FAST ACTING MAGNETIC ACTUATORS FOR AUTOMOTIVE APPLICATIONS

Veit Zöppig, Eberhard Kallenbach, Frank Beyer and Jens Baumbach
Steinbeis Transferzentrum Mechatronik, Ilmenau, Germany
Tom Ströhla and Matthias Kallenbach
Technische Universität Ilmenau, Germany

Introduction
Magnetic reversal stroke actuators are increasingly applied in modern combustion engine concepts in order to operate valves with extremely small switching times. This leads to significant reductions of the fuel consumption, the exhaust gas emissions and to an improvement of the functional quality and the drivers comfort. The main requirements on these valves are extremely small switching times (0.05 ms to 3 ms), strokes in the range of some millimeters, good controllability, high robustness, small power consumption and small volume and weight. Due to the strong interactions between the magnetic, mechanic, electronic and control sub-systems such magnetic valves are mechatronic systems. The paper describes their development and optimization process using a model based systematic approach according to standard VDI 2206 [8].

Drive principle choice
The design of mechatronic systems is characterized by three phases: system design, domain specific design and system integration. The system design is characterized by the selection of the optimal elements. Obviously the actuation principle determines the main functionality of the here discussed valves. The actuation of valves can be described as an alternating motion with variable dwelling times (see Fig. 1). This actuation type can in principle be implemented with many different actuator principles. If, however, at strokes of 0.1 to 25 mm very short switching times from 0.1 to 3 ms – depending on the application – are required only few actuators are available. Below the Millimeter range for injection valves piezo drives dominate but in the Millimeter range for electromechanical valve trains and throttle controls electromagnets are the first choice.

![Fig. 1 Alternating motion with variable dwelling times (t₁ pickup time, t₂ drop-out time, t₁₁ dwelling time in initial position, t₁₂ dwelling time in end position, t₂ cycle time, δₕ normal stroke)](image)

If both short switching times and high switching frequencies are required, the power losses prevent the use of conventional solenoid actuators. A simplified calculation example shows the following results for a conventional actuator. Assuming a spring constant of 500 N/m, a moving mass of 30 g, a required pickup time of 2 ms and a stroke of 25 mm the needed accelerating force is 380 N. For this force one has to apply a maximum current of 122.5 A. Thus, electrical power losses of 15 kW result.
This simple example shows the need for principles with an improved energy management like resonant actuators. By the application of these types of actuators an effective reduction of the switching time can be achieved at low power losses. The armature and the retracting spring form a spring-mass system in resonant actuators. The armature motion is dominated by the characteristic frequency of the spring-mass system. The solenoids only serve the purpose to catch and hold the armature in the two end positions of the actuator. A further advantage is that the switching times less depends from the operating conditions (see Fig. 2).

![Diagram of resonant actuators](image)

**Fig. 2** Basic principle of resonant actuators (left) and force-displacement-characteristic of a resonance actuator (right) ($F_H$ holding force, $F_F$ spring force, $W_p$ potential energy of attracted armature, $W_{mech}$ max. mechanical useful energy of a single solenoid)

**Actuator optimization process**

In order to realize the desired short switching times nearby the boundaries of the physics, all major influences on the dynamics have to be taken into account during the actuator optimization process. The following conditions must be fulfilled: optimal selection of the basic shape of the magnetic actuator (see Table 1), over-excitation until saturation of the magnetic circuit, advanced energy management (energy storage elements should be integrated in the actuator, direct drive with volume-integration).

**Table 1 Basic shapes of resonant actuators**

<table>
<thead>
<tr>
<th>Construction of U-magnet</th>
<th>Construction of U-magnet</th>
<th>Construction of E-magnet</th>
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<tr>
<td>particularly suitable for:</td>
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<tr>
<td>• low spring rate</td>
<td>• good trapping</td>
<td>• fast switching times</td>
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<tr>
<td>advantages:</td>
<td>advantages:</td>
<td>advantages:</td>
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<tr>
<td>• high frequency</td>
<td>• high frequency</td>
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<tr>
<td>• adapted force vs. stroke characteristic curve</td>
<td>• simple assembly</td>
<td>• symmetrical load</td>
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<tr>
<td>disadvantages:</td>
<td>disadvantages:</td>
<td>disadvantages:</td>
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<tr>
<td>• asymmetrical load</td>
<td>• asymmetrical load</td>
<td>• mechanical stop</td>
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<td>• mechanical stop</td>
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<td>• expensive coil technology</td>
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The application of a design flow based on a network model approach with optimization tools is the key to match all the different static and dynamic requirements during the design process (see [4] for details).
Control system

In comparison with other magnetic actuator types the resonant actuator system is more robust but the current-controllability is reduced. This defines challenging requirements on the time resolution and precision of the control system. In the case of typical automotive applications like valve train valves the control areas shown in Fig. 3 can be defined. The stronger the load changes the better the system needs to be controlled. Due to cost restrictions the control must be achieved without a position sensor. All information needed for the control (position, velocity) must be extracted from other system signals or their derivatives, e.g. the current signals.

![Control areas of the armature motion](image)

The electronics need for the control of multiple actuators must be embedded in the combustion engine management with distributed networking controllers. The semiconductor industry offers dedicated controllers for these kinds of applications. The upcoming hybrid controllers (MCU with DSP kernel and motion control oriented peripherals, specified for the automotive temperature range) are well suited for these kinds of applications. Fig. 4 shows a block scheme for a realized control system for pulse charging valves [1]. One controller is used in order to operate four flap valves (it means 8 coils) for pulse charging. The system integration is achieved over a high-speed CAN bus connection. For a synchronous behavior to the engine operation a direct crankshaft sensor signal is used.

![Control block scheme for a four valve control system based on MC56F8346 hybrid controller](image)
Application example

The above described resonant actuation principle was used for different automotive applications in the last years, e.g. airpulse charging valve, full variable valve train and injection valve.

In cooperation with Mahle Filtersysteme GmbH an airpulse charging valve was developed [1]. By the well defined and synchronized opening or closing of a flap valve situated in the intake manifold of combustion engines a dynamic charging can be realized. This leads to higher torques at lower rotational frequencies, as well as to reduced fuel consumption (see Fig. 5).

Such a flap valve can be used for some other effects with. These are the temperature control charging (either heating or cooling), the load adaptation without throttle valve and the selective cylinder switch-off. The realized prototype shows switching times of 2 ms at a movement range of 45° (i.e. ± 22.5°). The control electronics take advantage from an increased intermediate circuit voltage (up to 60 V) at a standard vehicle power supply (12 V). This is achieved by an energy recovery circuit. Thus, a sufficient over-excitation becomes feasible.

The ongoing testing of the valves with different engine types will deliver further experimental results in the next few months.

References