# Magnetic Field Driven Unconventional Actuators – Design Rules and Application Potential

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In this paper, the operating principle, design and structure of actuators containing of magnetostrictive or magnetorheological materials are described. These materials have been available on the market for a few years. As a consequence, such actuators are increasingly being used in adaptronic applications. Magnetic shape memory alloys, on the contrary, are for the most part still in stages of R&D. Yet, due to their promising potential for application in actuators, they are also discussed in this paper.

## 1. Introduction

Actuators play an important role in the implementation of adaptronic systems or structures [1]. This means electrically controllable positioning elements for generating displacements and/or forces such that, for instance, the geometry of a structure or the vibration behaviour of a system can automatically be adapted to different operating or environmental conditions. This task can be accomplished by means of a wide range of actuating principles. However, over the past few years unconventional actuators – that is, positioning elements which are not based on conventional electromagnetic or fluid principles – are gaining in importance.

Among unconventional actuators piezoelectric solid-state materials and electrorheological fluids are some of the most known. Actuators involving these materials are controlled by means of electric fields. This may be a significant criterion in special applications where magnetic fields cannot be used. A disadvantage, however, may lie in the fact that the necessary field strengths are generated by electrical potentials reaching into the kilovolts. If such high voltages are unwanted or even damaging, unconventional actuators such as those described here can be implemented. Here, actuator displacements and forces are controlled by means of magnetic fields, thus avoiding high electrical voltages.

The following review introduces the principles and the design of magnetic field driven unconventional actuators based on giant magnetostrictive alloys, magnetorheological fluids as well as magnetic shape memory alloys. Since adaptronic applications are mainly implemented on the macro scale, only actuators with bulk material are taken into account.

## 2. Actuators with giant magnetostrictive materials

From the user's point of view the magnetostrictive effect is the magnetic counterpart of the better known inverse piezoelectric effect. Both solid-state effects facilitate the generation of high forces and dynamics.

### *2.1. Physical effect*

When a ferromagnetic crystal is magnetized its shape changes with increasing field strength. This phenomenon is labeled magnetostrictive effect. The most important part of magnetostriction is the Joule effect discovered in 1842. It is based on the fact that the magnetism domains turn in the direction of magnetization and move their borders. Thus the ferromagnetic body changes its shape but its volume is kept unvaried. The term magnetostrictive effect usually indicates this effect, as the change in volume of common giant magnetostrictive materials can be neglected with respect to their effect. In the following the term magnetostrictive effect is to indicate the Joule effect in accordance with the prevailing linguistic usage. Although, strictly speaking, magnetostriction is to be taken as the magnetic counterpart of the quadratic, electrostrictive effect, its mathematical description in practice is given by an equation system that formally corresponds to the linear state equations for the direct or inverse piezoelectric effect.

### *2.2. Materials*

In alloys with components of iron, nickel or cobalt the magnetostrictive effect causes strains in the range of 10 to 30 μm/m, in giant-magnetostrictive materials of rare-earth iron alloys the effect attains values of up to 2000 μm/m. Since the beginning of the 1960s, giant magnetostrictive materials to be used in underwater sonar systems have been developed in the USA. The material which was developed there later, Terfenol-D, has a many times higher energy density than piezoelectric materials. Terfenol-D is the name given to the compound $Tb_{0.3}Dy_{0.7}Fe_2$ [2].

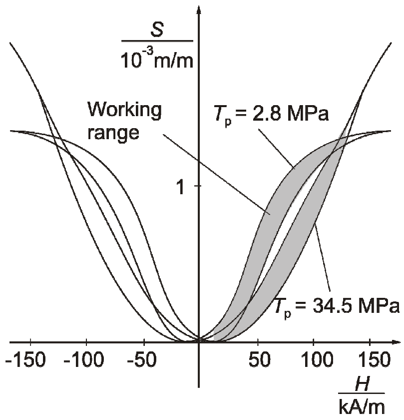



*Fig. 1. Characteristics S(H) of the giant magnetostrictive material Terfenol-D under different mechanical pre-loads $T_p$*

In Table 1 some characteristic parameters and values are provided for Terfenol-D, today's most frequently used material for magnetostrictive transducers. Phenomenologically, giant magnetostrictive materials behave analogously to ferroelectric materials. Their characteristic *S(H)*, like the dependence *S(E)* on piezoceramics, shows saturation and hysteresis, see Fig. 1 (*H*: magnetic field strength; *S*: strain). It is interesting that the strain achievable also seems to depend on the mechanical pre-stress $T_p$ of the material: it first increases with increasing $T_p$ and has a maximum at approx. $T_p$ = 17 MPa, then it decreases. This behaviour which can also be observed in piezoceramics, though to a less marked degree, plays an important role for the optimal design of magnetostrictive transducers.

*Table1: Some characteristic values of the giant magnetostrictive material Terfenol-D*

| | | | |
|---|---|---|---|
| Magnetostrictive constant | $d_{33}$ | $1.5 \cdot 10^{-8}$ | V s/N |
| Relative permeability | $\mu_{33}^T/\mu_0$ | 9.3 | |
| | $\mu_{33}^S/\mu_0$ | 4.5 | |
| Elastic modulus | $c_{33}^H$ | (25...30) $10^3$ | N/mm$^2$ |
| | $c_{33}^B$ | (50...55) $10^3$ | N/mm$^2$ |
| Coupling factor | $k_{33}$ | ...0.75 | |
| Compressive strength | $T_t$ | 700 | N/mm$^2$ |
| Tensile strength | $T_p$ | 28 | N/mm$^2$ |
| Curie temperature | $\vartheta_C$ | 380 | °C |
| Density | $\rho$ | $9.25 \cdot 10^3$ | kg/m$^3$ |

### 2.3. Design of actuators with giant magnetostrictive materials

The bulk material must be pre-magnetized and mechanically pre-stressed, if the displacements have to be both positive and negative (the maximum pressure load allowed is considerably higher than the tension load, compare Table 1). Quasisatic actuators use giant magnetostrictive materials in these conditions for positioning, vibration control, stepping motors and fluid control applications. Using mechanical resonance is highly beneficial due to the giant dynamic strains whose peak-to-peak amplitudes are higher than the static ones. The main applications making use of resonance are high-power transducers. The interest in giant magnetostrictive materials in thin film form has grown over the past few years due to their potential as actuators in microsystems e. g. laser scanners, micropumps, and ultrasonic motors [3].

#### 2.3.1. Mechanical mounting

When conceiving transducers with giant magnetostrictive bulk materials, the transducers must be subject to an optimal pre-stress in order to achieve higher strains up to 50 %. A variable setting for compressive pre-stress facilitates the transducer's simple adaptation to the mechanical boundary conditions of the application. The pre-stress of the Terfenol rod can be performed for example by screw springs or plate springs.

Temperature has to be considered as a further factor of influence on the transducer function. When the Terfenol rod is subject to a change in temperature of e. g. 100 K, the thermal strain of the rod is in the same order of magnitude as magnetostriction. By means of construction principles known from mechanical engineering, such thermal longitudinal changes can be compensated.

#### 2.3.2. Magnetic circuit

The magnetic circuit consists of the Terfenol rod, the coil generating the magnetic field, the flux guide, and the permanent magnets. The flux guide made of highly-permeable, electrically non-conducting material (eddy currents!) reduces the magnetic stray flux and thus increases the medium magnetic field strength in Terfenol-D and provides for a most homogeneous possible field distribution. As the permeability rate of Terfenol is small ($\mu_r < 10$), i.e. this material only has a moderate magnetic conductance, the guiding of the magnetic flux has a great influence on the field distribution in the Terfenol rod. Fig. 2 shows different possibilities of the flux guide.

The mean standardized magnetic field strength achieved using a complete flux guide amounts to almost 100% for any outer radii $r_{coil}$ of the coil. Without flux guide the mean standardized field strength drops to 80 % already at $r_{coil}/r_{Ter} \approx 5$. If a complete flux guide is not possible because of particular requirements, the use of highly permeable pole shoes on both coil ends can increase the mean standardized field strength to approx. 90%, and by increasing the outer radius $r_{coil}$ the field inhomogeneity can be reduced to below 1%. Additionally, the complete flux guide affects a reduction of the copper losses in the field coil by a factor of three [4].

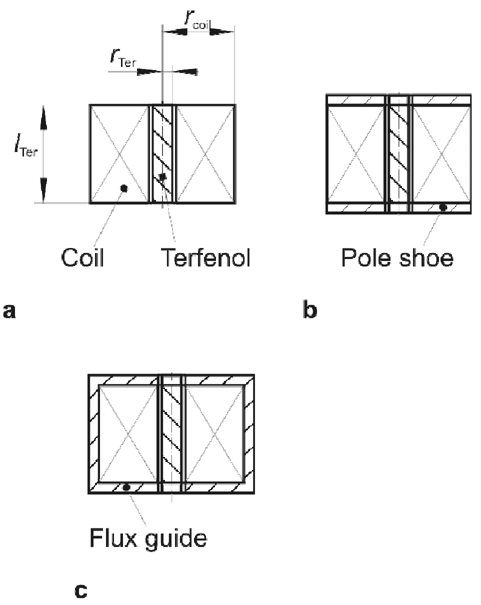



*Fig. 2. Possibilities of magnetic flux guide: (a) without flux guide; (b) with pole shoes; (c) with complete flux guide*

A closer examination also shows that only the three possibilities for the configuration of the Terfenol rod, the coil and the permanent magnet as shown in Fig. 3 are sensible. In the configuration MTC the requirement for a sufficiently high static magnetic field in the Terfenol rod (max. approx. 80 kA/m) leads to an outer diameter of the Terfenol hollow rod of at least 13 to 20 mm;

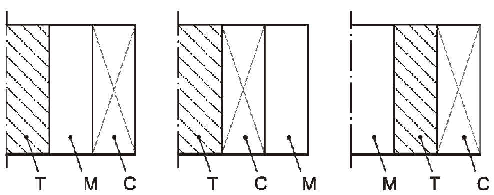



*Fig. 3. Sensible configuration of Terfenaol rod (T), field coil (C) and permanent magnet (M) (pole shoes not shown)*

this minimum dimension restricts the application of the MTC configuration so much that it can only be used in particular cases. Furthermore, it is shown that, compared to the TMC configuration, the TCM configuration has a considerably lower field inhomogeneity, less copper losses and a good coupling of the magnetic alternating field. It can be concluded that the use of the TCM configuration should be given priority.

### *2.4. Application examples*

#### *2.4.1. Sonar underwater transducer*

The electromechanical equivalent circuit of a magnetostrictive transducer approximately corresponds to a high-quality electro-mechanical oscillation circuit. Thus, one of the earliest application fields for magnetostrictive transducers concerns sound generation, in which, due to the lower sound velocity compared to piezo transducers, oscillation frequencies down to the sonar range are feasible. Butler and Ciosek [5] implemented a sonar underwater transducer in the form of an octagonal ring with a diameter of approx. 25 cm which was driven by 16 Terfenol rods, see Fig. 4. It produces a maximum output acoustic power of 350 W at an eigen frequency of 775 Hz.

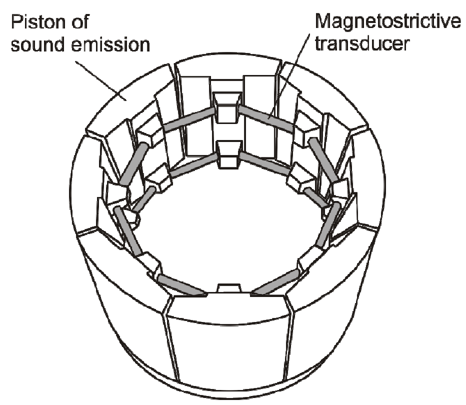
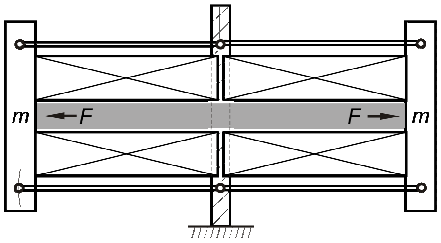



*Fig. 4. Basic structure of an underwater sonar system (according to [5]*

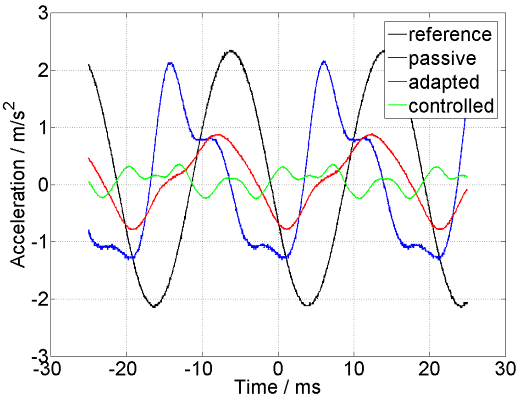
#### *2.4.2. Tunable pendulum actuator for vibration attenuation*

The task of structural vibration attenuation is increasingly being approached with the development of active system solutions, exceeding passive systems in terms of bandwidth and attenuation performance. A tuned mass damper is a typical passive solution suitable for attenuating a predominant tonal vibration disturbance, but it augments the vibration level over a wide frequency band above its resonance. By incorporating active materials, the device acquires broadband attenuation capability, and the frequency of predominant attenuation can be shifted [6].

The pendulum actuator in Fig. 5a makes use of a special kinematic arrangement to increase the displacement of the seismic mass, thereby imparting the tuned mass damper with a high force-to-mass ratio [7]. The device acquires adaptive properties through the use of high-force electromechanically transductive materials such as piezoelectrics or magnetoelastics implemented at the core of the pendulum actuator; setting the operating point of the transducer element enables the fundamental frequency of the device to be tuned or adapted to a changing set of operating conditions. An appropriate dynamic control signal enables the device to generate harmonic forces or – when implemented within a closed control loop – to affect vibration attenuation in structures afflicted by a dominant disturbance frequency.




**a**




**b**

*Fig. 5 Tunable pendulum actuator*

Fig. 5b proves the passive structural vibration attenuation capability of a pendulum actuator making use of magnetostrictive material. Despite its nonlinear kinematics, the pendulum damper exhibits a pronounced anti-resonance when attached to a vibrating structure. Simulation as well as experimental results illustrate the harmonic nature of the device and explore its tunability. A shift from 44 Hz to 56 Hz is achieved by varying the operating point of the active material. Current developments demonstrate the vibration attenuation potential of the pendulum actuator in active control. In one case, manual adjustment of the driving signal to the pendulum actuator results in an approximately 18 dB reduction in acceleration of the vibrating structure.

### *2.5. Comparison between piezoelectric and magnetostrictive transducers*

The corresponding formal and analytical description of the magnetostrictive and the piezoelectric effect suggest a user-oriented comparison between the most important material features. Transducers with these materials have maximum strains in the range of thousandths and huge forces up to the range of kilonewtons, their response times lie in the range of micro- and milliseconds, and they have high electromechanical efficiencies.

As both materials are brittle, they cannot easily be machined. For the applications as actuators the following differences may represent important criteria for a decision [8].

- With 380°C, the Curie temperature of the magnetostrictive material is higher than that of piezoceramics (165°C to 300°C), i.e. it can be operated under higher temperatures. Compared with piezoceramics the magnetostrictive features only disappear until the temperature falls below the Curie point.
- The energy density in giant magnetostrictive materials is considerably higher than in piezo materials. Consequently, less active material is needed for the construction of powerful actuators. This advantage, however, is partly wrecked by the space needed for the coil that generates the magnetic field and for the magnetic flux guide.
- The current control of magnetostrictive transducers avoids high voltages, but higher currents than in piezo transducers can occur (high inductive voltages when switching the magnetic field are sinked with the aid of reverse diodes).
- Compared to magnetostrictive materials the variety of commercially available piezoceramics is much wider. In addition, different effects (longitudinal, transversal) can be made use of, whereas, at present, in the field of magnetostriction only the longitudinal mode is used for actuators.
- Piezo transducers can retain their static displacement almost without the supply of electrical energy, whereas magnetostrictive transducers require magnetization with direct current or permanent magnets for a static displacement.

Today mainly piezo transducers are used, which are ready-made and commercially available in a great variety. For magnetostrictive actuators, however, there are only a few suppliers, who have the magnetostrictive material on offer in a few forms and dimensions. Moreover, at present, magnetostrictive material is considerably more expensive than piezoceramics.

## 3. Actuators with magnetorheological fluids

Electrorheological and magnetorheological fluids, whose flow resistance can be adapted continuously by electric and magnetic fields, respectively, have been known approx. since about 1945, but initially exhibited some disadvantages in technical applications.

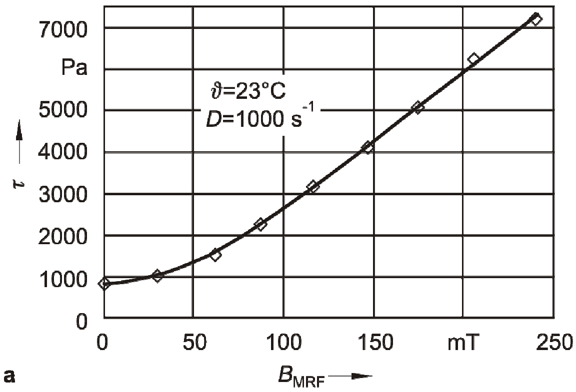
### 3.1. Physical effect

Magnetorheological (MR) fluids are suspensions consisting of magnetizable particles in a low-permeability base fluid. Under the influence of a magnetic field the suspensions change in their magnetic, electric, thermal, acoustic and optical properties and in particular in their rheological behaviour. The flow resistance increases considerably with a growing magnetic flux density. The suspended particles form magnetic dipoles which align according to the magnetic field lines, interact and form chains and agglomerates. These chains can be mechanically loaded and lead to the creation of a yield stress and an increase in flow resistance. This magnetorheological effect was first described at the end of the 1940s. The process is fully variable and reversible, i.e. after turning off the magnetic field the particles return to their original statistical distribution. The switching times for the structural changes are within a range of a few milliseconds.

### 3.2. Materials

The suspended magnetizable particles have a diameter ranging from 1 µm to 10 µm and a density of approx. 7 g/cm$^3$. They often consist of carbony iron alloys and can account for up to 60% of the suspension's weight. Mostly silicon and mineral oils are used as a low-permeability base fluid. The base fluid is required to have a low viscosity and to be stable within a wide range of temperature. The third component, the stabilizer, shall prevent the particles from sedimenting and coagulating. The density of the whole suspension ranges approx. from 3 g/cm$^3$ to 4 g/cm$^3$ [9].

At room temperature the base viscosity of common suspensions amounts to several hundreds of mPa•s. At first, the transmittable shear stress $\tau$ increases with growing magnetic flux density $B_{MRF}$ according to a power function. At medium magnetic inductions a linear increase occurs, see Fig. 6a. An increase of $\tau$ can be attained by increasing the particles' share in volume or by using bigger particles while maintaining the particles' same share in volume. However, both methods lead to a drastic increase in base viscosity and thus to a reduction of the MR effect.



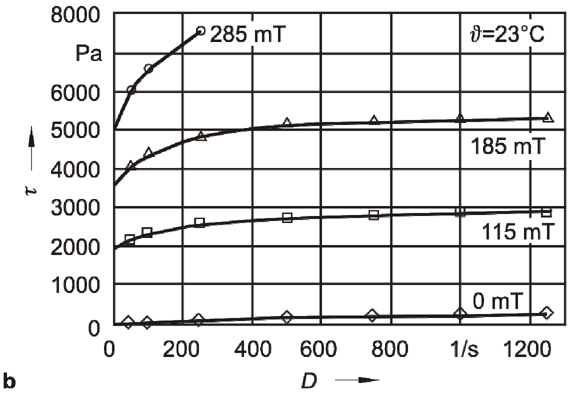




*Fig. 6. Characteristics of MR fluid DEA 252: (a) shear stress $\tau$ as a function of the flux density $B_{MRF}$ in the MR fluid; (b) shear stress $\tau$ as a function of the shear rate D with $B_{MRF}$ as a parameter [10]*

In the magnetic control field MR suspensions form a yield stress $\tau_y$, that is determined by the chain-shaped configuration of the suspended particles. Without a control field, ideal MR fluids behave like Newtonian fluids, i.e. under shear the shear stress $\tau$ shows a linear dependence on the shear rate $D$, see Fig. 6b. Under the influence of a control field they have the properties of a Bingham body; the yield stress increases as the strength of the control field increases. While flowing, a plateau of identical flow velocity is formed (plug flow). The width of this plug increases according to the increase in the strength of the control field; if the plug covers the whole channel width, there is no volume flow.

### 3.3. Design of energy transducers based on MR fluids

When designing the MR fluid energy transducer, the starting points are the requirements of the mechanical application, e.g. the minimum and maximum forces and the construction volume required. Other requisites result from the type of application, e.g. electrical power requirement, response time, and from the surrounding conditions, e.g. the range of operating temperature.

### 3.3.1. Transducer principles

Energy transducers using MR fluids are based on three principles, which can occur alone or in combination: shear mode, flow mode and squeeze mode. In MR-fluid energy transducers the fluid is located in a gap in the magnetic flux guide. The field lines of the magnetic control field run perpendicular to the fluid’s shear/flow direction. The working modes of MR-fluid energy transducers are shown in Fig. 7 [8]. In the shear mode the plates move parallel to one another, and the transferred force or the torque can be controlled by the magnetic field. Possible applications of the shear mode include clutches and brakes as well as electrically controllable dampers. In the flow mode the MR fluid flows through a gap in the magnetic flux guide. The control field influences the flow

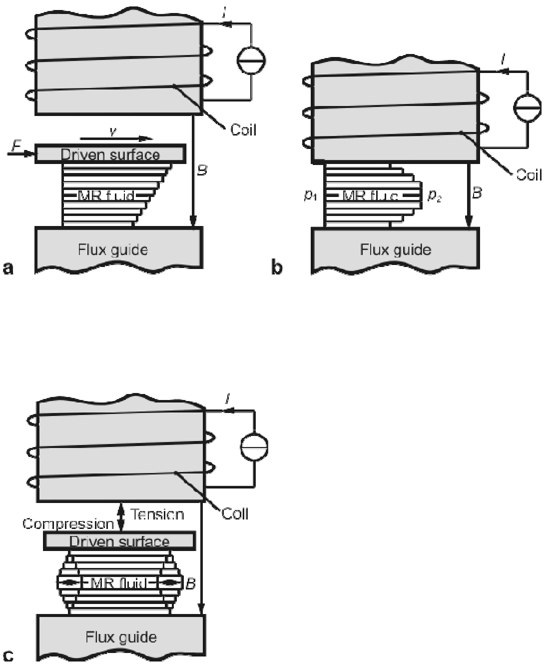



*Fig. 7. Working modes of MR fluid energy transducers: (a) shear mode; (b) flow mode; (c) squeeze mode*

resistance of the MR fluid and thus the pressure drop across such a valve. MR fluid valves do not need moved mechanical parts. They are mainly used in shock absorbers and vibration dampers as well as in hydraulic systems with the MR fluid as the hydraulic medium. In the squeeze mode the distance between two parallel plates changes, which causes a squeeze flow. In this mode relatively high forces can be achieved, and it is especially suitable for the damping of vibrations with low amplitudes up to one millimetre and high dynamic forces (e.g. in machine tools).

### 3.3.2. Magnetic conception

In energy transducers based on MR fluids the essential drive parameter is the field $B_{\mathrm{MRF}}$ which reacts in the magnetorheological fluid. As the maximum shear stress transmitted by an MR fluid is limited by its saturation magnetization, the maximum $B_{\mathrm{MRF}}$ value should be at the beginning of saturation effects in the MR fluid. The flux guide has to operate below its magnetic saturation; then the magnetic resistance of the circuit is almost exclusively determined by the working spaces of the MR fluid, as MR fluids have a relative permeability of $\mu_r < 10$. This value is of the same order of magnitude as that of Terfenol; thus, statements and results of Section 2.3.2 (including Figs. 2 and 3) can be adopted by analogy.

### 3.3.3. Rheological conception

Clutches and brakes based on MR fluids in the shear mode can be implemented according to two different construction types: disc clutch and cylindrical clutch. Compared to the cylindrical clutch the disc clutch has a smaller construction volume and a lower weight which can be further reduced by designing the clutch for lower maximum inductions in the MR fluid. Thus, also the electrical control power of the disc clutch decreases. However, in the case of the disc clutch it has to be considered that at high revolution rates of the clutch and at low magnetic flux densities the suspended particles move outwards through the MR fluid gaps creating a depletion area of particles in the gaps [11].

Dampers with MR fluids for higher vibration amplitudes are mainly built up in the flow mode, integrating the valve with MR fluid in the piston, or in the case of double tube dampers in the bypass. When designing the valves with MR fluid in particular at high piston velocities it has to be taken into account that the time spent by the suspended particles in the magnetic field of the MR fluid valve must be sufficiently long. However, with the aid of the valve length also a determined damper behaviour depending on the piston velocity can be adjusted, e.g. first, at low piston velocities the damping force increases with growing speed, then at high velocities it changes into an almost constant range [12].

Dampers for low vibration amplitudes are preferably built up in the squeeze mode in particular at high force amplitudes. Due to low vibration amplitudes dampers in the squeeze mode frequently display a viscoelastic behaviour. The elastic vibration components determine among other things a decrease of the energy dissipated by the damper. A reduction of the elastic vibration components can be implemented by an electrical control adapted to the damper movement. A possible application field of squeeze flow dampers are machine tools in which the resonance ratios that occur with high force amplitude can be reduced.

## 3.4. Application examples

### 3.4.1. Vibration dampers

One of the first MR actuator products was a vibration damper for driver seats in trucks or construction machinery operating in open terrain. The controllable vibration damper in Fig. 8a serves for the decoupling of the driver's seat and the chassis of the automobile; the damping behaviour of this system is shown in Fig. 8b. Without an electrical control, only a slight basic damping is effective, which results in a considerable resonance ratio at 2.5 Hz and a good vibration isolation at frequencies $f > 4$ Hz. With a very hard damping the resonance peak can almost be eliminated; this, however, determines a poorer vibration isolation at frequencies $f > 6.5$ Hz. An adaptive vibration damping is possible, when the damper with MR fluid is electrically controlled depending on the driving situation: the high amplitudes of the resonance oscillations are damped, and the good vibration isolation at frequencies $f > 4$ Hz are preserved [13].

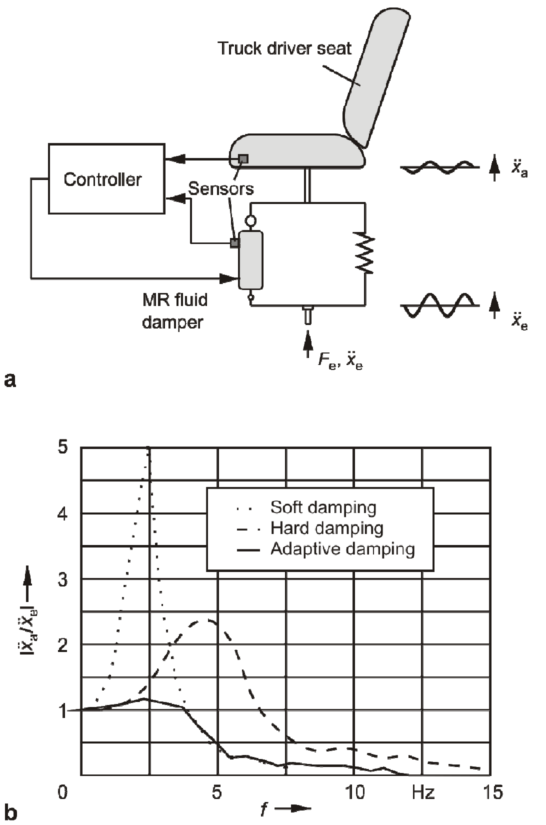


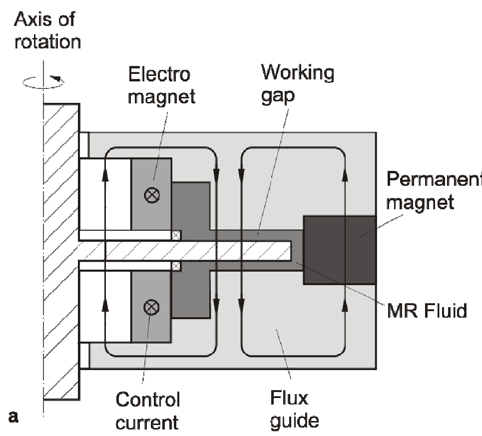

*Fig. 8. MR fluid damper for driver seats: (a) system configuration; (b) vibration amplitude response [9]*

### 3.4.2. MR Actuator for a Vehicle Door Assistant

Easy operation of vehicle doors is an important distinguishing feature for the competitiveness of car producers. Recently, several approaches are presented in order to assist the entry for passengers by means such as door protection, variable detent position or a exit assisting function. A semi-active actuator is sufficient for such supporting functionalities, since the door is basically moved and guided by the user, while the realised functions are designed for assistance only. Actuators based on MRF are predestined for the motion control of automotive doors due to their high dynamical and almost linear generation of force.

Beside requirements like a good controllability and reproducibility of torque the actuator must offer a certain holding torque without electrical feeding, in order to fix the automotive door in any position for a long time, especially when the engine is turned off. Since the rotatory MR actuator should be integrated vertically between the hinges of the door, strong limitations of space as well as weight must be considered, too. The proposed rotational MR actuator is based on the direct shear mode using several circular working gaps filled with magnetorheological fluids and interfused by the operating magnetic field.

The approach in Fig. 9a deals with an arrangement of a permanent magnet and an electromagnet by superimposing both magnetic fields within the working gaps [14]. The current-free torque is realised by the permanent magnet, while by an appropriate feeding of the electromagnet the torque can be decreased due to its opposing field or increased by applying a field in the same direction as the field from the permanent magnet. Thus, a continuous actuator torque for the door's braking can be adjusted by changing the feeding current from a maximum negative value towards its maximum positive quantity, see Fig. 9b.



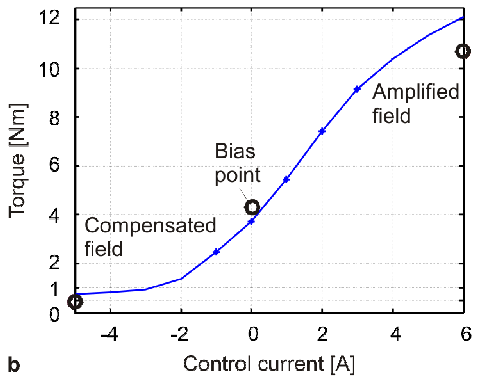



*Fig. 9. Vehicle door assistant: (a) basic structure (with amplified field), (b) operating characteristic [14]*

This described operating method includes three characteristic working points for the considered application: First, less actuation force for changing the door's position is achieved when the field of the electromagnet compensates the field of the permanent magnet. Second, the current-free torque for fixing the door is guaranteed by the permanent magnet ("bias point"). Third, maximum torque, e.g. for the exit assisting function, is generated, when both fields are in accordance and reach their maximum value.

### *3.5. Comparison between ER and MR fluid actuators*

Electrorheological (ER) fluids have also been known since the 1940s and show rheological properties similar to those of MR fluids. Whereas, MR fluids react to magnetic fields, ER fluids change their flow resistance when influenced by electric fields. The electric field strength for the control of ER fluids usually amounts to some kV/mm. The ER effect is also reversible, and the response times of ER fluids to changes in the electric field also lie within a few milliseconds.

The main differences between actuators based on ER fluids and those based on MR fluids result from their different interactions with electric and magnetic field [8]:

- Actuators with MR fluids are current driven; for the control of the field coil voltages below 10 V and currents below 2 A can suffice under quasi-static conditions. Actuators with ER fluids are voltage-driven; they require high voltages (some kilovolts) at a low current flow (few mA). The maximum driving power of comparable ER and MR fluid energy transducers is similar at temperatures < 80°C and lies within a range of some watts.
- MR fluids are less sensitive to soiling (foreign bodies, including air bubbles) than ER fluids. However, both fluids are hygroscopic and thus should be protected from air moisture as that determines a tendency to particle coagulation.
- The base viscosity at room temperature of common ER fluids with a value below 100 mPa·s is lower than in most MR fluids, hereby ER fluids determine considerably lower flow losses in hydraulic circuits. However, the shear stresses transmitted with an MR fluid are higher by one order of magnitude than in the case of ER fluids. With ER fluids shear stresses up to approx. 10 kPa can be transmitted, whereas in the case of MR fluids shear stresses of 100 kPa have been measured.
- The electrical conductivity of ER fluids increases with rising temperature according to a power function. Thus in a number of applications (e.g. clutches, brakes, dampers in the shear mode) an upper temperature limit results not from the chemical stability of the ER fluid but from the high electrical driving power of the ER fluid energy transducer. A comparable behaviour does not exist in MR fluids. Common MR fluids can be used with temperatures of 150°C and more.
- In ER fluids, smooth particles can be suspended which have a considerably lower density than those employed in the iron or ferrite particles in the case of MR fluids. In this way in ER suspensions a reduction of abrasion with a low tendency to sedimentation and a low base viscosity can be achieved. So-called homogeneous ER fluids in which an increase of the dynamic viscosity occurs in the electric field show neither sedimentation nor abrasion. However, their ER effect is lower.

Generally, both MR and ER fluids can be employed in actuators with controllable fluids. The decision in favour of one of the fluids is determined by the requirements of the single application. That means that the actuator to be implemented with its marginal conditions leads to the type of fluid to be adopted.

## 4. Actuators with magnetic shape memory alloys

Materials have existed for a few years, which unlike more widely known thermally actuated shape memory alloys, can be modified in shape by means of magnetic fields. Although these magnetic shape memory alloys are still in stages of research and development, they are also discussed in the following since they are likely to play an important role in future adaptronic applications.

### 4.1. *Physical effect*

The first report of large magnetically induced strain in a single crystal is dated back to 1968. A few years later, a giant 3.4% reversible strain was reported in the magnetically hard direction of a Dysprosium single crystal subjected to a magnetic field of 8000 kA/m at 4.2 K [15]. To date, the exact mechanism of large reversible strains achieved through the application of an external magnetic field is not thoroughly understood. It is proposed that this can either be due to structural transformations in martensite phases, twin variant conversion and reorientation, or by the magnetic force generated due to non-uniform magnetic field, which can deform the martensite and induce twin variant rearrangement. The key to obtaining high strains is to cut the samples so that the twin boundaries are aligned at 45° to the sample axis.

### 4.2. *Materials*

Currently, NiMnGa and some Fe-based magnetic shape memory (MSM) alloys seem to be the most promising materials. Due to the reorientation or detwinning of the magnetic martensite variants with twinned structures, the materials exhibit huge strokes of up to 10% at room temperature, triggered by a magnetic field in the presence of a mechanical preload as in Terfenol-D and operating at frequencies up to the kilohertz range. The MSM effect in these alloys is observed when the material is in its martensite state. Therefore, its crystal structure has been systematically studied along with transformation temperatures and the Curie temperatures. High transformation temperatures and Curie temperatures are essential requirements in increasing the operating temperature range of MSM materials. Shifts in the NiMnGa composition can significantly affect the maximum operating temperature of the MSM material. Till now, the MSM effect has been observed at temperatures up to 65°C.

MSM material can be made to change its shape in different ways, such as to elongate axially, bend or twist. So far, actuators developing linear axial motion are most common. Usually, the material is pre-stressed. The corresponding *S(H)* curves are presented in Fig. 10. MSM materials may also find potential application in the form of ribbons and composites. In composite materials MSM alloy in plate, fibre or powder form is combined with a polymer matrix. Accordingly, the selection of a suitable polymer matrix, which will minimize potential reaction and will accommodate the strain of the MSM alloy, is of prime importance. MSM composites offer the advantage that less bulk material is needed and higher frequencies can be achieved.

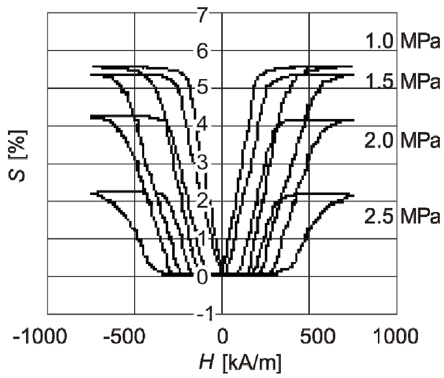



*Fig. 10. Magnetic field induced strain S vs. magnetic field H of a NiMnGa MSM material*

### 4.3. *Design of actuators with MSM*

The basic structure of an MSM actuator is presented in Fig. 11. Coils are needed to generate the magnetic control field subjected to the MSM element, and ferromagnetic flux guides (“cores”) are used to increase and concentrate the field. A helical or disk spring guarantees mechanical prestress and makes sure that the MSM element returns to the initial state after each displacement.

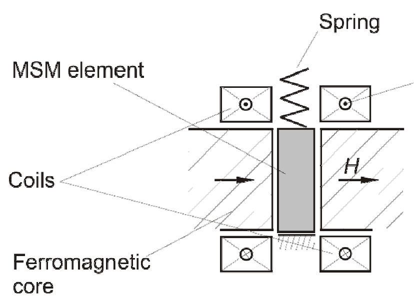



*Fig. 11. Basic structure of a linear MSM actuator*

The basic feature is that the magnetic field *H* is applied perpendicularly to the MSM element axis. The magnetic circuit to drive the element must be designed to achieve a field strength of 300…500 kA/m at the surface of the sample. Lower magnetic fields can be applied when the so-called twinning stress of the MSM material is reduced. This has a direct effect in reducing the size, efficiency, and power consumption of the actuator.

The magnetic field strength is roughly dependent on the electrical current. Therefore, MSM actuators are best driven with current sources. If connected to voltage sources, a time delay in the operation occurs. Biasing permanent magnets (PM) are used to increase the field strength and reduce the power consumption of the coils. Beyond that PMs define the magnetic operating point, so the mechanical frequency of the device can be the same as the electrical frequency of the sinusoidal excitation.

The pre-stress on the sample is usually between 0.5 and 1 MPa. Proper pre-stressing is crucial in optimum actuator operation, as it affects the actuator's force and stroke capability. Both the pre-stress as well as the load the actuator is working against must be taken into account. The optimal load to achieve the maximum magnetic field induced strain is about 1…1.5 MPa. However values of 2 MPa or higher can be reached with proper alloy development and low twinning stress materials.

Hysteresis exists in the relationship between the strain and the actuator input current, as well as between the strain and the stress. Hysteresis is caused by the internal properties of the MSM material. The hysteresis of the MSM material has to be taken into account in the design of a specific MSM actuator application. The hysteresis dampens unwanted mechanical vibrations and higher harmonics of current and in that way eases the control of the application. In addition, it reduces vibrations and overshooting of the MSM actuator upon rapid shape changes of the element.

As a consequence of the non-linear properties, an iteractive procedure is necessary when selecting the appropriate dimensions of an MSM element. A preliminary value of the cross-sectional area and the length   can be determined from

$$A_{cross} = \frac{F_{\mathrm{b}}}{\hat{\sigma}_{mag} - 2\sigma_{\mathrm{TW}}}, \quad l_z = \frac{2s}{\varepsilon_0},$$

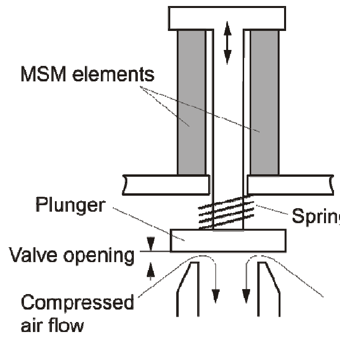
where $F_{\mathrm{b}}$ and $s$ are the blocking push force and the stroke of the actuator, $\varepsilon_0$ is the free strain, $\sigma_{\mathrm{TW}}$ is the twinning stress at half the free strain of the MSM material and $\hat{\sigma}_{mag}$ is the maximum value of the magnetic field induced stress [16].

### 4.4. Application examples

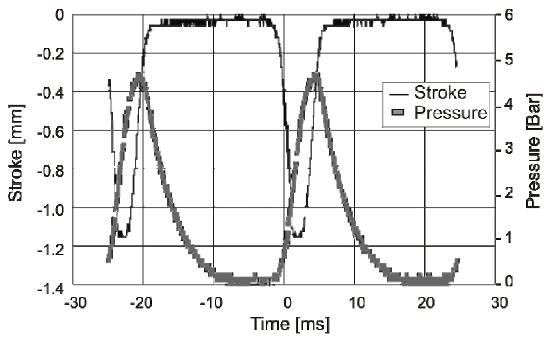
MSM material, which is suitable for the construction of an actuator, has been available in numbers necessary for research in laboratories only since the turn of the century. This is the reason why there are no successful commercial applications of MSM actuators yet. Consequently, the following examples are just demonstrations.

#### 4.4.1. Valve drive

An MSM actuator was used in a proportional valve to control airflow. A simplified construction of this valve is given in Fig. 12a. Fig. 12b demonstrates the valve opening and closing the airway at a frequency of 40 Hz. In the valve application, the fast response (< 4 ms) of the MSM actuator is utilized. Because the material shape change is large the valve opening is also large without displacement amplification. This makes the structure more robust and easy to manufacture. The magnitude of valve opening can be controlled via the coil current [17].




**a**




**b**

*Fig. 12. Principle of a proportional MSM valve: (a) basic structure,(b) pressure and stroke of the valve as a function of time [17]*

By means of other actuator designs referred to in the literature, forces of up to 1 kN were realised, but generally the force depends on the actuator construction and can be much higher. Fatigue test results that showed that the stroke of the actuator does not decrease after 200 million cycles of the alternating magnetic field reveal that MSM actuators can operate long times without significant fatigue of the actuating element.

#### 4.4.2. Multistable actuator

The device in Fig. 13 is a push-pull actuator: two pieces (A and B) of MSM material act in opposite directions. The magnetic fields are created by coils and concentrated by ferromagnetic cores. The overall length of the device is kept constant by using non-ferromagnetic material. The mobile part of this actuator is in the middle part between the two MSM samples [18].

The principle is the following:

a) At first, $MSM_A$ contains mainly $M_1$ martensite and $MSM_B$ contains mainly $M_2$ martensite. The $M_1$ martensite is larger in the x-direction than the $M_2$ martensite.

b) A current pulse in the A coil creates a magnetic field through the $MSM_A$ sample in the y-direction. The $M_2$ martensite fraction increases (the $MSM_A$ expands and the $MSM_B$ contracts) producing a strain in the material. The mobile part moves to the right.

c) No current is then applied. Due to the hysteretic behaviour of the MSM, the displacement of the mobile part is maintained.

d) A current pulse is applied in the B coil to obtain a displacement to the left, and so on.

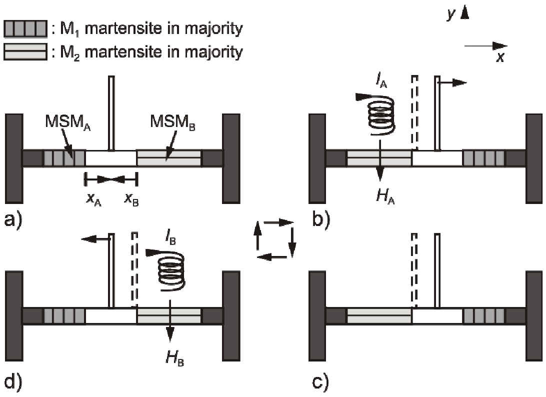



*Fig. 13. Principle of a multistable MSM actuator [18]*

During this procedure, two stable positions of the mobile part are obtained. Furthermore, a stable position depends on the magnitude and the time duration of the current pulses. In fact, an infinite number of stable positions can be reached. This actuator is then multistable. In customary MSM actuators (i.e. with spring to obtain reversible motion), the current must be applied continuously. With the multistable actuator, current losses due to the Joule effect in the copper coils are decreased, and this also permits a reduction of the coils size.

### *4.5. Comparison between MSM actuators on the one hand and magnetostrictive as well as SM actuators on the other hand*

In future, many of today's actuators based on giant magnetostrictive materials or thermally activated shape memory (SM) alloys could be replaced by MSM actuators by means of respective progress in material development. Therefore, it is helpful, if the user compares the characteristics of these actuator materials. Some differences are particularly pointed out in the following paragraphs.

- Giant magnetostrictive materials can deliver strains on the order of 0.1%; MSM (and SM) alloys deliver strains almost as large as 10%.
- Magnetostrictive material can do work against a large load under a small applied field; MSM alloys can deliver large strains for a large applied field, but support only small loads.
- The actuation energy densities of magnetostrictive and MSM materials are almost equal but two orders of magnitude lower than thermally actuated SM alloys.
- The blocking stress of MSM alloys (2…3 MPa) is significantly smaller than the one of thermally actuated SM alloys (150…200 MPa).
- MSM alloys have large strains like classical SM alloys, but can provide a 100 times shorter time response.
- MSM alloys are also thermal shape memory alloys. Thus, any design taking advantage of MSM actuation has to carefully control the MSM element's temperature.

Provided the operating temperature range of MSM material will be achieved in future, the potential of MSM technology will be extended, e.g. to automotive applications. Also the size of the core and coils needed for field generation have to be taken into account. Hybrid actuation by combined stress, magnetic as well as temperature fields may also become an interesting development task.

## 5. Conclusion

Actuators on the basis of giant magnetostrictive materials and magnetorheological fluids are the magnetic counterparts of the better known piezoelectric actuators driven by electric fields or actuators with electrorheological fluids. Both types of solid-state actuators on the one hand and controllable fluids on the other hand have comparable actuator-relevant data (forces, displacements, switching times, etc.). In this respect magnetic-field driven actuators, for example, always represent interesting alternatives, when the use of piezoelectric actuators or actuators with ER fluids seems unfavourable or impossible because of the operating or surrounding conditions resulting from a special application.

Actuators based on magnetic shape memory alloys are currently still in stages of R&D as opposed to actuators consisting of magnetostrictive and magnetorheological fluids which are considered established. Regardless of the different stages of development of actuators driven by magnetic fields, it generally applies that all components of the magnetic circuit, namely the active material, the flux guide including the exciter coil, and the permanent magnets exhibit a nonlinear behaviour and influence each other. Furthermore, strong interdependences exist with the driving power amplifier and the mechanical load, so that always the system as a whole has to be examined and optimized in order to achieve best possible results.

The current state of development of the unconventional actuators described here is reported regularly in the form of review presentations at the biennial "Actuator" conference in Bremen. (The next one takes place June 9th-11th 2008.)

References to sources of the active materials discussed here can be found for example in the internet under the following addresses.

Magnetostrictive materials (as of April 2008):

www.etrema-usa.com
www.txre.net
www.materitek.net

Magnetorheological fluids (April 2008):

www.mrfluid.com

www.isc.fraunhofer.de
Contact: Dr. Böse;
email: boese@isc.fhg.de

www.inorganics.basf.com
Contact: Dr. Kieburg;
email: christoffer.kieburg@basf.com

www.fuchs-europe.de
email: Rolf.Luther@fuchs-oil.de

Magnetic shape memory alloys (April 2008):

www.adaptamat.com

www.msm-krystall.de
email: arno.mecklenburg@msm.krystall.de

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