Analysis of the performance of fast acting miniature solenoid actuator for digital valves

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Digital hydraulic valve systems consist of several on/off valves connected in parallel. These valves require a small, fast acting and energy efficient actuator. This article studies the performance of five soft magnetic materials for the magnetic circuit of a solenoid actuator, as well as the effect of the number of coil turns and the size of the coil on the response time and the energy consumption of the actuator. The studied actuator is utilised as the pilot actuator of a miniature valve. The performance is evaluated with finite element simulations and experimental tests. A response time of less than 0.5 ms is achieved with a 0.4 mm armature movement.

Keywords: Digital hydraulics, electromagnetic actuator, finite element method

Target audience: Mobile Hydraulics, industrial hydraulics

1 Introduction

Parallel digital hydraulic valve systems are still in an early stage of their development, but in several cases they have already proven to produce superior results compared to traditional technologies. The basic building block of a digital valve system is an on/off valve. A digital flow control unit (DFCU) consists of several on/off valves connected in parallel and it is the equivalent of one control edge of a proportional valve. Building a high performance DFCU for a digital valve system requires approximately seven fast on/off valves.1 The valves must be integrated into a small package in order for the digital valve systems to be competitive against traditional spool type valves. The currently sold commercial on/off valves are not well suited to be used in digital valve systems, since the valves are generally too large and their response time is poor. Therefore, it is necessary to develop smaller and faster on/off valves.

Miniature valves designed for a digital valve system have been developed previously, however, these valves are directly actuated by a solenoid and therefore their flow capacity is limited.2/3 The author et al. have developed a pilot actuated miniature valve with a larger flow capacity4 and this research aims to improve the properties of its pilot actuator. This paper investigates the factors affecting the response time and the energy consumption of the pilot actuator, which is a very small plunger type solenoid.

2 The actuator

Figure 1 shows the structure of the actuator. The magnetic circuit of the actuator consists of the moving armature, the lower body, which contains the bore where the armature moves, and the frame which houses the coil. When the solenoid is energised, the induced magnetic force moves the armature upwards. When it is de-energised, the armature is returned to its original position by a return spring.

Since the actuator opens a hydraulic valve, its movement must be large enough to open a suitable flow channel. The smallest practical movement has been estimated to be 0.2 mm. This is large enough so that the valve should not get blocked with the contaminants in the hydraulic fluid. However, a larger movement would increase the flow capacity of the pilot valve and reduce the manufacturing tolerances.
The coil is the largest part of the actuator and thus it limits the minimum distance between the actuators, when several valves are integrated in the same manifold. Therefore, the goal of this research is to design an actuator with a coil diameter of approximately 10 mm. This allows placing four actuators side-by-side within the 50 mm width limit of Cetop 3 subplate. The closing and the opening response times of the actuator should be less than 0.5 ms and the energy consumption during the opening phase as well as during the holding state should be as low as possible. In addition to the actuators, the control electronics of the valve system are preferably integrated to the same package. This requires compact electronics, which often cannot handle large currents. Therefore, the actuator should also be designed to function properly with as low current levels as possible.

The maximum operating frequency of a solenoid actuator is usually limited by excessive heating and thus the heat losses in the actuator should be minimised. There are two main ways in which losses are produced in a solenoid actuator; resistive heating in the coil and resistive heating due to eddy currents in the material of the magnetic circuit. The resistive heating power $P$ in the coil can be calculated with Equation (1), where $R$ is the resistance of the coil and $I$ is the coil current. The resistance of the coil depends on the resistivity of copper $\rho_c$, the area of the wire cross section $A_w$ and the length of the wire $l_w$ according to Equation (2).

$$P = RI^2$$  \hspace{1cm} (1)

$$R = \frac{\rho_c l_w}{A_w}$$  \hspace{1cm} (2)

The force generated by the actuator is induced by the magnetomotive force $F_m$, which can be calculated with Equation (3) where $N$ is the number of coil turns. Equation (1) shows that in order to reduce the energy loss from the resistive heating with a static current, e.g. during the holding state, the resistance and the current of the coil should be minimised. However, when the current is reduced, the number of coil turns must be increased in order to maintain a constant magnetomotive force. When the dimensions of the coil are constant, increasing the number of coil turns on the other hand increases the resistance of the coil and this counteracts the power loss reduction gained by reducing coil current. Therefore, when the dimensions of the coil and the magnetomotive force are constant, the resistive heating of the coil is also constant regardless of the ratio between the coil turns and the coil current. Thus, the number of coil turns can be selected to minimise the coil inductance, which delays the response of the actuator, or to minimise the holding current without affecting the resistive heating of the coil during the holding phase. In addition to the coil dimensions, the resistive heating is affected by the fill factor, which describes how much of the volume of the coil is filled with the copper of the wire.

The dimensions of the coil also affect the reluctance of the magnetic circuit. When the size of the coil is reduced, the path of the magnetic flux around the coil shortens, which reduces the required magnetomotive force to induce a certain force. This consequently reduces the current requirements.
The switching energy $E_{\text{switch}}$ during the opening or the closing phase of the valve can be calculated by integrating the electrical power input to the coil with Equation (4) where $U$ is the voltage across the coil.

$$E_{\text{switch}} = \int_{0}^{t_{\text{switch}}} P(t)dt = \int_{0}^{t_{\text{switch}}} U(t)I(t)dt$$

Because the response time of the actuator is less than a millisecond, the dynamic electromagnetic effects are a major factor in delaying the response. The most important phenomena affecting the response time are the inductance of the coil and the eddy currents formed in the core material of the solenoid. Especially the amount of eddy currents formed during the switching of the actuator is dependent on the material and the geometry of the magnetic circuit. Reducing the length of the magnetic flux path reduces the volume where the eddy currents are formed, which reduces the heat generation during the switching of the actuator.

In high speed electromagnetic actuators, laminated metal is often used as the material of the magnetic circuit in order to reduce the eddy currents. Laminated material is, however, difficult to apply in very small dimensions and axial symmetric geometry and therefore four homogenous metals and one soft magnetic composite material were selected for this study. Table 1 displays the properties of the materials and Figure 2 displays the relation between the magnetic flux density and the magnetic field strength (BH curve) for each material. Since the BH curve of Stavax was not available, the BH curve of similar AISI 430 is used instead in the simulations. The BH curve of AISI 12L14 was measured at Aalto University and the curves for AISI 430, Pure iron and Permendur were taken from the material library of Finite Element Method Magnetics- simulation program. An ideal material for the magnetic circuit would have zero electrical conductivity, infinite permeability and a high saturation magnetic flux density which does not limit the generated magnetic force.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical conductivity [MS/m]</th>
<th>Magnetic flux density @ 4000 A/m [T]</th>
<th>Saturation magnetic flux density [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stavax ESR</td>
<td>1.82</td>
<td>1.35</td>
<td>1.7</td>
</tr>
<tr>
<td>Pure iron</td>
<td>10.44</td>
<td>1.80</td>
<td>2.2</td>
</tr>
<tr>
<td>Permendur</td>
<td>2.5</td>
<td>2.22</td>
<td>2.4</td>
</tr>
<tr>
<td>Somaloy /5/</td>
<td>0.0038</td>
<td>1.23</td>
<td>1.9</td>
</tr>
<tr>
<td>AISI 12L14</td>
<td>5.75</td>
<td>1.82</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 1 The properties of the materials.

![Figure 2 The BH curves used in the simulations.](image-url)
Stavax ESR is a modified AISI 420 martensitic stainless steel with a good corrosion resistance. It has a low electrical conductivity but also a comparably low saturation magnetic flux density. AISI 12L14 is a free machining low carbon steel with good magnetic properties but poor corrosion resistance. Pure iron has an excellent permeability and saturation magnetic flux density, but its electrical conductivity is very high. Permendur is an alloy with 49 % iron, 49 % cobalt and 2 % vanadium. It has the highest saturation magnetic flux density of the tested materials and its electrical conductivity is quite low, however, it is difficult to machine and expensive. Somaloy is a soft magnetic composite material, which is manufactured by compressing insulated soft magnetic powder /5/. It has mediocre magnetic properties, but its electrical conductivity is extremely low and therefore it is the least affected by eddy current delay.

The frame of the actuator contains the major part of the magnetic circuit and thus it also has the most significant impact on the response of the actuator. Therefore, in this study only the material of the frame is changed in the tests and the simulations.

3 Methods

3.1 FEM simulation

The solenoid actuator is modelled with Comsol Multiphysics 4.3b finite element simulation program. A 2-dimensional axisymmetric model is used for the geometry. The electric and magnetic fields are modelled using the Magnetic Fields physics interface from the AC/DC-module /6/. The nonmagnetic areas of the geometry, e.g. space filled with air, fluid or nonmagnetic metal, are modelled as air. The magnetic areas of the geometry are divided into three separate domains; the frame, the armature and the body.

The coil is simulated as a Multi-turn Coil Domain. The domain is a homogenous area where the current density $J$ is calculated according to Equation (5) where $A_{coil}$ is the area of the domain. The resistance of the coil is calculated with Equation (2). The diameters of the wires in the simulations are defined to be the same as in the prototype coils.

$$J = \frac{NI}{A_{coil}}$$  \hspace{1cm} (5)

The coil is linked to a simulated electric circuit which consists of a large capacitor and a lumped resistance representing the current sense resistor, the switches of the electronics and the conductor resistance. This way also the back electromotive force, created by the moving armature, and the saturation of the magnetic circuit affect the current. The capacitance is used to supply the high current during the boost phase and its value is the same in the simulation and in the control electronics of the prototype.

The Moving Mesh -interface is utilized in Comsol Multiphysics to simulate the movement of the armature. Most of the mesh is stationary, however, the mesh of the armature is able to slide vertically along the mesh of the lower body of the actuator. The meshes of the fluid domains above and below the armature compress or expand according to the movement of the armature. Since the height of the fluid domain above the armature would decrease to zero, when the armature collides with the core, the simulations are stopped slightly before the collision.

The mesh consists of approximately 24 thousand elements and it is displayed in Figure 3. The mesh was concluded to be sufficiently refined by increasing the number of elements to 80 thousand without any significant effect on the results. A time step of 5 $\mu$s was used in the transient simulations. This was also determined to be sufficiently small by decreasing the time step to half without significant changes in the simulation results.
The acceleration $a$ of the armature is calculated with Equation (6), where $F$ is the magnetic force calculated by integrating the Maxwell stress tensor over the boundaries of the armature, $F_{k0}$ is the return spring force when the armature is in contact with the core, $k$ is the spring constant ($7 \text{kN/m}$), $z$ is the distance between the armature and the core and $m$ is the mass of the armature ($0.819 \text{g}$). The flow or pressure forces are not taken to account since the experimental tests are done with a dry actuator. The pilot valve, in which the designed actuator is going to be utilised, also has a pressure compensated spool which is not significantly affected by pressure or flow forces.

$$a = \frac{F - (F_{k0} - kz)}{m}$$  \hspace{1cm} (6)

### 3.2 Experimental tests

A test actuator shown in Figure 4 was built according to the CAD model in Figure 1. The lower body, which is made of AISI 12L14, is a fixed part in the test actuator. The frame and the coil can easily be replaced to test different materials, geometries and coils. The diameter of the armature in the test actuator is 5 mm and it is also made of AISI 12L14.

There are six different coils and ten different frames for the actuator. The coils have 80, 140 or 200 turns and there are 3 mm and 6 mm high versions of each coil. The wire diameters and the calculated fill factors for the coils are displayed in Table 2. There are two frames made of each material, each with either 3 mm or a 6 mm deep pocket for the coil. The length of the core is 0.7 mm less than the depth of the pocket. The diameter of the core is 5.2 mm and the outer diameter of the coil pocket is 10 mm.

<table>
<thead>
<tr>
<th>Coil height / turns</th>
<th>80 turns</th>
<th>140 turns</th>
<th>200 turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mm Wire diameter</td>
<td>0.2 mm 35 %</td>
<td>0.17 mm 44 %</td>
<td>0.15 mm 49 %</td>
</tr>
<tr>
<td>Fill factor</td>
<td>35 %</td>
<td>44 %</td>
<td>49 %</td>
</tr>
<tr>
<td>6 mm Wire diameter</td>
<td>0.315 mm 43 %</td>
<td>0.236 mm 43 %</td>
<td>0.2 mm 44 %</td>
</tr>
<tr>
<td>Fill factor</td>
<td>43 %</td>
<td>43 %</td>
<td>44 %</td>
</tr>
</tbody>
</table>

*Table 2 Coil parameters.*
The current for the solenoid is controlled with a full H-bridge, which is supplied with two different voltage levels, 24 V for the boost phase and a low coil dependent voltage for the holding current. With the full H-bridge it is also possible to invert the direction of the coil current, in order to quickly dissipate the remaining magnetisation from the solenoid when it is de-energised.

The position of the armature is measured with Keyence LK-G5001P laser distance sensor and LK-H150 laser head using a 5 μs sample time. The data from the position, current and coil voltage measurements are recorded with a National Instruments PCI-6259 data acquisition card and xPC target software with a 10 μs sample time.

The length of the armature movement was adjusted with a spacer shown in Figure 1 and movements of 0.2 mm, 0.4 mm and 0.6 mm were tested. The force of the return spring was measured to be approximately 8 N when the armature is in contact with the core. Because the return spring is short and stiff, its force decreases quickly as the armature moves further away from the core. When the distance between the armature and the core is 0.6 mm, the spring force is only 4 N. This significantly reduces the delay before the armature starts to move during the opening phase, compared to a situation where the spring force would be nearly constant.

Different positive and negative boost current settings were used for different coils. Also the holding current was adjusted according to the number of coil turns so that the magnetomotive force during the holding phase was always 40 A. Table 3 displays the settings used with each coil.

<table>
<thead>
<tr>
<th></th>
<th>80 turns</th>
<th>140 turns</th>
<th>200 turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holding current</td>
<td>0.5 A</td>
<td>0.29 A</td>
<td>0.2 A</td>
</tr>
<tr>
<td>Opening boost length</td>
<td>0.4 ms</td>
<td>0.5 ms</td>
<td>0.6 ms</td>
</tr>
<tr>
<td>Closing boost length</td>
<td>0.12 ms</td>
<td>0.25 ms</td>
<td>0.3 ms</td>
</tr>
</tbody>
</table>

Table 3 The holding current and the boost settings for different coils.

4 Results and discussion

4.1 Response time

4.1.1 Opening phase

The response time of a spring-return solenoid actuator consists of a delay, when the force of the return spring is still larger than the magnetic force, and the movement time. The response time is defined as the time from the
beginning of the control signal, i.e. connecting the boost voltage to the coil, to the time when the armature has moved 90 % of its movement.

*Figure 5* shows the measured and simulated positions of the armature during the opening phase. The material in this example is Permendur and the trajectories are shown for 0.2 mm and 0.4 mm movements with 80 and 140 turn coils. The simulated trajectories correspond well to the measured trajectories, although the simulated trajectories are slightly delayed compared to the measured ones.

*Figure 5* The simulated and the measured responses for the actuator with a Permendur frame, 80 and 140 turn coils and a 0.2 mm and 0.4 mm movements.

*Figure 6* shows the measured and simulated responses of the actuator with different materials for a 0.4 mm movement, 140 turn coil and 3 mm coil height. It seems that the material selection has only a minor impact on the response time of the actuator. The largest measured response time differences shown in Figure 6 are approximately 30 μs. Differences as small as this can also be caused by variations in the initial orientation of the armature or some other uncontrolled parameter in the test setup. With a 6 mm high coil the differences between the materials are even smaller.

*Figure 6* The simulated and the measured openings of the actuator with different materials.

*Figure 7* shows on the left side the average response times for different materials with all the coils and 0.2, 0.4 and 0.6 mm movements. Somaloy is marginally the fastest material, on average 6 % faster than the slowest material Stavax. Somaloy’s response time is the fastest because only a very small amount of eddy currents form in the material due to its very low electrical conductivity. Stavax on the other hand has the second lowest electrical conductivity of the tested materials, but its saturation magnetic flux density is also low and therefore the actuator cannot produce as large a force as with the other materials. Even though pure iron has a very high
electrical conductivity and therefore much more eddy currents are induced than in the other materials, it is still not the slowest material because of its excellent permeability and high saturation magnetic flux density. The material selection seems to always be a compromise between permeability and electrical conductivity but both of them have to be good in order to gain good results. Other material properties that should be taken into account are corrosion resistance, wear resistance, machinability and price.

Figure 7 displays on the right side the average response times with all the materials with both coil heights, different numbers of coil turns and different movements. The response time seems to increase linearly as the number of coil turns is increased. On average, the response time increases by 41% when increasing coil turns from 80 to 140 and by 76 % when switching from 80 to 200 turns. An increase in the movement of the armature has a smaller impact on the response time. Since the actuator was measured dry in these tests, the impact of the movement length will be greater when the armature is surrounded by fluid, which slows its movement. The actuator was on average 2 % faster with the 3 mm high coils and corresponding frames than with the larger coils. The fastest average response time of 0.24 ms time was achieved with a 0.2 mm movement and an 80 turn coil.

Figure 7 The average measured response times with different materials for movements of 0.2, 0.4 and 0.6 mm. On the right the average measured response times with different numbers of coil turns and movements.

4.1.2 Closing phase

The differences between the response times with different materials during the closing phase are slightly larger than during the opening cycle. Figure 8 shows the armature position with the five materials during the closing phase of the actuator with a 3 mm high 140 turn coil and a 0.4 mm movement. This example represents well also the average response with the other coils and geometries. The materials with a lower electrical conductivity have a faster closing response because they are less affected by the eddy current delay.

Figure 8 The measured position with different materials during the closing phase with a 0.4 mm movement.
4.2 Energy consumption

4.2.1 Opening cycle

*Figure 9* shows the simulated and the measured current during the opening phase for two materials and two coil heights. The materials have clearly differently shaped measured current curves and the simulation model generates their shape fairly well. The maximum current with the 6 mm high coils with 140 turns is approximately 14 A, but with the 3 mm high coils the maximum current is only 7 A. Because of its squared influence on the resistive heating, the lower current reduces heat losses significantly, even though the resistance of the smaller coil is double compared to the larger one.

![Figure 9](image)

*Figure 9 The current during the opening phase with two materials and different height coils with 140 turns.*

The energy consumptions of the opening cycles are simulated and measured in such a way that the boost voltage pulse is high during the whole movement of the armature, and the power is integrated according to Equation (4) with the response time of the actuator as the upper limit. In practise it is not necessary to keep the boost current high until the end of the armature movement, but instead the boost pulse could be shorter to save energy. However, it would be difficult to determine the optimal boost length and therefore this simplified approach was chosen in this study.

The average measured switching energy with different coils and armature movements is displayed in Figure 10. The results show that using a coil with a 6 mm, instead of 3 mm, height can lead to as much as 80 % larger energy consumption during the boost phase. This is caused mainly by the high peak current, which is limited by the higher resistance in the coils with a smaller size and a larger number of turns. Another reason for the higher switching energy with the larger coils is the required larger magnetic circuit, where more eddy currents are generated.
On the left side of Figure 11 is shown a breakdown of the simulated switching energy of the actuator with different materials and geometries during the opening phase. Over half of the energy is converted to heat in the coil. Another significant portion is converted to heat by eddy currents in the magnetic circuit and the size of this portion depends largely on the electrical conductivity of the material. Only approximately 6% of the switching energy is converted to kinetic energy of the armature and about a fifth of the energy is stored in the magnetic field. However, after the switching also the kinetic energy and the energy stored in the magnetic field are converted to heat either in the actuator or in the control electronics.

The right side of Figure 11 shows how the energy consumption builds up as a function of time during the opening phase. The simulations show that the eddy current losses are initially much larger than the resistive losses in the coil. When the magnetic circuit is saturated after approximately 0.25 ms, eddy currents are no longer formed but instead the coil current starts rising faster as the inductance of the coil decreases. Therefore, also the heat production of the coil increases rapidly. It could be beneficial to reduce the coil voltage or to switch to holding voltage at this point to reduce the resistive heating in the coil.
4.2.2 Holding power

Figure 12 shows the simulated required holding power as a function of the generated holding force. There are two curves for each material, one for the 3 mm high coil and one for the 6 mm high coil. The induced force is affected by the material of the magnetic circuit and also by the length of the circuit. The figure clearly shows that the lower permeabilities and saturation magnetic flux densities of Somaloy and Stavax lead to an increase in the required holding power. A smaller coil also requires more power than a larger coil to induce the same force. This is because of the increased resistance of the coil. However, at the same time the magnetic circuit shortens because of the smaller coil and this reduces the reluctance of the circuit, therefore increasing the induced force. The net effect in reducing the size of the coil is still negative regarding the required holding power.

The highest holding force is achieved with Permendur and the lowest force with Somaloy. To induce, for example, a 12 N holding force, an actuator with a 6 mm high coil and a Permendur frame requires 40 mW of power whereas an actuator with Somaloy frame requires 200 mW.

5 Conclusions

This article analysed the performance of five soft magnetic materials as the material for the magnetic circuit of a miniature solenoid actuator. In addition, the influence of the number of coil turns and the size of the coil on the response time and the energy consumption of the actuator was studied. A finite element model of the solenoid actuator was introduced and the simulation results were compared to experimental results. The results from the introduced model seem to be accurate enough to be used in analysing the performance of different actuator structures and materials. FEM simulations can also produce information about quantities which are practically impossible to measure, such as the eddy current density in the magnetic circuit.

In a very small actuator, such as the studied one, the material of the magnetic circuit does not have a large impact on the response time of the actuator. If the material of all the parts in the magnetic circuit would be changed, the effect would be greater than the effect shown in this study, however, it is still far smaller than for example the effect of coil inductance. The material selection has a more significant effect on the energy consumption of the actuator, especially on the required holding power. Low electrical conductivity and high permeability of the material enable a low switching energy. On the other hand, low holding power requires also a high saturation magnetic flux density in addition to high permeability. All of these properties are rarely found in the same material. Soft magnetic composites such as Somaloy are probably the best choice for a switching valve which is
ycled rapidly. For a parallel digital valve system, where valves are not constantly switched, they may not be the most energy efficient solution because of their lower permeability, which increases the required holding power.

The response time of the actuator is largely determined by the inductance of the coil i.e. the number of coil turns. Decreasing the number of coil turns improves the response time, however, it also requires increasing the coil current which leads to increased energy loss. The effect of a large inductance on the response time can on the other hand be negated by increasing the boost voltage accordingly.

Another factor which affects the switching energy and holding power is the dimensions of the coil. The switching energy is reduced by decreasing the length of the magnetic circuit, i.e. the size of the coil, however, this also increases the resistance of the coil, which increases holding power. The compromise between the switching energy and the holding energy consumption depends largely on the average switching frequency of the actuator. It could be beneficial to choose the size of the coils in a digital valve system in such a way that the smaller valves, which are cycled more often, have a coil which uses less energy during switching and the larger, rarely cycled, valves are optimised for low holding power. In other words, the smaller valves should have a smaller coil than the larger valves.

By taking into account these three factors, the material of the magnetic circuit, the geometry of the magnetic circuit and the inductance of the coil, it is possible to design a very fast acting solenoid actuator, while keeping its energy consumption suitable for an integrated digital valve package.

**Nomenclature**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Power input to the solenoid coil</td>
<td>[W]</td>
</tr>
<tr>
<td>R</td>
<td>Coil resistance</td>
<td>[Ω]</td>
</tr>
<tr>
<td>I</td>
<td>Coil current</td>
<td>[A]</td>
</tr>
<tr>
<td>ρc</td>
<td>Resistivity of copper</td>
<td>[Ωm]</td>
</tr>
<tr>
<td>l_w</td>
<td>Length of the coil wire</td>
<td>[m]</td>
</tr>
<tr>
<td>A_w</td>
<td>Area of the cross section of the wire</td>
<td>[m²]</td>
</tr>
<tr>
<td>F_m</td>
<td>Magnetomotive force</td>
<td>[A]</td>
</tr>
<tr>
<td>N</td>
<td>Coil turns</td>
<td>[-]</td>
</tr>
<tr>
<td>E_switch</td>
<td>Switching energy</td>
<td>[J]</td>
</tr>
<tr>
<td>t_switch</td>
<td>Switching time</td>
<td>[s]</td>
</tr>
<tr>
<td>U</td>
<td>Coil voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>J</td>
<td>Current density</td>
<td>[A/m²]</td>
</tr>
<tr>
<td>A_coil</td>
<td>Area of the cross section of the coil</td>
<td>[m²]</td>
</tr>
<tr>
<td>a</td>
<td>Acceleration of the armature</td>
<td>[m/s²]</td>
</tr>
<tr>
<td>F</td>
<td>Magnetic force produced by the coil</td>
<td>[N]</td>
</tr>
<tr>
<td>k</td>
<td>Spring constant of the return spring</td>
<td>[N/m]</td>
</tr>
<tr>
<td>z</td>
<td>Distance between the armature and the core</td>
<td>[m]</td>
</tr>
<tr>
<td>m</td>
<td>Mass of the armature</td>
<td>[kg]</td>
</tr>
</tbody>
</table>
Acknowledgements

This research was conducted as a part of Project DiHy, which is a part of EFFIMA program funded by Finnish Metals and Engineering Competence Cluster (FIMECC).

References


