International Journal of Fluid Power 12 (2011) No. 2 pp. 49-56

GENETIC OPTIMIZATION OF A FAST SOLENOID ACTUATOR FOR A DIGITAL HYDRAULIC VALVE

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ABSTRACT

A fast response electromagnet to actuate a digital hydraulic valve was designed. A computational model of the electromagnet was optimized for fast response and low energy consumption using a finite element method and genetic optimization. The actuator was constructed and attached to a commercial valve body, and measurements were made validate the computational model. The new actuator greatly increased the applicability of the valve in digital hydraulics applications.

Keywords: solenoid on/off valve, fast valve, finite element method, genetic optimization

1 Introduction

The electromagnetic design of a solenoid spool valve has had a little attention while this actuator type has been in use more than one hundred years. Recently, digital hydraulics has placed new demands on the operating performance of such valves. The valve should have a rapid response time while keeping its energy consumption minimal (Linjama, 2008). Both of these properties are greatly affected by the solenoid (an electromagnet), that controls the spool of the valve.

In this paper, a design process is presented for a solenoid actuator, which can be attached to a commercial Parker D1VW NS6 valve body. The design aims for fast response and low energy consumption while complying to the other requirements of its operating environment. The tools of computational electromagnetics are used to model the solenoid, and based on that model, genetic optimization is used to attain the desired properties.

Previously, novel electromagnetic valve actuators have been designed for digital hydraulics, exploiting computational electromagnetics (Uusitalo, 2009; Uusitalo, 2009; Uusitalo, 2007). Genetic optimization has been typically applied to antenna design problems in electromagnetics, but also widely to actuator and machine design coupled to FEM computation (Weile, 1997; Skaar, 2004; Rahmat-Samii, 1999; Rovio, 2010; Dias, 2002). In this work, improvement in digital hydraulics valve performance is sought by coupling FEM computation to genetic optimization.

Genetic optimization and similar methods are well suited for problems where the nature of the objective function is unknown. One only needs to be able to evaluate its value at the points of the search space. In this paper, the values of the objective function are obtained through a finite element method computation. The use of a FEM is justified due to its accuracy in dynamic simulations, as compared to magnetic reluctance circuit models for example. A design can only be practically optimized through modeling if the model is sufficiently accurate.

2 Electromagnetic Dynamical Behavior

The performance of a solenoid valve is governed by the driving electronics and electromagnetic properties of its electromagnet. A detailed discussion on these is found in Uusitalo (2009). The main emphasis is put on the electromagnetic dynamical behaviour of the electromagnet, which needs to be well understood in order to recognize what affects the response time of the valve. In order to move the spool of the valve, the magnetic force acting on the plunger which pushes the spool needs to be larger than the forces acting on the opposite direction of the movement. Therefore, in order to design a fast response valve actuator, one needs to

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This manuscript was received on 15 February 2011 and was accepted after revision for publication on 06 July 2011

generate a sufficiently large magnetic force as fast as possible. A traditional solenoid actuator design, shown in Fig. 1, is taken as the design paradigm.

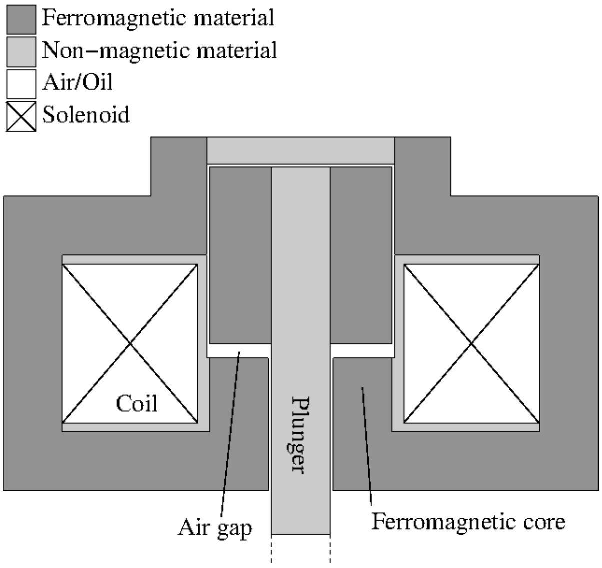
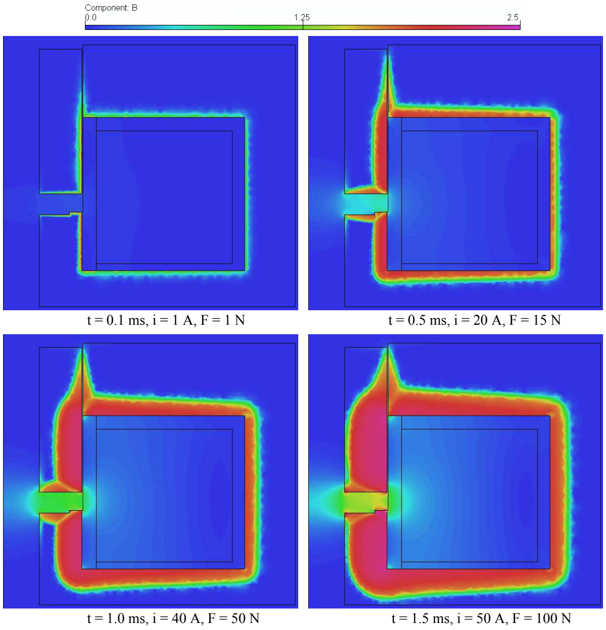


Fig. 1: *The structure of the electromagnet of a solenoid valve. The same structure is used throughout the optimization, where the length and coil wire measures are varied*

When voltage is applied across the coil, its current, or magnetomotive force starts to increase. This increase is not sudden, and this slows down the actuator response. In principle, the larger and more powerful the electromagnet is, the larger its inductance is, limiting the increase of the magnetomotive force. Also, the larger the coil voltage and thicker (thus less resistive) the coil wire, the faster is the increase in magnetomotive force with input power.



t = 0.1 ms, i = 1 A, F = 1 N
t = 0.5 ms, i = 20 A, F = 15 N
t = 1.0 ms, i = 40 A, F = 50 N
t = 1.5 ms, i = 50 A, F = 100 N

Fig. 2: *The penetration of the magnetic field into the ferromagnetic and conducting core when a step voltage of 24 V is applied across the coil using the design reported in this paper*

The magnetomotive force creates a magnetic field around the coil and penetrates to the ferromagnetic core and the plunger. This also occurs with a dynamical delay. As the magnetomotive force increases, it creates a changing magnetic field which, according to Faraday's law, generates an electromotive force. As the ferromagnetic core and the plunger material conduct electricity, eddy currents are created in the core and in the plunger. In turn, these eddy currents generate a magnetic field of their own, opposed to the field generated by the coil. This effect slows down the build-up of the magnetic field in the core and the plunger (Brauer, 2004; Brauer, 2007), limiting the magnetic force generated. Figure 2 represents an example of this effect. Lamination or special materials with lower conductivity could be used in the magnetic core to decrease eddy current generation, but they usually have a negative effect on durability, magnetic permeability, or the material and manufacturing cost.

These two phenomena described above also create a contradiction, or a room for a trade-off. The faster the magnetomotive force increase is, the slower the magnetic field penetrates the ferromagnetic core and the plunger. With slower magnetomotive force increase, magnetic field penetration is relatively faster, but the field is weaker. Also, the larger the current, the more heat the actuator produces. Due to this interplay between electromagnet geometry and size, coil size and shape, wire thickness, and the coil input, a sophisticated optimization is needed to design a well performing solenoid actuator.

The spool movement also affects the magnetic field and the force, mainly by reducing the air gap, and also by affecting the inductance of the coil and creating another EMF. However, these phenomena are neglected in this analysis, as most of the precious time is spent before the spool even moves. This assumption holds when the initial force needed to move the spool is rather large, due to counter-forces acting on the spool. Additionally, the movement time is so short that these effects are hardly visible in the spool movement. Therefore, the marginal gain in accuracy would not justify the increased computational burden required to take these phenomena into account. For more detailed discussion about this subject, see Uusitalo (2009).

3 The Model and Genetic Optimization

The tools of computational electromagnetics offer rather precise methods for modeling electromagnetic and electromechanical devices. The computational precision of these methods enables one not only to verify designs, but also to fine tune them for better performance. This can either be done by an engineer by hand, or as suggested here, by using an automated procedure. An engineer would only be needed to initialize and supervise the operation, leading to better results with less human effort. Heuristic optimization methods are applicable for such task. In this section, it is described how finite element method and genetic optimization are used to achieve better solenoid actuator design.

3.1 The Actuator Model

A finite element transient model of the electromagnet is used to study how rapidly the magnetic force acts on the plunger, when a step voltage is applied across the coil. The electromagnet could be well modeled as 2D rotationally symmetric, providing also fast computation. The computational model can be seen in Fig. 6. The conductivity and nonlinear permeability of the ferromagnetic materials in the core and in the plunger was taken into account. Armco iron was used in ferromagnetic parts, with conductivity of $1.04 \cdot 10^7$ S/m and B-H curve in Fig. 3. The material around the coils was non-magnetic steel ($\mu \approx \mu_0$), with conductivity $\sigma = 1.39 \cdot 10^6$ S/m.

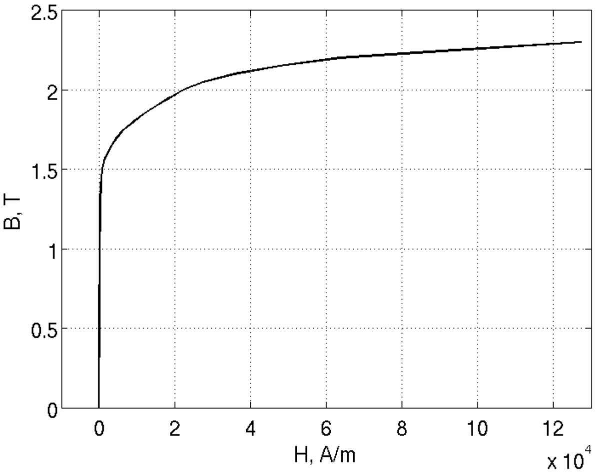


Fig. 3: *The B-H curve of Armco iron, which was used as ferromagnetic core material*

A magnetic vector potential formulation was used for computation, which can be written

$$\nabla \cdot \mu^{-1} \nabla A = -\sigma \left(\nabla V(t) + \frac{\partial A}{\partial t} \right) \tag{1}$$

where A is the vector potential and $\sigma V(t)$ is the source current of the coil. Boundary condition $A = 0$ was used, constraining the magnetic field inside the computational domain. The modelling software used was *Vector Fields OPERA*. The force acting on the plunger was computed from the solution of the magnetic field using Maxwell's stress tensor (Bianchi, 2005):

$$F = \int \mu_0^{-1} \left(\left(\nabla A \nabla A^{\mathrm{T}} \right) - 1/2 \left(\nabla A^{\mathrm{T}} \nabla A \right) I \right) n da \tag{2}$$

where the volume V encloses the ferromagnetic part of the plunger.

The energy consumption of the actuator can be calculated from the coil current, as integral

$$E(t) = R \int \left[i(t') \right]^2 dt' \tag{3}$$

where R is the coil resistance, which depends on coil shape, fill factor, and wire thickness.

With the aid of FEM, it is possible to map the geometry and other physical properties of the electromagnet into how well it performs the given task: generating the needed magnetic force as fast as possible, without consuming too much energy and without producing too much heat. A parametrized model of the electromagnet was created, which described the shape of the coil, the ferromagnetic core, and the plunger with few parameters of length as well as the radius of the coil wire. It was also necessary to ensure that the model could be constructed and that the actuator could endure in its operating environment, mainly in terms of mechanical strength. Therefore, some details of the model were fixed as constants due to these reasons, or because some measures are known not be highly sensitive for the performance of the valve. For example, the thickness of the ferromagnetic core at the outer radius of the coil was fixed, as it has no effect on the performance as long as it is thick enough. Furthermore, a large enough fluid flow path was left in the middle of the plunger, ensuring that the plunger movement is not decelerated too much by the viscous forces.

Table 1: Parameters of the solenoid actuator model. The parameter limits restrict the size of the actuator close to the commercial one.

Parameter	Description	Min. value	Max. value
plunger_r1	Inner radius of the plunger	1 mm	4 mm
plunger_w	Width of the plunger	3 mm	15 mm
plunger_l	Length of the plunger	5 mm	20 mm
coil_w	Width of the coil	5 mm	20 mm
coil_l	Length of the coil	5 mm	40 mm
coil_pos	Vert. Position of the coil	-10 mm	10 mm
wire_r	Radius of the coil wire	0.3 mm	0.6 mm

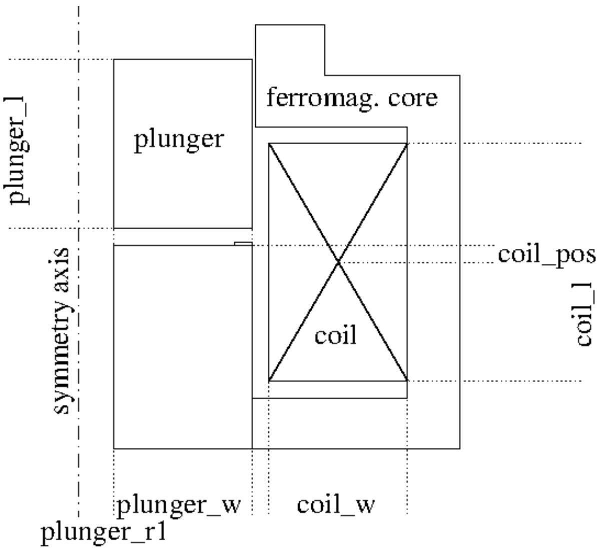


Fig. 4: *The solenoid actuator model and its parameters*

Now, it is possible to turn the actuator model into a function, $M: (\mathbf{x}, t) \rightarrow \mathbf{y}(t)$, where the elements of vector $\mathbf{x}$ are the parameters of the model, t is the time elapsed since the source voltage was applied, and the elements of vector $\mathbf{y}(t)$ are some desired output values, like energy consumption $E(t)$, coil current $i(t)$, plunger mass *m*, and magnetic force *F(t)* acting on the plunger. The function *M* has no analytical form as it compasses the construction, FEM analysis, and the post-processing of the model. The actuator model and the parameters x are presented in Table 1 and Fig. 4. The fill factor of the coil was assumed to be 0.6.

3.2 Genetic Optimization

Genetic optimization imitates the process of biological natural selection and evolution (Eiben, 2003). As one individual actuator is characterized by the parameter vector $\mathbf{x}_i$, the genetic algorithm is initialized by randomly selecting the values for the elements $x_{ij} \rightarrow \mathbf{R}$ of $\mathbf{x}_i$ from a predefined range, creating a population X of n actuators $X = \{x_1 , x_2 , . . ., x_n\}$. The fitness of each individual is being evaluated with the fitness function $f : X \rightarrow \mathbf{R}$. Fitness function is chosen to be such that it reflects how well the individual actuator performs the given task, the design challenge. The individuals $\boldsymbol{x}_i$ with the largest values of fitness $f(\boldsymbol{x}_i)$ are chosen to survive and to generate the next generation of actuators.

After the selection for survival, the surviving individuals $\boldsymbol{x}_i$ are mutated and crossbred with each other to produce the second generation of actuators. The cycle goes on by evaluating their fitnesses and breeding new generations of actuators for *N* generations. The actuator with the largest value of fitness in the whole process will be presented as the outcome of the optimization.

A multiplicity of things affects how efficient method a genetic optimization will be. The most important one is the fitness function. It should describe well enough what kind of actuator the human designer wants to attain. Also the population size *n*, the number of generations *N* and the methods for mutation, cross-over and the selection for breeding have an impact on that (Rahmat-Samii, 1999). In this work, the genetic algorithm used was The Genetic Algorithm Optimization Toolbox (GAOT) for Matlab 5 (Houck, 1995).

The fitness of the individual solenoid actuator was computed using the fitness function $f = M \circ P_t: X \rightarrow Y \rightarrow R$, where M maps the parameters $\mathbf{x} \rightarrow X$ to post-processing data $\mathbf{y} \rightarrow Y$ of FEM computation and P_t maps this post-processing data to a positive real value, the fitness of an actuator. In our computation, P_t had the form

$$
\begin{aligned}
&P_t\left(F(t), E(t), m\right) \\
&= F(t)/m - 10^4 \cdot \exp\left(\left(E(t) - 0.45J\right) \cdot 1000\right)
\end{aligned}
\tag{4}
$$

where *m* is the mass of the spool and the optimization was made setting *t* = 2 ms. That is, the larger the acceleration of the spool at time *t* = 2 ms, the greater the fitness, and if the energy consumption exceeds 0.45 J by the time *t* = 2 ms, an exponential cost is subtracted from the fitness. Coil input voltage of 24 V was used in the optimization. These specific values were chosen based on previous design attempts. Another possibility would be multiobjective optimization that would optimize both acceleration and energy consumption (Dias, 2002). However, it was not employed since a clear emphasis was put on maximizing the acceleration.

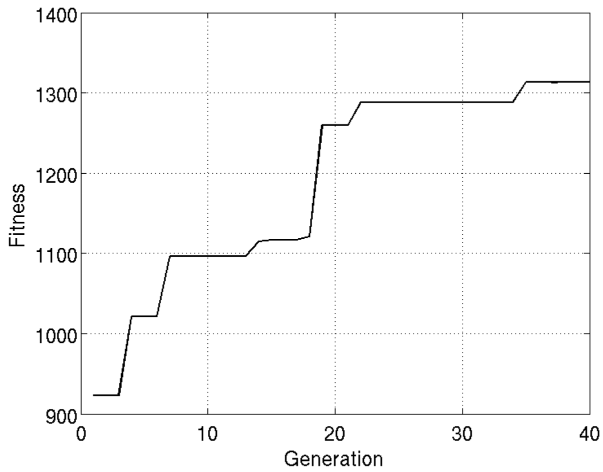


Fig. 5: *Evolution of the fitness figure during 40 generations of genetic optimization. The saturation of fitness figure with respect to the generation hints that a nearly optimal solution is reached. However, no guarantee of this can be obtained.*

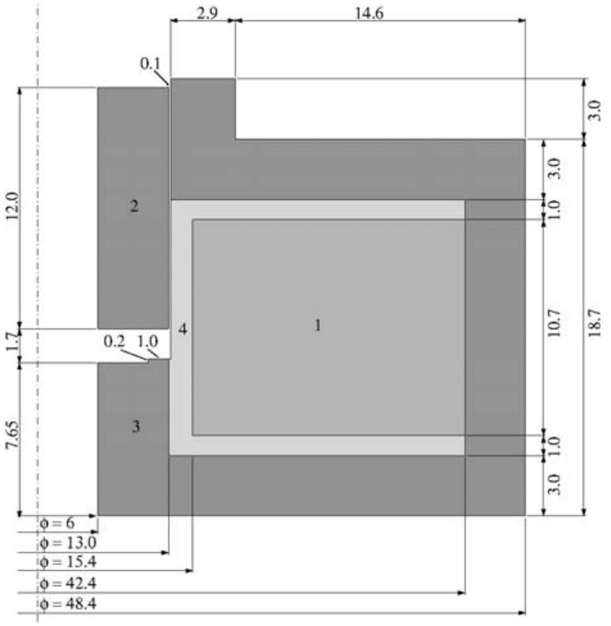


Fig. 6: *The resulted electromagnetic actuator design. Lengths are in mm, rounded to construction tolerance of 0.1 mm. Region 1 is the coil, region 2 is the ferromagnetic part of the plunger, region 3 is the ferromagnetic core, and region 4 is non-magnetic material. The resulted radius of the coil wire was 0.5 mm*

With a population size of 20 and with 20 generations, the optimization takes about 8 hours on a computer with a Pentium 4 processor. Each FEM computation takes about the same amount of time, so the optimization time grows linearly with the number of generations. In Fig. 5 is the fitness evolution of our solenoid actuator during 40 generations of genetic optimization. In Fig. 6 is the resulted layout of the actuator.

The non-specific nature of the fitness function *f*, called objective function in general optimization, narrows down the choice of optimization methods one could use to maximize it. One has no guarantee of its properties, which are often essential for various optimization methods to operate. However, genetic optimization and various other heuristic methods are well suited for objective functions of this type. In genetic optimization, the objective function does not need to be continuous or differentiable, the search space does not need to be a convex set, and the method is suited for global optimization (Rahmat-Samii, 1999).

Despite the good traits, the computation time can be long, as with the population size of *n* with *N* generations, *nN* evaluations of the fitness function are needed, although it is possible to compute individuals of one generation in parallel. In addition, genetic optimization can give no guarantee that the found solution is the *optimal* one. In the engineering field however, near optimal solutions are often as highly appreciated as optimal ones.

4 Results

First, a series of computational results were obtained in order to test the effect of different input voltage pulses on the response time and heat production for the solenoid. Next, the actuator was constructed and measured in its genuine operating environment, in order to obtain reliable results and to verify the validity of the computational model.

4.1 Computational Results

The performance of the final layout of the solenoid actuator was analyzed using the finite element transient solver. The effect of coil voltage pulses of 24 V and 48 V of different lengths were modeled, and the response time of the valve was estimated using the computed magnetic force on the plunger.

The effects of plunger movement on the force were therefore disregarded, and a pessimistic estimate on the force opposing the movement was used to take friction and viscous forces into account. The heat production and switching energy of the solenoid actuator were estimated from the computed coil current. As nearly all the electrical energy put to the system transforms to heat, the average heat power estimate of the solenoid actuator is

$$P_{\mathrm{d}} = \frac{1}{T}\int U(t)\,i(t)\,dt \qquad (5)$$

where *U(t)* is the input voltage pulse and *T* is the period when the switching frequency is $f = 1/T$. The switching energy estimate of the valve is

$$E_{\mathrm{s}} = U\int i(t)\,dt \qquad (6)$$

where *U* is the applied voltage and t_0 is the length of the voltage pulse.

The computed current of the coil with different inputs is presented in Fig. 7. The computed resistance of the coil is 0.17 Ω at 20° C and 0.22 Ω at 80° C. The maximum current our power supply could withstand was about 100 A.

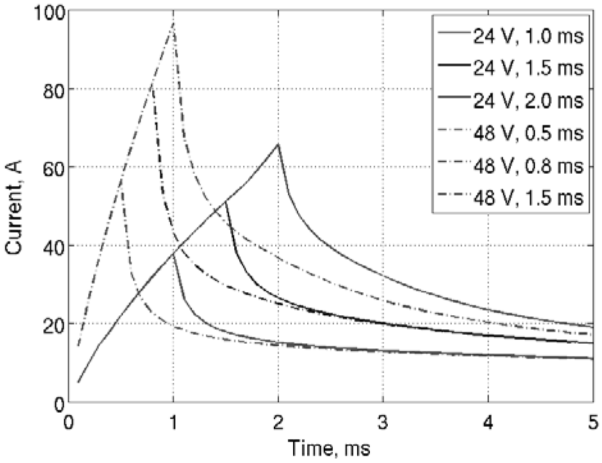


Fig. 7: *Current of the solenoid actuator with different input voltage pulses*

The computed average heat production of the coil when the plunger is moved back and forth with different frequencies, is presented in Fig. 8. The calculation is based on input energy during a single stroke of the plunger, using the previous information about the current *i(t)*. This is justified by the fact that almost all the energy put to the system ends up in heat. The resulting temperature of the solenoid actuator was not modeled. However, it was estimated that the solenoid actuator should withstand heat production of 30 W, without reaching temperature over 80° C. Temperatures above that would degenerate the hydraulic oil faster.

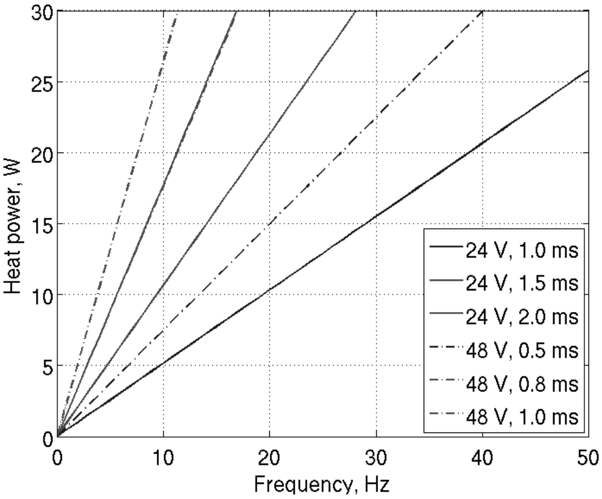


Fig. 8: *Average heat production of the actuator with different input voltage pulses*

The computation of heat power should give an estimate on the maximum continuous switching frequency using different coil inputs. The computed switching energy is 1.0 J with 1.5 ms input pulse of 24 V and 2.6 J with 1.0 ms input pulse of 48 V.

The computed position of the plunger is in the Fig. 9. The computation is based on the magnetic force acting on the actuator, and constant counter-force estimate of 40 N was used. The magnitude of the opposing force was based on experience on NS6 valve type and was kept constant to act as a pessimistic upper bound. As the movement distance was 1.5 mm, Fig. 9 gives response time estimates with different coil inputs.

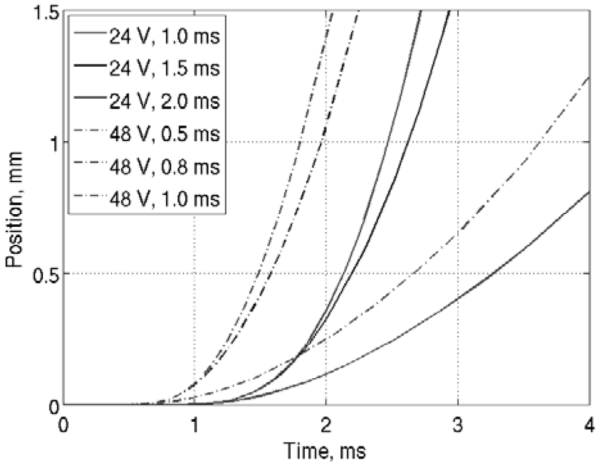


Fig. 9: *Estimated position of the plunger after various voltage pulses applied to the coil*

4.2 Measurement Results

The performance of the solenoid actuator was measured as a part of a hydraulic circuit. It was attached to a Parker D1VW NS6 valve body and the input pressure of the system was 100 bar. The volumetric fluid flow trough an open valve was about 100 l/min and the corresponding pressure difference over the valve was 10 bar. Measurements were made by applying coil voltage pulses of 24 V and 48 V of several lengths. It was tested that the valve could operate with volumetric fluid flow of 260 l/min, the maximum our system could produce.

The response time of the valve was interpreted from the input pressure measurement of the valve: the interval between the beginning of the voltage pulse and the time when the input pressure begins to change considerably. The measured response times, maximum currents, switching energies and maximum continuous switching frequencies are presented in Table 2. The measured current plots are in Fig. 10.

Table 2: Measured response times (both opening and closing the valve), switching energies, maximum currents, and maximum continuous frequencies of the valve with different coil inputs

	Input pulse			
	24 V	24 V	48 V	48 V
	1.5 ms	2.0 ms	0.8 ms	1.0 ms
Response time (open) [ms]	2.6	2.4	1.8	1.7
Response time (close) [ms]	3.1	3.0	2.6	2.2
Switching energy [J]	1.1	1.8	1.7	2.7
Peak current [A]	52	67	77	94
Max. cont. freq [Hz]	28	15	20	13

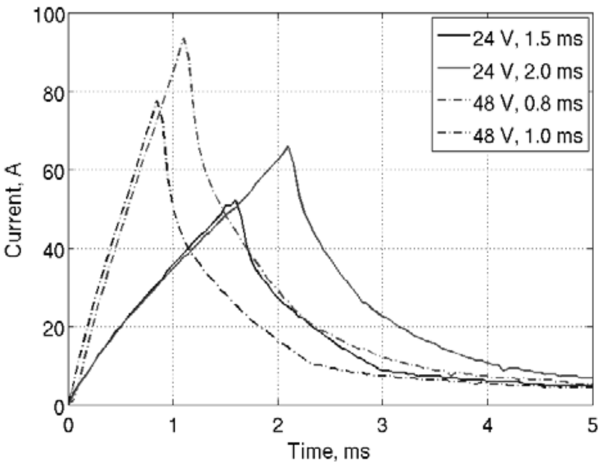


Fig. 10: *Measured current of the solenoid actuator with different input voltage pulses. Notice the agreement in ascending slopes with the computational results in Fig. 7 but also the difference in descending slopes. The difference is explained by the decrease in inductance as the air gap has been closed*

5 Conclusions

A solenoid actuator for NS6 hydraulic valve was designed and optimized. As the requirements were a fast response time and low power consumption, a parametrized model of the actuator was constructed to predict these properties. Genetic optimization based on that model was used to find a good design of the solenoid actuator.

The measurement results agreed well with the computational results. This indicates, that the accuracy of the model and the computation were sufficient to optimize an actual real world device, not only the model of it. In Table 3 the comparison of the computational and measurement results, as well as comparison to a commercial solenoid actuator of NS6 valve are presented (Mikkola, 2007). This comparison reveals a huge improvement in performance with respect to the commercial actuator. However, the response time was probably not the main concern in this particular commercial actuator design.

In our case, the design challenge was to minimize the solenoid actuator response time with given energy consumption and size bound. These were adjusted by the genetic optimization fitness function and search space limitations, respectively. On the other hand, in many engineering applications, a multitude of parameters might be needed to optimize simultaneously to find a suitable trade-off. For such purposes, multiobjective genetic optimization is an option.

A further trade-off needs to be made in model accuracy versus computational burden. In this work, the optimization was based only on the electromagnetic simulation neglecting the motional effects, which resulted in fairly light computation. Fluid dynamics simulation, thermal and stress analysis were done separately to ensure the viability of the design. Results from such a multiphysics simulation could also be incorporated into the fitness function evaluation, if one is assured about its usefulness.

Table 3: Comparison of the computational and measured results of the designed solenoid actuator and a commercial solenoid actuator when attached to a commercial NS6 valve body

Property	Parker D1VW	Computation	Measurement
Response time, 24 V	17 ms	2.7 ms	3.0 ms
Response time, 48 V	12 ms	2.1 ms	2.2 ms
Switching energy	1 J	1.0 – 2.6 J	1.1 –2.7 Hz
Peak current	10 A	51 – 97 A	52 – 94 Hz
Max. freq.	20 Hz	100 Hz	100 Hz
Max. cont. freq.	4 Hz	11 – 28 Hz	13 – 28 Hz
Pressure durability	350 bar	–	200 bar

Nomenclature

A	Magnetic vector potential	[Wb/m]
B	Magnetic flux density	[T]
E	Energy	[J]
E_s	Switching energy	[J]
F	Force	[N]
f	Frequency	[Hz]
H	Magnetic field intensity	[A/m]
i	Current	[A]
m	Mass	[kg]
P_d	Heat power	[W]
R	Resistance	[Ω]
t	Time	[s]
T	Period	[s]
U	Voltage	[V]
μ	Permeability	[N/A^2]
σ	Conductivity	[1/(Ωm)]

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