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Position Control of a Bidirectional Moving Magnet Actuator Based on Contactless Hall-Effect Transducer

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***Abstract*- In this paper it is studied an open loop command method for controlling the position of a bidirectional moving magnet actuator with elastic magnetic forces (MMAEMF). This type of actuator has, due to its design, an equilibrium position that allows displacement of the actuator's rod in both directions. To energize and drive the actuator it is used a method of adjusting the duty-cycle of a PWM signal and MOSFET transistors. As a feedback non-contact displacement transducer it is used an arrangement of two linear ratiometric Hall sensors and a small permanent magnet disc attached to the mobile actuator's rod that moves between the two fixed sensors. Both input data, acquired from the sensors, and output PWM signal is processed through the pins of an open-source electronics prototyping platform based on Atmel microcontroller. Analog data acquired from the sensor is converted to distance after a calibration method through a lookup table. The setup allows measurements to be taken with 0.1 mm precision of the actuator's rod position and to plot the static characteristic of displacement for a range up to ±5mm.**

***Keywords*: magnetic actuator, control, Hall Effect, contactless transducer**

I. Introduction

Magnetic actuators have important advantages over conventional mechanical drives: simplicity, flexibility and reliability. A proportional actuator ensures an output quantity (force, displacement, etc.) proportional to an electrical input signal. The majority of actuators from the high accuracy systems don't have a linear functional characteristic, for example the displacement of the mobile axle depends on the square of the command current (integral effect). Using return coil springs, a linear integral actuator can be converted into a linear proportional actuator, but after several cycles of operation spring damage can appear, such as fatigue and fractures.

As a consequence of recent achievements in advanced magnetic materials and developments in the area of power electronics, microprocessors and digital control strategies, and due to the continuous application of high performance motion control systems, currently there is a high research activity and development of electromagnetic actuators with permanent magnets for applications that include all economic sectors.

Position control with linear actuators represents a very important aspect for automation in industry. In time, several methods of control were studied and are well established in scientific literature. One of them is the Peak and Hold (P&H) technique studied in [1] applied as a boosting method for duty cycle value of a pulse width modulation (PWM) signal. This technique allows no overshoots in the actuator response. These tasks are accomplished by tuning the amplitude and length time of the peak and hold phases. Other methods are fast switching on-off solenoid valve based on PWM associated with Proportional Integrative (PI) controller and hysteresis based controller as in [2]. It appears that the method for controlling a solenoid valve plunger position using PI controller with constant switching frequency is more appropriate than the method using hysteresis control, because the first method leads to an increased valve life time.

Low cost controllers, especially for on/off driving, can be achieved using both PWM control and direct drive. For reaching this purpose it is necessary to monitor in real time the system response in order to estimate the regulator parameters. As a result, started from frequency domain transfer functions, PWM control leads to a good quality in tracking of the signal response as in [3]. In industrial applications, advanced manufacturing systems need a great variety of conventional proportional actuators ensembles based on DC, AC and step motors, moving coils and other motors. These ensembles of a proportional actuator are complex in construction, contain delicate moving and sensing elements, and are expensive to manufacture and maintain. Examples of applications in [4] include fluid flow control in hydraulic servo systems, grasping motions in robot fingers, robot joints, positioning systems, machine tool drives, actuated human interface devices, etc.

II. Moving-Magnet Type Linear Actuator with Elastic Magnetic Forces (MMAEMF)

A moving magnet type actuator with linear motion (MMAEMF) has a stator coil with two fixed NdFeB disc shaped permanent magnets and a mobile element (translator) formed from a shaft with one or more permanent magnets attached to it (Fig. 1). The fixed and mobile magnets are disposed with poles of same name face to face. Such actuator with a short stroke is useful for robotic applications. The pole-pieces between the magnets are made of magnetic material and act as a magnetic field concentrators as in [5]. Large forces and strokes are obtained in tubular permanent magnet actuators and motors, in configurations where the translator has more than three magnets and the stator is formed of more coils arranged in sequence so that some coils are in phase [6-10]. The moving magnet actuator can have a proportional action if repulsive forces (elastic-magnetic forces) are established between the two fixed magnets and the moving magnet(s). Reference [11] mentioned such a technical solution. Preliminary researches for this actuator are presented in [12], however, further analysis and experimental results for such devices have been achieved in [13]. The performance of the actuator was studied analytical through numerical field analysis software COMSOL Multiphysics, based on the finite element method, and capable of analyzing multiphysics problems (Fig. 2).

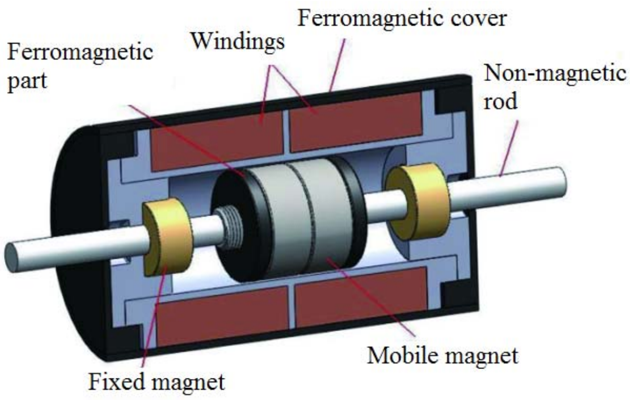

Fig. 1. Basic principle of a MMARMF.

The equation solved by COMSOL is:

$$\nabla \times \left(\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}\right) = J_\theta^{(ext)} \quad (1)$$

where $\boldsymbol{A} = A_\theta \boldsymbol{e}_\theta$ is the magnetic vector potential and $\mathbf{J} = J_\theta \mathbf{e}_\theta$ is the externally generated current density, with $J_\theta^{(ext)} = \pm \frac{N\,i}{(R_{cext} - R_{c\,\mathrm{int}})\,L_c}$ in the coil.

The force acting in axial direction can be determined using Maxwell's magnetic surface stress tensor, T_{nmz}, and integrating on the surface of the mobile part as in

$$F_z = \iint_{S_{ext}} \left[(\mathbf{n}\cdot\mathbf{H})\cdot\mathbf{B}^{\mathrm{T}} - \frac{1}{2}\mathbf{n}\cdot(\mathbf{H}\cdot\mathbf{B})\right]\mathrm{d}A = \iint_{S_{ext}} T_{\mathrm{nmz}}\mathrm{d}A \quad (2)$$

where **n** is the normal pointing outwards from the permanent magnets and iron discs.

Specific advantages of these actuating systems include their high precision and protection against overload, inherent to the system where they are applied in. Simulation and experimental results obtained on the experimental model were in an acceptable agreement in the construction of a prototype actuator and concluded that the prototype has a linear input-output characteristic for a stroke in the range ±2.5 mm and has a force to current ratio proportional for a range from 0 to 3 N.

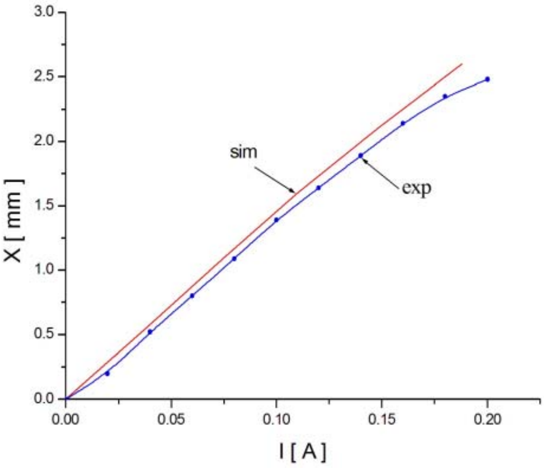

Fig. 2. Displacement vs. current characteristics (simulated and experimental).

III. Command Method and Displacement Feedback

To energize and drive this type of moving-magnet linear actuator with elastic magnetic forces (MMAEMF), it is utilized a method of adjusting the duty-cycle of a PWM signal (Pulse Width Modulation) and fed to the MOSFET transistors connected to the actuator.

PWM works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle.

As experimental equipment it is used an open-source electronics prototyping platform commercially available based on Atmel microcontroller, named Arduino Mega ADK, and RFP30N06LE MOSFET which allows adjusting the duty-cycle of a PWM signal through a linear potentiometer that controls the position of the actuator.

The Arduino Mega ADK is a microcontroller board based on the ATmega2560, it has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button as presented in [14].

Preprogrammed into the onboard microcontroller chip is a boot loader that allows uploading programs into the microcontroller memory without needing a chip (device) programmer.

With the potentiometer set at 50% of its range the actuator remains in the equilibrium position and by sliding the potentiometer back or forward the actuator's rod moves in one direction or the other, respectively.

The main advantage of PWM is that power loss in the switching devices is very low. The loads driven by PWM signal have a low pass behavior and they act as an integrator or as a first order lag circuit. This observation allows using digital methods in driving the actuator, because due to the low pass load behavior, the square wave is only a carrier for the low frequency driving signal.

To control high load currents required to energize the actuator coil it is used an interface specially designed for the Arduino Mega board (Fig. 3) which allows to adapt a standard computer power supply (or other power source) to use the Arduino to switch high current. With RFP30N06LE MOSFETs, the current can be controlled directly from the Arduino Mega board.

The experimental hardware provides 6 PWM outputs via screw terminals. A protection diode has been added to the power input of this version of the board. The protection against counter EMF generated when using inductive loads is accomplished by the aid of diodes parallel mounted between collector and emitter of the power transistors. For this practical circuitry 1N4007 diodes were used. The diode acts as a protection for the transistor from back voltage generated when the coil shuts off or if the coil is energized with reverse polarity.

This experimental setup can be implemented into a PI control system that allows a closed loop precise control of the position of the actuator rod. By varying the amplitude of the input signal, the dynamic behavior of such actuators can also be studied.

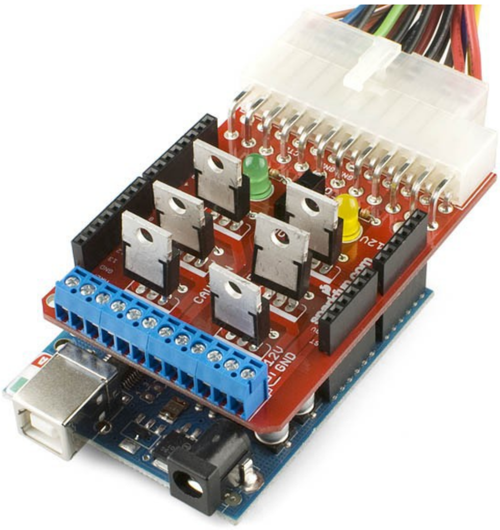

Fig. 3. Arduino with Power Driver Shield Kit mounted on top with 6 high load current RFP30N06LE MOSFETS outputs.

As a feedback mechanism it is used an arrangement of two fixed Hall sensors aligned towards each other and a small permanent magnet attached to the mobile rod of the actuator which acts as non-contact linear transducer. For the experiments it is used sensors with bipolar switching mode that shows distinct switching behavior for the both poles of the induced magnetic flux. With the South Pole directed towards the sensing side of the IC, its output is switched low and with the North Pole applied to the sensing side forces the IC's output to go high (Fig. 4). These sensors have three pins, V_{DD} (connects power supply to the chip), a *GND* (Ground) and V_{OUT} (output from the circuit). Essentially, the DC offset of a ratiometric, linear Hall IC (Integrated Circuit) relates to its deviation from the nominal quiescent output voltage (i.e., 1/2 supply).

The Allegro A1302 is a continuous-time, ratiometric, linear Hall-Effect sensor ICs. It is optimized to accurately provide a voltage output that is proportional to an applied magnetic field. This device has a quiescent output voltage that is 50% of the supply voltage and output sensitivity of 1.3 mV/G.

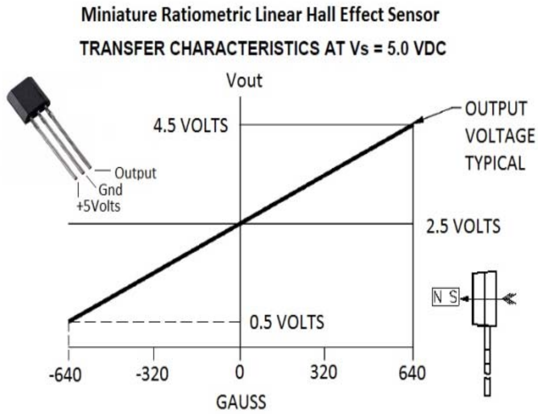

Fig. 4. Miniature ratiometric linear Hall Effect sensor.

The Hall-Effect integrated circuit included in each device includes a Hall circuit, a linear amplifier, and a CMOS Class A output structure. Integrating the Hall circuit and the amplifier on a single chip minimizes many of the problems normally associated with low voltage level analog signals. High precision in output levels is obtained by internal gain and offset trim adjustments made at end-of-line during the manufacturing process. These features make the A1302 ideal for use in position sensing systems, for both linear target motion and rotational target motion. They are well-suited for industrial applications over extended temperature ranges, from –40°C to 125°C according to [15].

Each device has a BiCMOS monolithic circuit which integrates a Hall element, improved temperature-compensating circuitry to reduce the intrinsic sensitivity drift of the Hall element, a small-signal high-gain amplifier, and a rail-to-rail low-impedance output stage.

A proprietary dynamic offset cancellation technique, with an internal high-frequency clock, reduces the residual offset voltage normally caused by device overmolding, temperature dependencies, and thermal stress. The high frequency clock allows for a greater sampling rate, which results in higher accuracy and faster signal processing capability. This technique produces devices that have an extremely stable quiescent output voltage, are immune to mechanical stress, and have precise recoverability after temperature cycling.

This sensor model was chosen because this type allows accurate readings for a variation of the rod displacement in steps of 0.1 mm.

The signals delivered by these transducers are acquired and processed through the Atmel microcontroller on the Arduino board through the analogic pins.

It takes about 100 µs to read an analog input, the maximum reading rate is about 10,000 times a second, so any discrete changes in the magnetic field sensed by the Hall IC is captured.

IV. Experimental Setup

During testing, the environment temperature was measured with a temperature sensing probe. The measured temperature was approx. 25°C. The calibration was accomplished by constructing a system with micrometric screw adjusting mechanism that allowed measurements with a precision of 0.1 mm of the variation of the magnetic field generated by the magnet. Measurements were taken from the saturation point of the Hall sensor with the magnet touching the sensor and changing position axially away from the sensor with 0.1 mm steps. This allowed also measuring the effective air gap necessary to determine the distance between the sensors in order to cover the proposed displacement stroke of the actuator and the thickness of the magnet.

A system calibration or individual 'look-up' table is required for each configuration sensor-magnet type.

In order to obtain an acceptable linearity of the static characteristic (sensor output voltage vs. magnet displacement) it is used an arrangement of two sensors of the same type with same sensitivity mounted with the sensing plate face to face in order to cover together a longer range (Fig. 5).

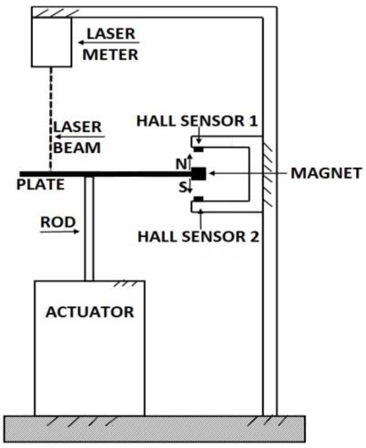

Fig. 5. Principle of the double arangement of the Hall sensors for sensing the displacement.

Using a cylinder magnet (8.4 x Ø5 mm) in conjunction with Allegro A1302 arrangement (sensitivity 1.3mV/G) covers the actuator's maximum stroke while maintaining the smallest effective air gap (Fig. 6) and allows accurate readings for a variation of the rod displacement 0.1 mm precision.

To test the accuracy of the innovative measurement system it was plotted the displacement generated by the actuator vs. current characteristic for I=0-2A, values obtained with a LASER meter model presented in [16] and the Hall arrangement (Fig. 7). The output value from double Hall arrangement sensors was converted in displacement using a look-up table method. The graphic shown in Fig. 8 indicates that the system is reliable for making measurement with precision of 0.1 mm for displacement's range of up to 10 mm.

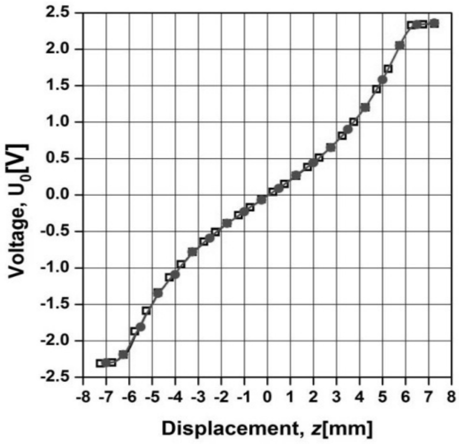

Fig. 6. Double Hall arangement calibration measurements.

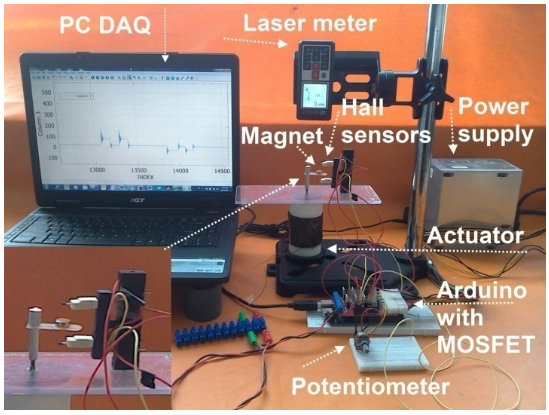

Fig. 7. Experimental setup snapshot with detail.

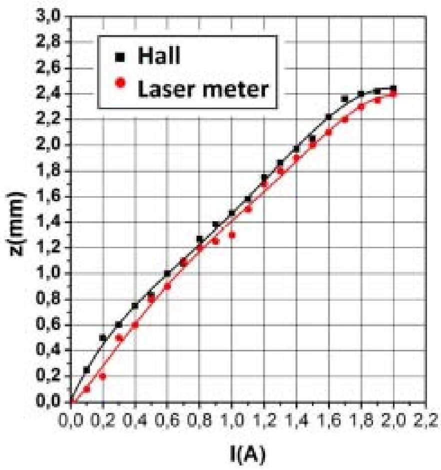

Fig. 8. Displacement characteristic Hall arrangement vs. Laser meter.

V. CONCLUSIONS

In this paper it is studied an open loop method for driving linear bidirectional moving-magnet actuator with repulsive magnetic forces (MMAEMF).

The method uses an open-source electronics prototyping platform based on Atmel microcontroller and MOSFET transistors which allows adjusting the duty-cycle of a PWM signal through a linear potentiometer and control the position of the actuator. As a feedback non-contact displacement transducer it is used an arrangement of two linear ratiometric Hall sensors and a small permanent magnet disc attached to the mobile actuator's rod that moves between the two fixed sensors.

The method consists of using an analog flux density transducer based on Hall Effect and a microcontroller board for acquiring and processing the analog data delivered by the transducer.

Although the static characteristic, sensor output voltage vs. displacement, for an individual Hall Effect sensor is nonlinear, by using an arrangement of two sensors it is possible to obtain a very good linearity for this characteristic.

It is observed that the proposed arrangement of two Hall Effect sensors offers a very good linearity of the static characteristic for ± 2.5 mm displacement range and a quasilinear behavior for ± 5 mm displacement range.

Also it can be observed that the signal processing according the proposed method offers a bipolar behavior of the static characteristic. Therefore, it is very easy to determine the sense of the displacement around a neutral equilibrium position.

The experimental results indicate that this method is very reliable and also it can be used for future dynamic studies of the actuator behavior.

The method studied can be implemented into a PI controller system that allows a closed loop for precise control of the position of the actuator rod. By varying the amplitude of the input signal, the dynamic behavior of such actuators can also be studied.

REFERENCES

[1] R. Amirante, A. Innone, and L.A. Catalano, "Boosted PWM open loop control of hydraulic proportional valves:," *Energy Conversion and Management*, vol. 49, no. 8, pp. 2225–2236, 2008.

[2] Najjari Behrouz et al., "Modelling and Controller Design of Electro-Pneumatic Actuator Based on PWM," *IAES International Journal of Robotics and Automation (IJRA)*, vol. 1, no. 3, pp. 125-136, 2012.

[3] S. Cajetinac, D. Seslija, S. Aleksandrov, and M. Todorovic, "PWM Control and Identification of Frequency Characteristics of a Pneumatic Actuator using PLC Controller," *Electronics and Electrical Engineering*, vol. 123, no. 7, 2012.

[4] M.F. Rahman, N.C. Cheung, and K.W. Lim, "Position Estimation in Solenoid Actuators," *IEEE Transactions on Industry Applications*, vol. 32(3) , pp. 552–559, 1996.

[5] H. Lu, J. Zhu, Z. Lin, and Y. Guo, "A Miniature Short Stroke Linear Actuator-Design and Analysis," *IEEE Transactions on Magnetics*, vol. 44(4) , pp. 497–504, 2008.

[6] B.L.J. Gysen, B.L.J. Lomonova, J.J.H Paulides , and A.J.A. Vandenput, "Analytical and Numerical Techniques for Solving Laplace and Poisson Equations in a Tubular Permanent-Magnet Actuator: Part I. Semi-Analytical Framework," *IEEE Transactions on Magnetics* , vol. 44(7) , pp. 1751–1760, 2008.

[7] J.Y. Choi, J.Y. Kim, S.M. Jang, and S.H. Lee, "Thrust Calculations and Measurements of Cylindrical Linear Actuator Using Transfer Relation Theorem," *IEEE Transactions on Magnetics*, vol. 44(7) , pp. 4081–4084, 2008.

[8] W.J. Kim and W.J. Murphy, "Development of a Novel Direct-Drive Tubular Linear Brushless Permanent-Magnet Motor," *International Journal of Control, Automation, and Systems*, vol. 2(3) , pp. 279–287, 2004.

[9] J. Wang, G.W. Jewell , and D. Howe, "A General Framework for the Analysis and Design of Tubular Linear Permanent Magnet Machines," *IEEE Transactions on Magnetics*, vol. 35(3) , pp. 1986–2000, 1999.

[10] J. Wang, D. Howe, and G.W. Jewell, "Analysis and Design Optimization of an Improved Axially Magnetized Tubular Permanent-Magnet Machine," *IEEE Transactions on Magnetics*, vol. 19(2) , pp. 289–295, 2004.

[11] Y. Hirabayashi, T. Oyama, H. Sohno , and S. Saito, "Moving Magnet-Type Actuator," US Patent n. 5434549, 1995.

[12] C. Astratini-Enache, R. Olaru , and C. Petrescu, "Moving Magnet Type Actuator with Ring Magnets," Journal of Electrical Engineering-Elektrotechnicky Casopis , vol. 61(7/s) , pp. 144–147, 2010.

[13] R. Olaru, C. Astratini-Enache, and C. Petrescu, "Analysis and design of a moving-magnet type linear actuator with repulsive magnetic forces," *International Journal of Applied Electromagnetics and Mechanics*, vol. 38 , pp. 127–137 , 2012.

[14] http://arduino.cc/en/Main/arduinoBoardMega

[15] http://www.allegromicro.com/en/Products/Magnetic-Linear-AndAngular-Position-Sensor-ICs/Linear-Position-Sensor-ICs/A1301-2.aspx

[16] http://www.boschtools.com/Products/Tools/Pages/Bosch ProductDetail.aspx?pid=GLM%20100%20C