Shape Memory Alloy**	**Magnetostrictive**	**Piezoelectric**
Material (brand name, chemical formula, supplier)	Vacodym (rare earth magnet) $Ne_2Fe_{14}B$ (VAC Hanau, Germany) www.vacuumschmelze.de	Nitinol $Ni_xTi_xO_xC_x$ (NDC Inc., USA) www.nitinol.com	Terfenol-D $Tb_{.27}Dy_{.73}Fe_{2...x}$ (Feredyn AB Uppsala, Sweden)	PIC (PZT-ceramics) Lead Zirconate Titanate (PI Ceramic, Germany) www.piceramic.de
Mechanical:				
density [gcm^{-3}]	7.5	6.5	9.25	7.8
Young's modulus [Nm^{-2}]	$15\cdot10^{10}$	$(41 \ldots 75)\cdot10^{9}$	$2.6\cdot10^{10}\ Y\|_{H=0}$ $5.5\cdot10^{10}\ Y\|_{B=0}$	$11\cdot10^{10}\ Y\|_{D=0}$ $6\cdot10^{10}\ Y\|_{E=0}$
compressive strength [Pa]	approx. $105\cdot10^{7}$	-	$70\cdot10^{7}$	-
tensile strength [Pa]	-	$(1.1 \ldots 1.3)\cdot10^{9}$	$2.8\cdot10^{7}$	$7.6\cdot10^{7}$
Thermal:				
thermal coefficient of expansion [K^{-1}]	$5\cdot10^{-6}\ \parallel$ $-1\cdot10^{-6}\ \perp$	$11\cdot10^{-6}$	$12\cdot10^{-6}$	ca. $2 \ldots 9\cdot10^{-6}$
thermal conductivity [$Wm^{-1}K^{-1}$]	9		-	2
Electrical:				
resistivity [Ωm]	$1.2 \ldots 1.6\cdot10^{-6}$	$8.2\cdot10^{-7}$	$0.6\cdot10^{-6}$	ca. $1\cdot10^{8} \ldots 1\cdot10^{11}$
Miscellaneous:			(magnetostrictive ef.)	(piezoelectric effect)
elongation [ppm]	approx. 0	up to 80000	1400 ... 2000	400 ... 700
Curie temperature [°C]	approx. 310		387	300 ... 350
coupling coefficient k_{33}	-	-	0.72	0.68
d-constant d_{33}	-	-	$1.7\cdot10^{-9}\ mA^{-1}$	$3\cdot10^{-10}\ mV^{-1}$
energy density [kJm^{-3}]	**200 ... 420**	10000 (1)	14 ... 30	0.8 ... 2

(1) Working / energy capacity per volume, related efficiency less than 3 %

Bipolar magnetic actuators offer interesting options for locking purposes in space applications because of the following advantages:

- High energy density of rare earth magnetic materials
  ➔ good force-to-mass ratio,
- Force-displacement characteristics of magnetic actuators fully compatible with typical requirements for locking applications,
- Feasibility of a bistable working principle
  ➔ zero power consumption in stable rest positions,
  ➔ multiple lock/release operation possible.

These properties lead to the conclusion that magnetic actuation can be regarded as one the best choices among the mentioned working principles for the design of locking devices. Design approaches used for bipolar magnetic actuators as well as technical data on these actuators will be presented in the following sections.

4. WORKING PRINCIPLES OF ELECTROMAGNETIC ACTUATORS

Magnetic actuators can be classified according to Fig. 5.

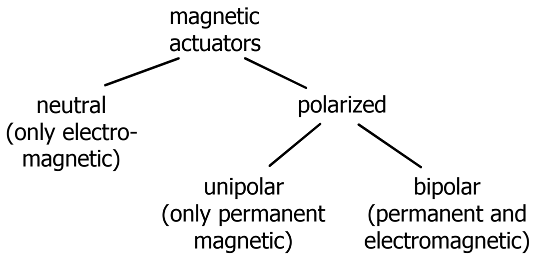

Fig. 5: *Classification of magnetic actuators [3]*

For bipolar magnetic actuators, three different working principles are known [3, 4]:

- Remanence principle,
- Compensation principle,
- Commutation principle.

When rare earth magnets are used, which is advisable for space applications because of their high energy density, the commutation principle should be applied in an actuator (Fig. 6).

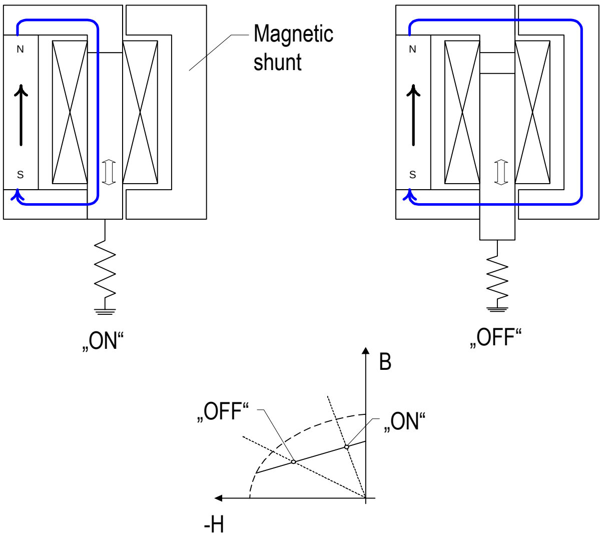

Fig. 6: *Commutation or Switch Principle*

In contrast to actuators based on the remanence or compensation principle, a reversal of magnetization of the permanent magnet and, hence, a high magnetizing field strength and actuator current are not necessary for the commutation principle. Here, the permanent magnetic flux in the active air gap is compensated by a coil, which allows the armature to start moving. This change in armature position and geometry causes the permanent magnetic flux to commutate to a new flux path that can be a magnetic shunt or a new working flux path, including a new active air gap. With respect to efficiency and force-to-mass ratio, the latter structure is more advantageous compared to those with a distinctive magnetic shunt and is therefore realized in the developed locking actuators.

5. DESIGN APPROACH FOR ELECTRO-MAGNETIC ACTUATORS

As for all engineering problems, the generic design process shown in Fig. 7 is valid for magnetic actuators too. Because of the strong interactions between the electrical, magnetic and mechanical subsystems of an electro-magneto-mechanical drive system, these interactions have to be designed and optimised carefully. Dynamic simulation at system level with analog simulators is a suitable approach for this task. For joint modelling of all subsystems in one simulation environment, the magnetic actuator should be described with a Magnetic Equivalent Network (MEN). Hence, such a magnetic network is a good starting point for the design of magnetic actuators. Possible approaches, benefits and problems with the establishment of MEN models are discussed in [5] to [7].

Because of the simplifications in network modelling of magnetic structures and the uncertainties in an early design phase, the actuator design should be detailed by means of Finite Element Analyses (FEA) of possible actuator designs. Compared to magnetic equivalent network models, FEA allows for more accurate calculation of the magnetic field distribution and derived integral quantities such as magnetic force on the armature to be moved.

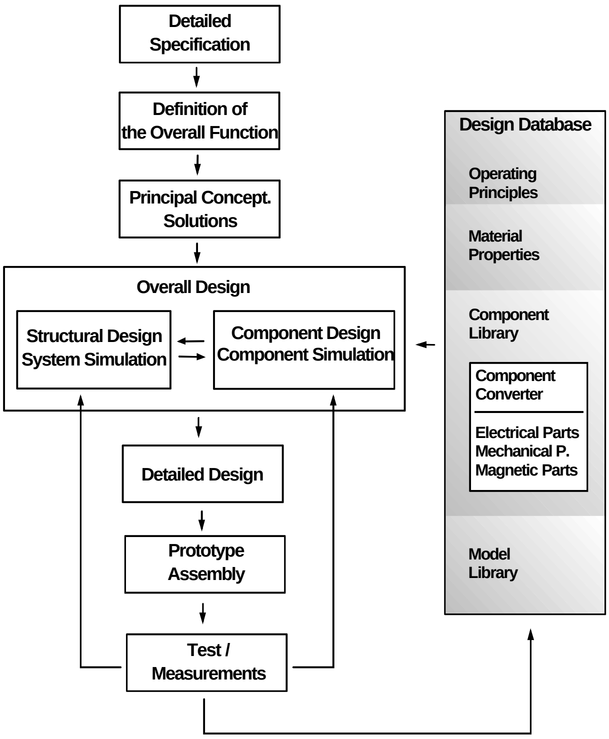

Fig. 7: *Generic design process*

6. DESIGN OF A LOCKING ACTUATOR

According to the generic specification for locking actuators (Table 1), one of the design goals for this actuator is to achieve large holding and small switching forces. The design process started with analytical estimations based on simple magnetic equivalent networks [3]. Different possible magnetic designs were then developed and analysed in depth using Finite Element Modelling (FEM) as shown in Fig. 8 and 9.

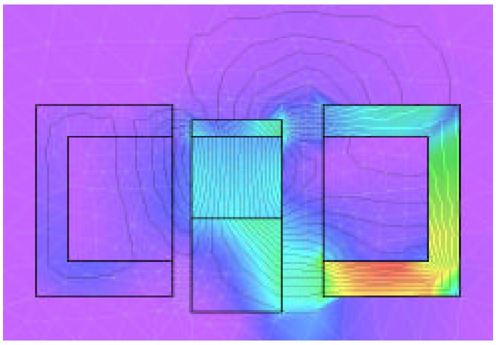

Fig. 8: *Magnetic flux density distribution of the locking actuator obtained by FEM [8]*

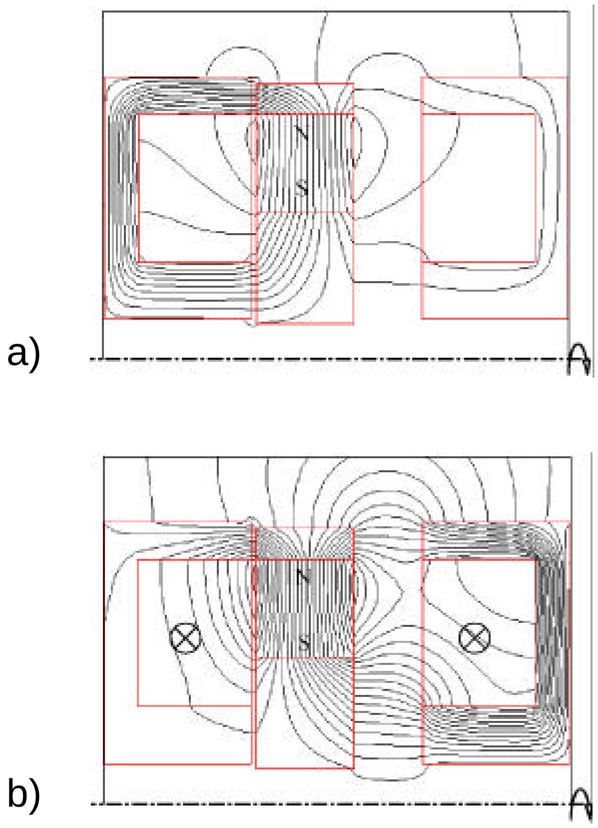

Fig. 9: *Magnetic field lines of the locking actuator obtained by FEM*
a) without current,
b) with current and armature in start position prior to movement

In a comprehensive evaluation of the different options, the design with the best balance between force-to-mass ratio, volume, ease of manufacturing and other criteria was designed in detail, manufactured and tested (Fig. 10 and 11).

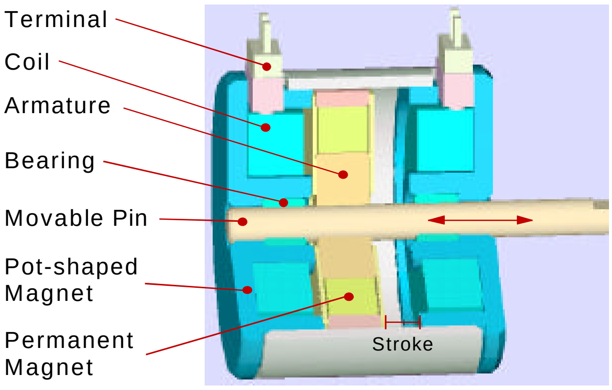

Fig. 10: *Bipolar magnetic locking actuator [8, 9]*

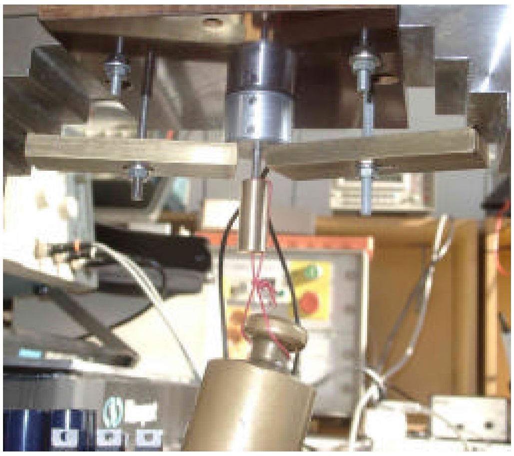

Fig. 11: *Test rig for static and dynamic measurements on the locking actuator*

For the developed bistable locking actuators for space applications, a buffered drive circuit is used, where the energy needed for each actuation is stored in a capacitor (Fig. 12). That way the high power demand of the actuator (more than 100 *VA* for some milliseconds) during switching cannot cause voltage drops or breakdowns on the satellite’s power bus. Measured actuator voltage and coil current for one actuation with the capacitor based drive circuit is shown in Fig. 13.

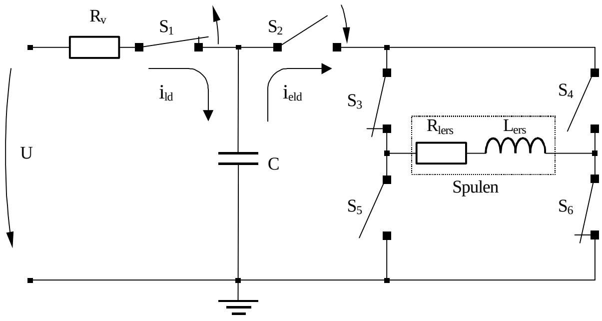

Fig. 12: *Schematic drive circuit for bipolar magnetic actuators [8]*

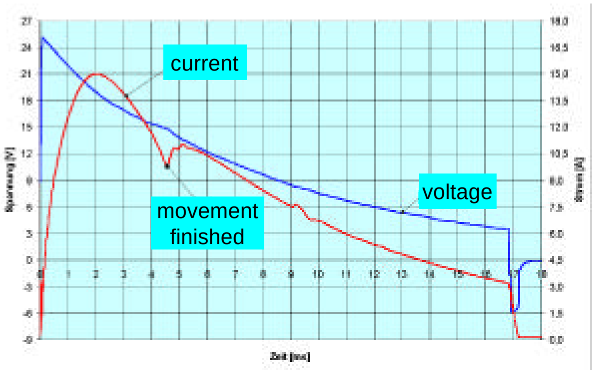

Fig. 13: *Measured dynamic behaviour of the locking actuator with capacitor based drive circuit*

7. DESIGN OF A LIFTING ACTUATOR

In addition to the locking actuator presented above, a miniature bistable magnetic actuator with almost equal forces during motion (here for lifting a mass) and holding was developed. Besides locking applications, this actuator can also be used in applications typical for conventional (neutral) lifting solenoids.

Unlike for the locking actuator as discussed before, the design of the lifting actuator started directly with the establishment and analysis of different possible magnetic architectures and circuits utilising the FEM method (Fig. 14 and 15). The knowledge previously obtained with the design and testing of the locking actuator has been an essential input for the new design cycle.

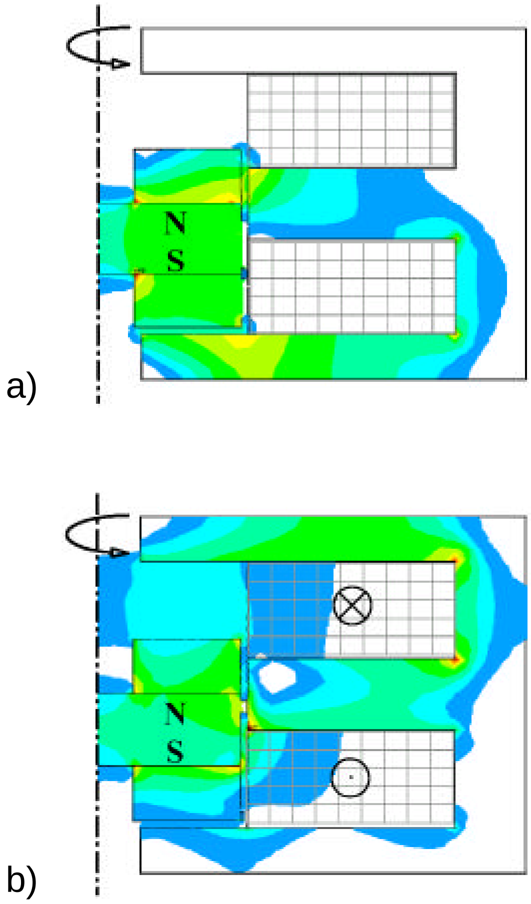

Fig. 14: *Flux density distribution in the lifting actuator obtained by FEM*
a) without current,
b) with current and armature in start position prior to movement

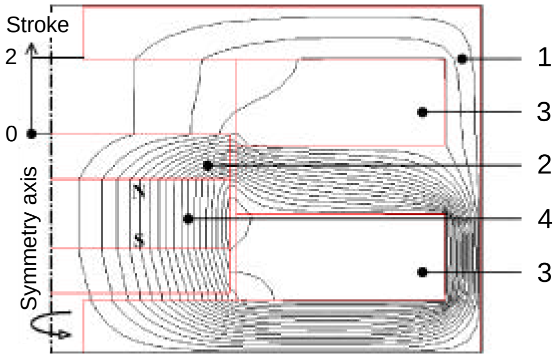

Fig. 15: *Principle design of the lifting actuator and magnetic field lines obtained by FEM; 1-Yoke, 2-Armature, 3-Coils, 4-Permanent magnet*

In Fig. 16, the resulting prototype is depicted. The permanent magnetic flux leads to force-displacement characteristics (without current through the coils) according to Fig. 17. In this figure, the measured forces are compared with the values obtained from FEA calculations. The good match between predicted and measured forces shows the benefits of using extended simulation techniques prior to prototype manufacturing.

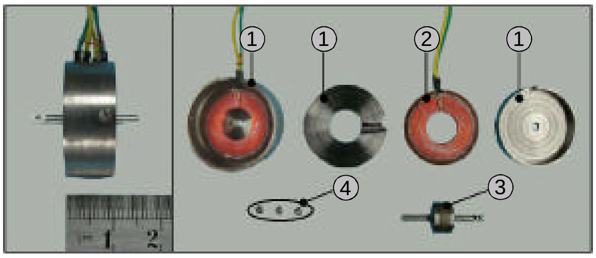

Fig. 16: *Prototype of the miniature lifting actuator; 1-Yoke Parts, 2-Coil, 3-Armature, 4-Mounting screws*

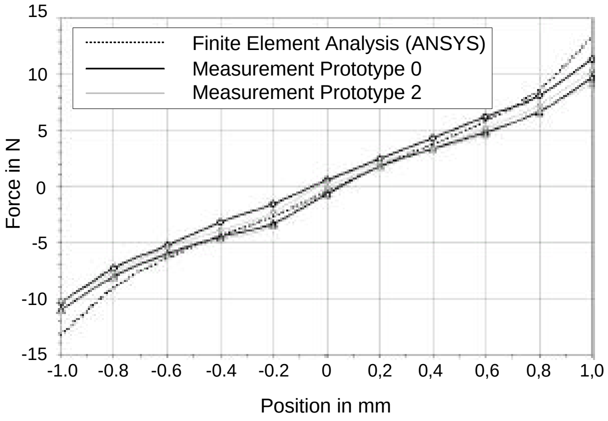

Fig. 17: *FEA based simulation and measurement of the force-displacement characteristics of the lifting magnet (without current)*

8. CONCLUSIONS AND OUTLOOK

Selected performance data of the actuator prototypes described above are shown in Table 3. The actuators fully meet the basic requirements for potential locking applications. In addition, the developed lifting magnet can be used in applications where not only a high holding force but also a high force during movement is needed.

Table 3: *Technical data of the developed prototypes*

	Locking actuator	**Lifting actuator**
Stroke	*3.0 mm*	*2.0 mm*
Holding force	*54 N*	*11 N*
Switching force	*10 N…20 N* (1)	*10.5 N* (1)
Switching time	*ca. 6 ms* (1)	*ca. 3 ms* (1)
Diameter x length	*25 mm* x *19 mm*	*24 mm* x *10 mm*
Mass	*46 g*	*23 g*

(1) Depending on drive electronics

Advantageous properties of bistable magnetic actuators, compared to linear actuators based on other physical principles, are:

- excellent force-to-mass ratio with respect to their dynamic behaviour,
- energy consumption only during actuation,
- large holding force,
- multiple lock/release operation on remote electrical command.

Possible applications of this actuator type in aerospace as well as in earthbound domains can be found with:

- locking of spacecraft equipment during launch,
- latching valves for fluid management, e.g. in satellite propulsion systems,
- handling and automation industry,
- actuators for the automotive sector.

Bistable magnetic linear actuators have the potential to replace conventional locking actuators in the future. Beside their use in space applications, an increasing use of this actuator type in ground applications can be anticipated as well.

ACKNOWLEDGEMENTS

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