Modulární elektromagnetický aktuátor ve funkci ventilu

Pospíšil Karel
Department of Theory of Electrical Engineering
Faculty of Electrical Engineering
University of West Bohemia
pospisik@kte.zcu.cz

Modular Electromagnetic Actuator in Valve Operation

Abstract – **A novel concept of modular electromagnetic actuator in valve operation is proposed. The actuator takes advantage of permanent magnets for assuring stable positions of the valve body and field coils for control of the valve operation. Modular design of the actuator allows both bistable and monostable modes. Presented is the basic concept of the actuator and experimental testing of the first laboratory prototype in bistable mode.**

Keywords – Actuators; Fluid Flow Control; Numerical Simulation; Valves.

I. Introduction and Motivation

Electromechanical actuators (solenoid actuators) are utilized as basic parts of the wide range of mechatronic systems. They are used mainly as manipulators or control elements of technological processes and systems. Especially, electromagnetic actuators in valve operation (electromagnetic valves or solenoid valves) are most frequently used elements for control of fluid flow in various industrial applications, where they are utilized mainly in on/off mode [1]. Therefore, innovation of electromagnetic valves has an impact on the modernization of many technical and technological fields. The important requirements for current state-of-the-art valves are (i) fast dynamic response, (ii) low energy consumption, (iii) operation safety (iv) high reliability and (v) embedded intelligence. [2]

The major goal of the paper is to present a novel concept of modular electromagnetic valve in coaxial design (straight valve). The concept in bistable mode is studied by experimental testing of the first laboratory prototype and also by numerical simulation [3].

II. Formulation of Technical Problem

At present, electromagnetic valves with returning springs are frequently used in industrial practice. Springs are very advantageous due to their simplicity and linear force characteristics in the case when working area of the spring is in the linear domain. A major problem with springs is so-called fatigue of material, when repeated spring loading causes elastic deformations or even irreversible plastic deformations that deteriorate the mechanical properties of the springs. Such degradation of spring may result in a slower response of the valve or unability to close the valve [1][4].

In order to remove problems with degradation of the springs, they are replaced by permanent magnets with small proneness to degradation. Moreover, permanent magnets can be placed not in the working area in the case of coaxial valves, but may be out of the channel in the magnetic circuit of the valve actuator[6]. By replacing the springs with the magnets, it is achieved that the movement of the valve is not controlled by the mechanical force generated by the action of the mechanical elements but by the electromagnetic field—valve becomes fully electromagnetic [5]. Thanks to permanent magnets, it is not necessary to place any elements creating the valve movement to the working area. This eliminates the influence of the flow medium on the elements controlling the movement of the valve. The basic arrangement of new concept is shown in Fig. I.

The presented concept is bistable as well as the previous TROMAG [5], but now the permanent magnets that are no longer located in the moving piston path but on the middle pillar of the magnetic circuit dividing the coils. The Rolypoly valve was designed with various shape of the plunger surface [6]. This shape is important for creating the force that holds movable plunger in the opened or closed position and the force must be as high as possible.

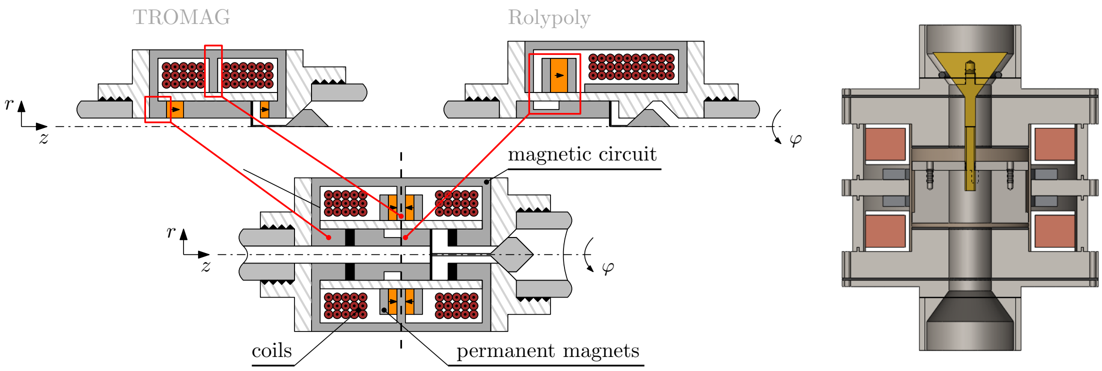


Figure I: **Basic concept of proposed valve together with illustration of the major changes from previous prototypes of the bistable valve TROMAG [5] and monostable valve Rolypoly [6] (left figure) and cross-section of prototype (right figure).**

The principal advantages of the new concept is the bistable mode secured only by the permanent magnet meanwhile (i) the permanent magnets are not demagnetized in the course of the whole operation (permanent magnets are outside of magnetic flux path), which contributes to the safety and reliability of the actuator, (ii) valve is designed as straight (coaxial valve), so that fluid pressure losses are reduced, (iii) the actuator does not contain any further movable elements such as drag-bars or springs and its cleaning is easy and, finally, (iv) the operation of opening and closing the valve can fully be controlled only by DC current.

III. Design of First Prototype

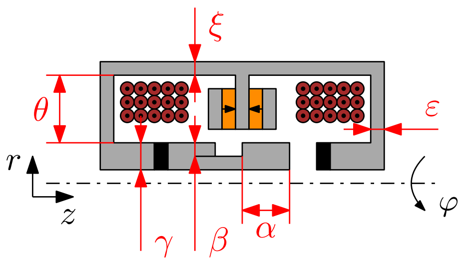
The first prototype of the proposed valve was developed on the basis of numerical study results by sensitivity analysis of valve actuator geometry and following design optimization of selected geometry parameters [3]. Sensitivity analysis based on described mathematical model was made for identification of geometry parameters with major influence on actuator operation. Fig. II shows the parameters of the magnetic circuit.

The Morris method was used for evaluation of parameters sensitivity [7]. The elementary effect for each analyzed parameter in the case of magnetic field energy W_m is described by expression

$$EE = \frac{W_\mathrm{m}(p_1,\ldots,p_i+\triangle p,\ldots,p_m) - W_\mathrm{m}(p_1,\ldots,p_m)}{\triangle p}\,, \tag{1}$$

where p represents geometry parameters (α, β, γ, ε, ξ, θ), $\triangle p$ is relative change of analyzed parameter p_i and $W_\mathrm{m}(p_1,\ldots,p_m)$ denotes appropriate energy function calculated without any changes in the parameters (nominal values). Symbol m stands for the number of parameters.

Analysis was made for maximum change $\triangle p$ equal to $10\,\%$ of the nominal value of the parameter. Achieved results are summarized in table, where elementary effects for each parameter are listed (red values indicate parameters with higher positive effects, blue values denote parameters with negative effects).



	α	β	γ	ε	ξ
EE ($p + 10\,\%$)	$+36$	-144	-44	-68	318
EE ($p - 10\,\%$)	-37	$+147$	$+8$	$+51$	-557

Figure II: **Arrangement of the magnetic circuit with analysed parameters and the results of sensitivity analysis**

IV. Experimental Testing

Experimental testing of the proposed concept was performed by the optical measurement of plunger dynamics by high-speed camera. Fig. III shows opening and also closing process for cycle operation of the valve and Fig. IV shows results of numerical simulation [3]. Switching time of one cycle was $50\,\mathrm{ms}$. For comparison, measured opening time was $t_\mathrm{o} \approx 47\,\mathrm{ms}$ ($45\,\mathrm{ms}$ for closing process) and calculated opening time was $t_\mathrm{o} = 48\,\mathrm{ms}$.

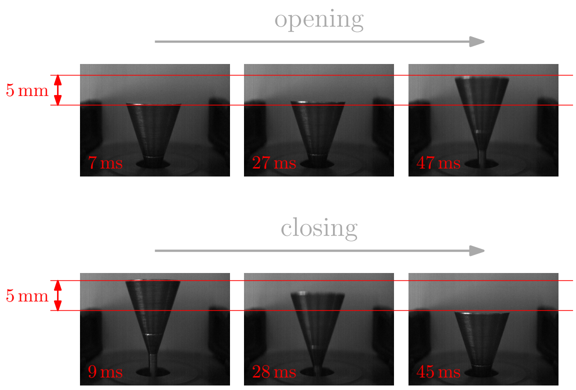


Figure III: **Opening (upper figure) and closing (lower figure) process captured by high-speed camera in the cycle valve operation (switching time 50 ms).**

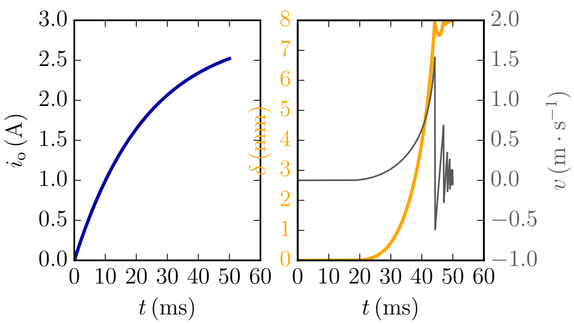


Figure IV: **Plunger dynamics simulation calculated for actuator prototype. Total closing time is equal to 48 ms.**

V. Conclusion and Future Research

Novel concept of a fully electromagnetic valve in bistable operation was presented. The concept was numerically studied and tested on the designed laboratory prototype by experimental measurement of valve body dynamics.

The following research in the course of valve simulation will be development of efficient algorithm for solution of complex numerical model. This model will consider voltage induced in the field coils by motion of the plunger. From practical point of view, induced voltage is very important for closed loop control system of the valve operation and observation of faultless opening and closing process.

The major goal from design viewpoint will be focused on topology optimization, which is necessary for design more efficient shape of magnetic circuit. The goal of optimization will be improvement of the valve dynamic response and reduction of its size and energy consumption. New laboratory prototype, designed on the base of optimization results will include also network of Hall sensors, optical position sensors and temperature probes for comprehensive evaluation of the prototype design and also the above algorithm for numerical simulation of the valve operation. Very important will be also development of an optimized valve body, with the aim to eliminate changes in fluid pressure.

Acknowledgment

This research has been supported by University of West Bohemia under the project SGS-2015-035 (*Development of advanced physical models and their experimental verification*) and by the project SVK-2017-008.

References

[1] Santosh V. A., Jackson, R. L., Choe, S. Y., Flowers, G. T., Suhling, J. C., Chang, Y. K., Ham J. K. *Reliability and life study of hydraulic solenoid valve. Part 1: A multi-physics finite element model*. Engineering Failure Analysis, 16.3, 2009.

[2] Mercorelli, P. *A motion sensorless control for intake valves in combustion engines*. IEEE Transactions on Industrial Electronics, 16.3, 2016.

[3] Pospíšil, K., Mach, F. *Numerical analysis and experimental testing of modular bistable electromagnetic actuator in valve operation*. 18th International Conference Computational Problems of Electrical Engineering, 2017.

[4] Santosh V. A., Jackson, R. L., Choe, S. Y., Flowers, G. T., Suhling, J. C., Chang, Y. K., Ham J. K. *Reliability and life study of hydraulic solenoid valve. Part 2: Experimental study*. 16.5, 2009.

[5] Mach, F., Kurfiřt, M., Doležel, I. *Robust magnetic flux-based fault detection of electromagnetic valve operation under uncertainty*. 2016 IEEE Conference on Electromagnetic Field Computation (CEFC), 2016.

[6] Mach, F., Kaminský, T., Doležel, I. *Monostable electromagnetic actuator for high-speed and fail-safe valve operation*. Electrical Engineering, 2017.

[7] Cropp, R. A. and Braddock, R. D., *The new Morris method: an efficient second-order screening method*. Reliability Engineering & System Safety, 78.0, 2002.