Development of a Barrier Structure Actuated by Three Shape Memory Alloy Springs

Sonia Degeratu*, Costel Caramida†, Laurentiu Alboteanu*, Irina Boncea*, Daniela Coman*, Monica S. Staicus* and Gabriela Tont**

[*] University of Craiova, Romania, sdegeratu@em.ucv.ro, lalboteanu@em.ucv.ro, irina.boncea@yahoo.com, amdcoman@yahoo.com, mstaicus@yahoo.com

[†] National Institute for Research, Development and Testing in Electrical Engineering, Craiova, Romania, costica_caramida@yahoo.com

[**] University of Oradea, Romania, gtont@uoradea.ro

***Abstract* - In this paper, the authors present an experimental analysis in order to highlight the behavior of a barrier structure model, actuated by three shape memory alloy (SMA) helical springs. The authors have developed this new barrier structure to increase the performances of conventional barriers, based on SMAs unique properties and their advantages. SMAs are advantageous for actuation because of their light weight, silent operation and flexibility. SMAs began to be increasingly present in industrial applications as well because they display high reliability and can replace the functions that make the motors or complex gears despite their simple construction. The actuator used in our model works as a linear actuator, contracting itself with great strength and speed, thus exerting the necessary force to lift the barrier arm when the SMA springs are heated by carrying an electric direct current. The designer can control the direction of actuation, the amount of force generated and the stroke of the actuator through various combinations that he can achieve with these three SMA springs. After a description of the accomplished model and of how it works, the authors present an experimental analysis of the behavior displayed by the SMA springs-based barrier structure. The experiments consisted in the determination of the SMA spring functioning time periods at constant value of the SMA spring activating electric current, and while maintaining the barrier arm stroke and weight constant.**

Keywords: *shape memory alloy (SMA) actuator, SMA spring, barrier structure experimental model, SMA spring functioning time periods.*

I. Introduction

In recent years, the use of SMA actuators in a wide variety of applications has had a really dynamic evolution. The increasing interest for the SMA actuators derives from their advantages, as compared to the traditional ones: its high plastic deformation, the force generated, the production of mechanical work, the low voltages for the supply of the SMA element, the high power/weight and stroke/weight ratios [1]–[7]. These advantages are a consequence of the unique and superior properties of SMAs, i.e. pseudo-elasticity, shape memory effects (one-way and two way), hysteresis behavior, vibration damping capacity [4], [6]–[10].

SMAs are smart materials that possess the ability to undergo shape change at low temperatures and retain this deformation until heated, at which point they return to their original shape [10]. This unique effect of returning to their initial geometry after a large inelastic deformation is known as the Shape Memory Effect (SME) [3], [10], [11]. The SME occurs due to martensitic phase transformation, between a low temperature phase, called martensite (M), and a high temperature parent phase, called austenite (A). A typical shape memory element has four relevant temperatures that define the different stages of actuation, thus providing the designer with a method for control. Simply put, the four temperatures define the start and finish transformations for martensite (Ms, Mf) and austenite (As, Af).

Due to their unique properties, there is increasing technological interest in the use of SMA for various applications: biomedical engineering, automotive industry, high precision engineering, robotics, electro-mechanical engineering, machine craft etc. [8]–[10], [13]–[18].

This paper presents an experimental model of a barrier structure, developed by the authors, that uses an actuator based on three Ni-Ti SMA springs. This barrier structure, dedicated to private parking systems, is an improved version of the experimental model presented in the papers [19]–[21]. The authors intensified the research in this direction given the great interest shown by some Romanian companies that produce such barriers.

The use of SMA spring as actuator in our barrier configuration provides the following advantages: reasonable force/motion characteristics, a compact size, a high work output, silent operation, design simplicity, and near step function operation [8], [10]–[12].

In the first part of this article the authors describe the accomplished experimental model and its operation mode. In the second part, they present an experimental analysis of the SMA springs-based barrier structure behavior.

The study of this experimental model is made with the purpose of anticipating the behavior of a real structure in terms of operating mode, the control and command of the structure through the SMA active elements.

II. Experimental Barrier Structure Description

The experimental model of the accomplished barrier structure driven by three SMA springs is shown in Fig. 1.

The shape memory effect enables any SMA spring to work as a linear actuator by contracting with great strength and at increased speed when heated. In our model, this translational motion is converted into a rotation motion of the barrier arm so that it will be lifted.

In this section, on the one hand, the authors make a description of the barrier structure experimental model, and, on the other hand, they comprehensively explain how the automatic motion of the barrier arm is controlled. The authors also explain how an SMA spring actually works emphasizing the advantages such a device really displays when used as actuator. The active shape-change control of the SMA spring, the miniaturization possibilities, the easy integration into the system structure, the automatic control of the barrier arm motion (using a programmable logic controller) thus underlies an effective increase in the efficiency of such barrier structures.

The so achieved model allows the structure behavior analysis to be made in various drive conditions and control of the SMA springs.

The main positions marked in Fig. 1 are described in detail below.

A. The Control Unit

This block (position 2 in Fig. 1) contains the following sources: for the supply of the SMA springs (5V), for LOGO (24V) and for powering the barrier control transmitter (24V).

The control unit block (Fig. 2) has the following outputs:

1, 2 - outputs for the stroke transducer;

3, 4 - outputs for the supply of the SMA springs;

5, 6 - LED for signaling barrier position (red - closed, green - open);

7, 8 - terminals for connection to an independent source (of variable voltage) for powering the SMA springs.

B. Data Acquisition System Velleman 4 CHANNEL SIGNAL RECORDER

The main features of the Data Acquisition System (position 3 in Fig. 1) are:

- record DC signals or slow moving signals over very long periods;

- the measurements are automatically stored on the hard disk for further processing;

- through the use of USB connection, there is no need for a power supply and installation is easy and straightforward;

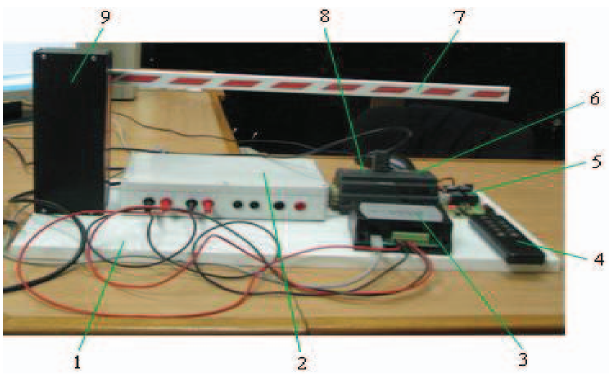

Fig. 1. Latest variant of the experimental arrangement of Ni–Ti SMA-based barrier: 1-seating base; 2-control unit; 3-Signal Recorder (Data Acquisition System); 4-remote control; 5-control receive; 6-Logo!Power; 7-barrier arm; 8–Siemens Logo!24Co (Programmable Logic Controller-PLC); 9-SMA spring-actuated mechanism unit.

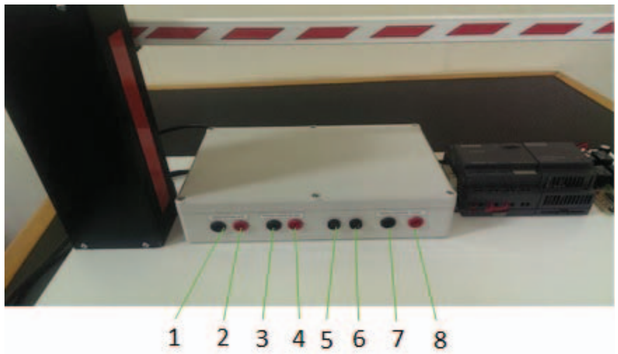

Fig. 2. The control unit of the accomplished model.

- signals are instantly displayed on the PC screen using analog or DVM display.

Hardware specification:

- USB connected and powered;
- four DC coupled input channels;
- input resistance: 1mOhm;
- maximum samples per second: 100;
- four input ranges: 3V / 6V / 15V and 30V;
- sensitivity: 10mV;
- accuracy: ± 3% of full scale;
- maximum input: 30V DC;
- power and recording/diagnostic LED.

Software specification:

- analogue trace or digital DVM readout;
- 4 simultaneous channels recording;
- minimum/maximum sample hold function for DVM;
- from 1 sec to 1000 sec per division;
- storage and recall of screens or data;
- automatic recording option for extended time recording;
- on screen markers for time and voltage;
- DLL included for own development.

System requirements:

- PC, running Win98SE or higher;
- free USB port;
- CD-ROM player [22].

C. AD-IR-DRIVER04 Module for the Remote Control

This module (position 5 in Fig. 1) is an electronic module with a microcontroller allowing the command of 4 independent channels using infrared remote controls. The module is provided with 4 relays of 5 A/ 250 V AC (Fig. 3), which can operate various elements of execution.

For the operation, one can utilize TV- COD RC5 remote controls (RCxxx, PILOTxxx type), universal remote controls or other models used frequently by color television sets. The desired buttons for the selections of the commands can be programmed, so one can choose to one's individual liking. By memorizing the operations buttons from the remote control means they remain the same even when the remote is not powered.

A manual K2 remote control is provided to reset the relays' status. The command of the relays can be made in 2 ways:

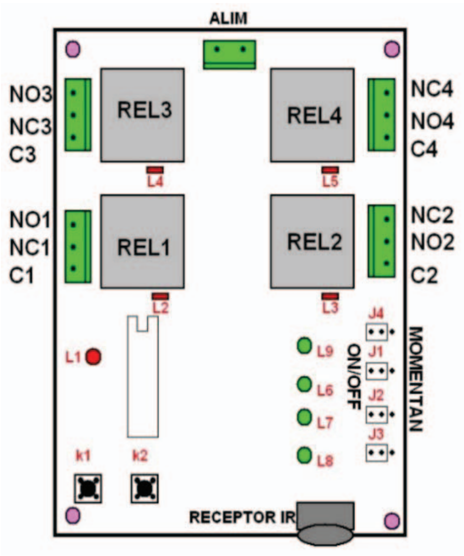

Fig. 3 Block circuit of module AD-IR-DRIVER04 [23].

command type ON/OFF and command type MOMENTAN.

The command module of ON/OFF or MOMENTAN relays is set with the help of PINs found on J1, J2, J3 and J4 modes.

The setting can be made in any configuration, all ON/OFF relays, all MOMENTAN relays or differently.

Remote programming is done as follows. The module should be powered-up so that remote control can be programmed, when LED L1 lights up, and for the start of the operation of learning of the remote controls buttons, press button K1, at which point LED L1 will switch off. Press the remote control button which is utilized for the command of relay REL1. The LED L1 will switch on confirming the takeover of the command. Next, press the desired buttons in order to command the relays REL2, REL3, REL4. LED1 will start blinking at every command. In this way, the desired buttons were memorized.

The main technical characteristics of the module are:

- power supply: 9 ÷ 12 V AC, 50 Hz or 12 V DC;
- the maximum input current: 0.15 A;
- intermediary frequency IR: 38 kHz;
- number of channels: 4;
- command relays: 4 OMRON 5 A per 250 V AC;
- command distance IR: 10 m;
- available remote control RC5: 38 kHz [23].

D. Programmable Logic Controller - PLC (Siemens Logo!24Co)

The logic module LOGO! Siemens (position 8 in Fig. 1) is the ideal controller for simple automation tasks in the industry and building services. The consistently modular design of LOGO! makes it extremely flexible. A wide range of modules allows individual expansion of LOGO! to 24 digital inputs, 16 digital outputs, 8 analog inputs and 2 analog outputs.

PLC LOGO! 24Co, used in the barrier model, is compact, easy to use and provides a low cost solution for control tasks of low complexity.

Together with the LOGO! Soft Comfort software, the configuration of the logical module is simply intuitive: program generation, project simulation and documentation are accomplished using drag and drop functions, allowing maximum ease of operation

The main technical data of the PLC LOGO! 24Co are:

- inputs: 8;
- input/supply voltage: 24 V DC;
- permissible range: 20.4 V – 28.8 V DC;
- „0” signal: 5 V DC;
- „1” signal: minim 12 V DC;
- input current: 2 mA (I3 - I6), 0.1 mA (I1, I2, I7, I8);
- outputs: 4;
- direct current: 0.3 A;
- short-circuit protection: electronic, approx. 1 A;
- switching frequency: 10 Hz;
- cycle time: <0.1 ms/function;
- display: no;
- emitted interference: in accordance with EN 55011;
- maximum program memory: 200 blocks;
- external memory module: LOGO! memory card [24].

Description of the command LOGO! Soft of the accomplished model is as follows.

The LOGO!Soft program for the barrier command is presented in Fig. 4. The digital input I3 controls the barrier (up/down) depending on the signal from the receiver output which in turn is driven by the remote control.

The signal from the stroke transducer is connected to the AI1 analog input. Through B004 Analog Threshold Trigger block, the output Q1 is set or reset depending on the threshold triggers On / Off corresponding to the position of the barrier, the SMA springs being powered up or not.

Barrier position is determined by the stroke transducer (Tc) positioned on the axis of the arm. The transducer supply voltage, U_{Tc}, is 5 V. The transducer stroke is 360^0.

Lifting barrier arm angle was set at 86^0, resulting in:

$$U_{Tc} * On = (U_{Tc} * 86) / 360 = 1.2 V \quad (1)$$

The amplification parameter of the Analog Threshold Trigger block is 100. Resultantly, the output Q_1 is 1 if the actual value of the input functions Ax is greater than Threshold On.

$$Threshold\ On = U_{Tc} * 100 = 120 \quad (2)$$

$$Threshold\ Off = 118 \quad (3)$$

The B002 and B003 Analog Threshold Trigger blocks command, at the outputs Q2 and Q3, the LEDs functioning which indicates the barrier position, respectively the red LED for the lowered position of the barrier and the green LED for the raised position of the barrier. These LEDs function as elements which signal when it is possible or not to go through the space of the barrier.

E. LOGO!Power Module

The mini power supply devices designed into the LOGO!POWER module (position 6 in Fig. 1) offer great performance in the smallest space and the excellent efficiency over the complete load range.

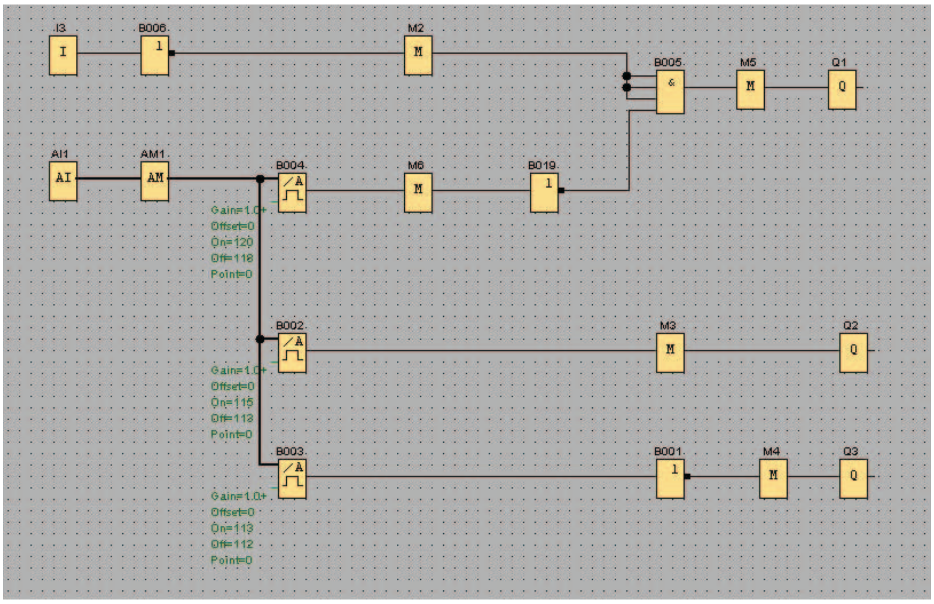

Fig. 4. LOGO!Soft barrier command.

The technical characteristics of the module are:

- power supply, type: 24 V / 1.3 A;
- input: 1 – phase AC or DC;
- rated voltage value Vin rated: 100 – 240 V;
- voltage range AC: 85 – 264 V;
- input voltage for DC: 110 – 300 V;
- overvoltage resistance: 2.3 x Vin rated, 1.3 ms;
- rated line frequency: 50 – 60 Hz;
- rated line range: 47 – 63 Hz;
- input current at rated input voltage 120 V rated value: 0.7 A;.
- input current at rated input voltage 230 V rated value: 0.35 A;
- switch-on current limiting (+ 25 0C), max.: 25 A;
- rated voltage Vout DC: 24 V;
- setting range: 22.2 – 26.4 V (set via potentiometer on the device front);
- status display: green LED for output voltage OK;
- startup delay, max.: 0.5 s;
- output current: 1.3 A;
- active power supplied typical: 30 W;
- efficiency at Vout rated, Iout rated: 85%;
- power loss at Vout rated, Iout rated: 6 W;
- active power loss during no-load operation max.:2 W;
- current limitation: 1.7 A [25].

F. Driving Mechanism Block

The barrier driving mechanism block (position 9 in Fig.1) is presented in Fig. 5. The actuator of this block is based on three SMA Electric Pistons (3) rigidly fixed at their piston-free ends on the fixed support (4). The other ends of the SMA Electric Pistons are fixed on a mobile support (5), from which the traction wires (6) depart towards the driving barrier arm system (8) on which a rotating stroke transducer, Tc (7) is mounted. This transducer is powered up by a voltage of 5 V and can accomplish a maximum stroke of 360^0. The accomplished mechanism allows a rotation of the barrier arm by 86 degrees at a complete stroke of 16 mm of the SMA Electric Pistons (when they are commanded electrically).

The main elements of this experimental arrangement are the three SMA Electric Pistons. The SMA Electric Piston is a linear actuator mechanism that shortens in length with great strength and speed when it is activated by carrying an electric direct current. An SMA spring placed inside makes all these possible.

The SMA Electric Piston was purchased from the Mondotronics, Inc. [26].

The SMA spring displays two entirely different forms or "phases" at the distinct temperatures M_f and A_f. At the "low" temperature (M_f), the SMA spring is extended, and can be stretched easily or deformed by a small force. But

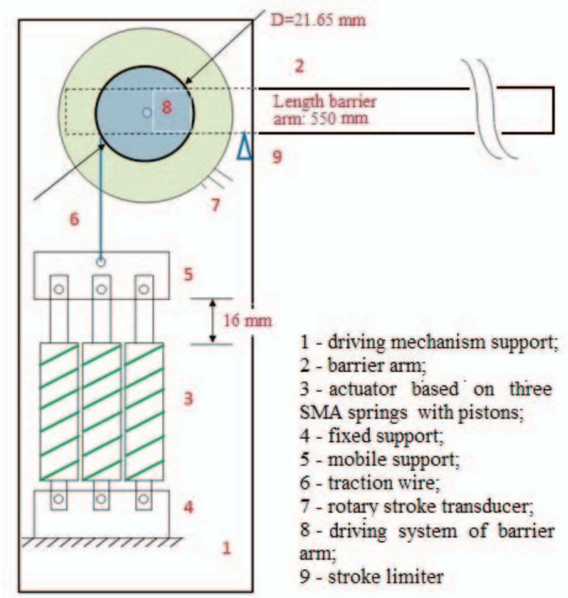

Fig. 5. Driving mechanism block of the experimental barrier structure.

when raised to the "high" temperature A_f, by applying an electric direct current, the SMA spring changes to a much harder form. In this phase, it shortens in length, and exerts the necessary force to lift the barrier arm.

The SMA Electric Piston used in our model can lift to 4.5 N against gravity, yet the SMA Electric Piston itself weighs only 0.1 N. The SMA Electric Piston was presented in detail in [17], [19], and [21]. Therefore, because of the way the mechanical coupling of the three SMA Electric Piston occurs the total force developed by the driving mechanism will be 13.5 N.

III. Electrical Circuit of Realised Model

The electrical circuit, with its component blocks, is shown in Fig. 6.

The power supply block comprises:

- source of 5V, for powering the three SMA springs and the race transducer;
- source of 24V, for supplying PLC (LOGO! POWER);
- source of 12V, for supplying lifting/lowering command receptor of the barrier arm (TRACO POWER).

The command part is composed of an infrared transmitter-receiver, which applies a voltage of 24V to the I3 digital input of PLC through a normally closed contact of the command receptor. The race transducer, whose axis is secured to the movable part of barrier, transmits a proportional signal to the AI1 analog input of PLC.

PLC uses the Q1 output and the R1 relay for powering the SMA springs. The Q3 output is used for signaling lowered position of the barrier through the red LED. The Q2 output is used for signaling raised position of the barrier by the green LED.

The switch K is used for powering the SMA springs from:

a) a 5 V internal power source, which ensures a constant direct current (2.89 A);

b) a 0-5 V external power source, which ensures a variable direct current.

IV. Experiments and Results

Because the SMA spring activates by electric heating, the contraction time varies greatly with the applied current; the higher the current, the faster the heating, and the faster the contraction. In the case of our model, the electric current for powering the SMA springs can come from two sources: internal power source or external variable source.

This paper presents the test results obtained with the experimental arrangement presented in Fig.1, using the internal power source.

The experiments consisted in the determination of the SMA spring functioning time periods: t_{sc}, t_a, t_{rel}, and t_r. These parameters have the following meaning:

- t_{sc} = time to start contracting, or the necessary time from the start of current application to reach the temperature A_s;
- t_a = time to actuate, or the contraction time, or the necessary time for the arm to reach the angular displacement of 86^0;

t_{rel} = time to relax, or the necessary time for the SMA spring to cool from a temperature greater or at least equal to A_f to the temperature M_s. In all cases the cooling process ended at 23.1^0C;

- t_r = time to reset, or the necessary time for the arm to return to its initial position. In this status, the SMA temperature is under M_f.

This test was carried out to analyze the operating mode and to have control over the active shape change of the SMA actuator.

The result for a complete up-down cycle of the barrier arm is shown in Fig. 7.

The supply voltage of the three SMA springs was U=2.79 V, DC, as seen in Fig. 8. This value is indicated by the voltage markers.

By using the two markers from the transducer race signal we were able to determine the values for all SMA spring functioning time periods: t_{sc}, t_a, t_{rel}, and t_r. As an example, in Fig. 9 the two transducer markers indicate the value for the time to actuate, t_a=1s.

The values obtained for t_{sc}, t_a, t_{rel}, t_r and for the supply voltage of the SMA springs are presented in Table 1

It follows that one can choose a corresponding value for the supply voltage of the three SMA springs so as to obtain a desired pair of actuate-reset time periods.

V. Conclusions

It is known that the barrier structures' performances are directly related to the actuators' driving systems' performance. Systems using shape memory alloys are used extensively in applications requiring high reliability, weight reduction of the dimensions, the absence of vibration, high precision when operating in repeated cycles.

The proposed barrier structure is relatively lightweight and has a simple configuration due to the fact that an SMA spring actuator offers efficiency in terms of energy, weight and space.

The analysis of the experimental results has demonstrated that our proposed model behaves quite well.

The results presented in this paper describe the behavior of analyzed barrier structure in case of a constant value for the supply voltage of the SMA springs and, therefore, for a constant value of their activating current.

For a given barrier structure, choosing the activating current values for the SMA actuator will be done so as to obtain the functioning times of the barrier required by the customer. Therefore, in future work, we will analyze the behavior of this structure at different values of SMA spring activating electric current in order to correctly choose the type of application.

These new barrier structures could prove potentially useful in: parking lots, toll gates, goods yards, railway and bridge barriers, apartment block access etc.

Acknowledgment

This work was supported by the grant number 7C/2014, awarded in the internal grants competition of the University of Craiova.

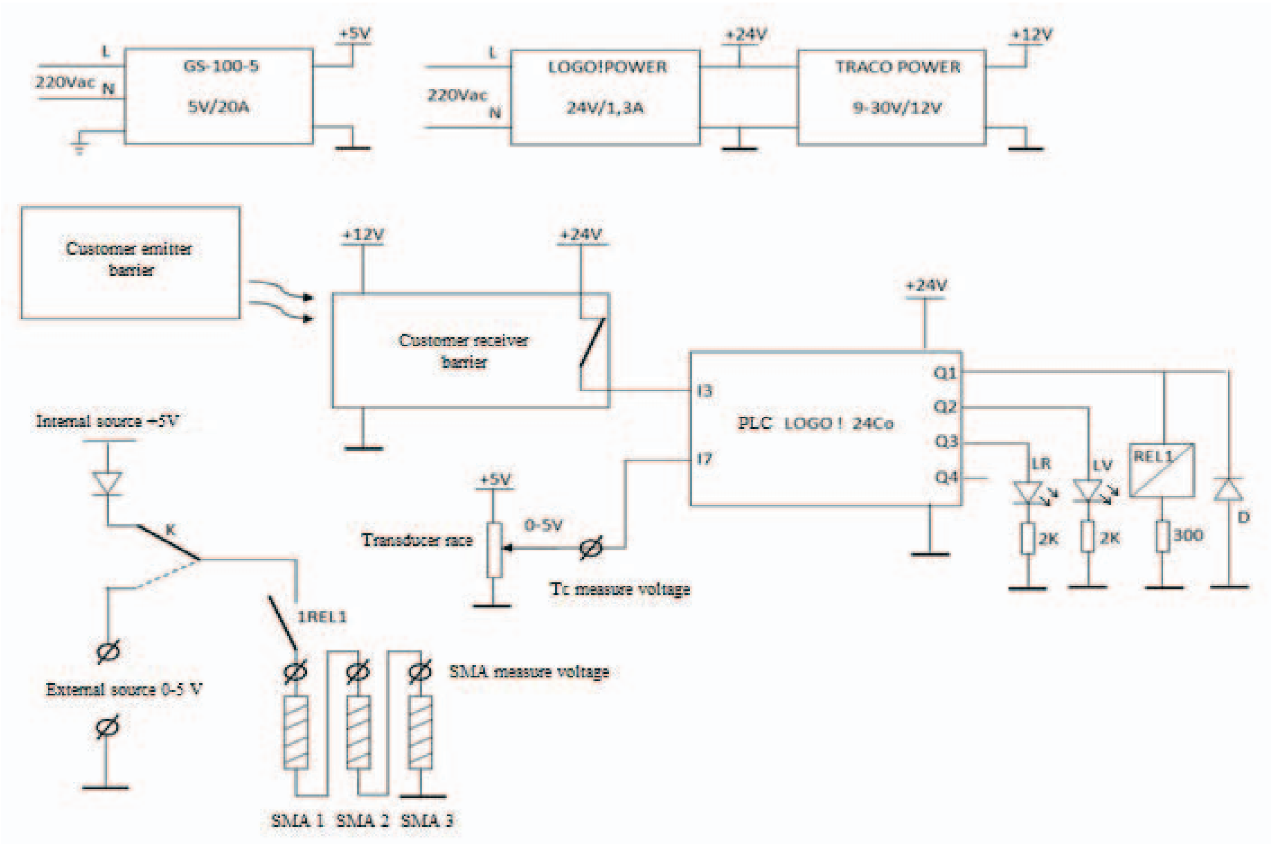

Fig. 6. Electrical circuit of accomplished model

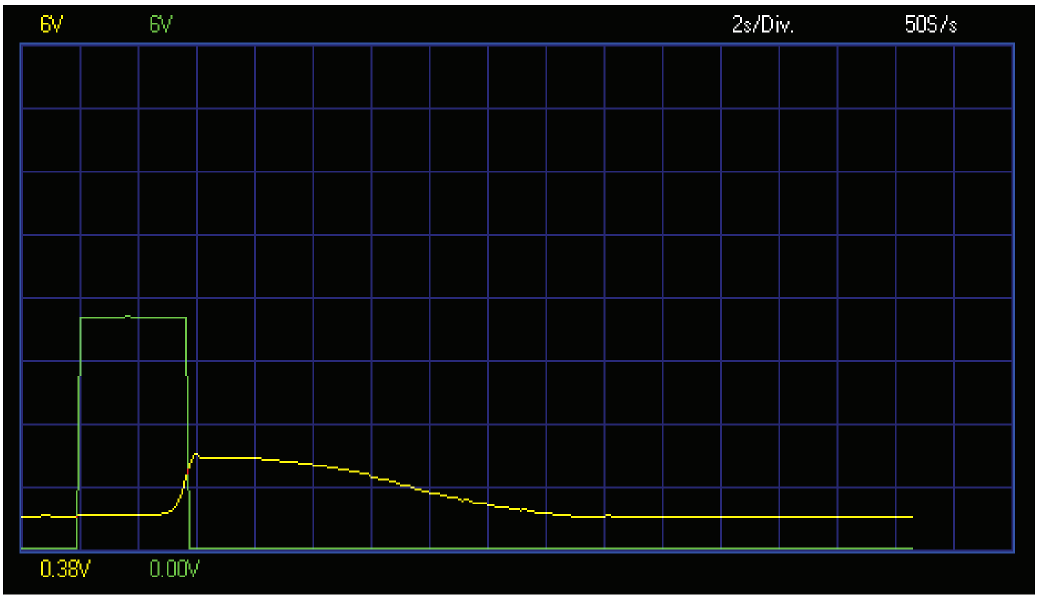

Fig. 7. A complete up-down cycle of the barrier arm:
signal from Tc transducer (SMA spring working time periods);
signal from power source of SMA springs.

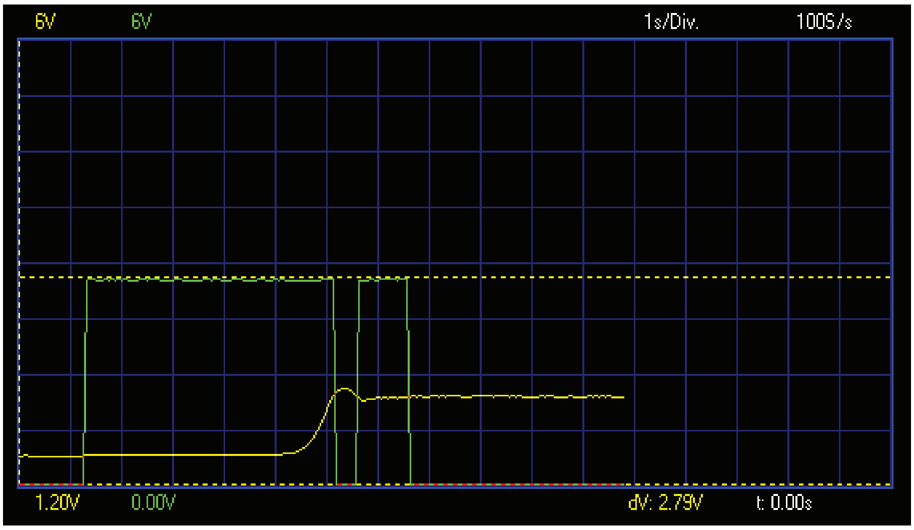

Fig. 8. The supply voltage of the three SMA springs (2.79 V) indicated by the voltage markers:
signal from Tc transducer (SMA spring working time periods);
signal from power source of SMA springs.

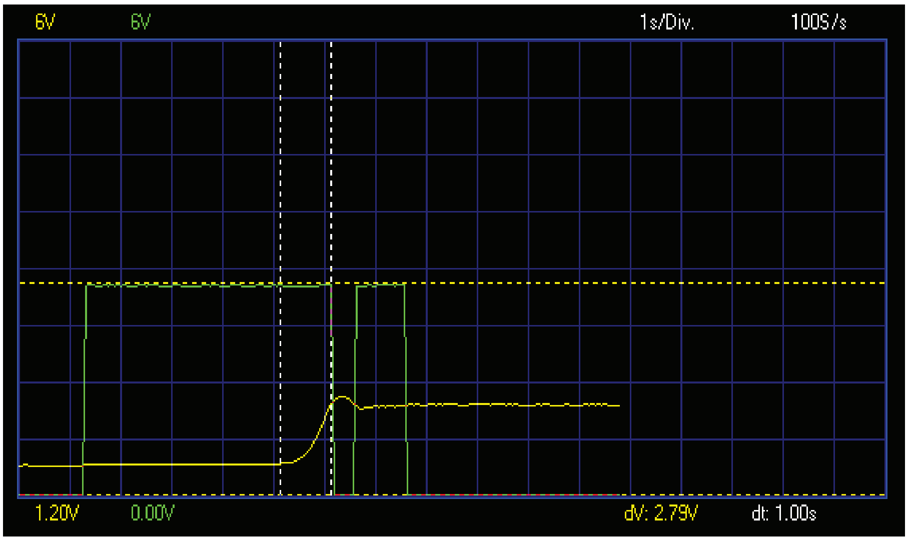

Fig. 9. The value for the time to actuate (t_a=1s) indicated by the transducer markers:
signal from Tc transducer (SMA spring working time periods);
signal from power source of SMA springs.

TABLE I.
FUNTIONING TIMES FOR THE ANALYZED BARRIER CORRESPONDING TO A COMPLETE UP-DOWN CYCLE

U [V]	t_{sc} [s]	t_a [s]	t_{rel} [s]	t_r [s]
2.79	3.91	1	3.81	13.56

Received on Juin 16, 2016
Editorial Approval on November 15, 2016

REFERENCES

[1] E. Torres-Jara, K. Gilpin, J. Karges, R.J. Wood, and D. Rus, “Compliant Modular Shape Memory Alloy Actuators,” *IEEE Robotics & Automation Magazine*, pp. 78–87, December 2010.

[2] K. Seung, K. Byungkyu, “Design parametric study based fabrication and evaluation of in-pipe moving mechanism using shapememory alloy actuators,” J. Mech Sci., vol. 22, pp. 96–102, 2008.

[3] W. Huang, *Shape memory alloys and their application to actuators for deployable structures*, Ph.D. Thesis, University of Cambridge, 1998.

[4] C. Mavroidis, “Development of actuators using shape memory alloys and electrorheological fluids,” J. Res Nondestr. Eval., vol. 14, pp. 1–32, 2002.

[5] G. Knowles, R. Bird, V. Birman, “Shape memory alloy springs used as reduced power/weight actuators,” Proceedings of ASME 2004 international mechanical engineering congress and exposition, Anaheim, California, USA, pp. 17–25, November, 2004.

[6] Yang K, Gu CL. “A compact and flexible actuator based on shape memory alloy springs,” J Mech. Eng. Sci., vol. 222, pp.1329–1337, 2008.

[7] H. Morawiec, "Structure formation and its effect on properties of shape memory alloys", Physics of Advanced Materials, Winter-school, Thesaloniki, Greece, pp. 14-18, January, 2008.

[8] S. Degeratu, N. Bizdoac, *Shape memory alloys: fundamentals, design and applications*, Universitaria Press, Craiova, Romania, 2003.

[9] H. Wu Ming and L. McD. Schetky, "Industrial applications for shape memory alloys", Proceedings of the International Conference on Shape Memory and Superelastic Technolgies, Pacific Grove, California, pp. 171-182, 2000.

[10] T. C. Waram, *Actuator Design Using Shape Memory Alloys*, Ontario Press, Canada, 1993.

[11] T. W. Duerig, et al, *Engineering Aspects of Shape Memory Alloys*, ButterworthHeinemann, London, 1990.

[12] K. Otsuka and C. M. Wayman, *Shape Memory Materials*, chap. 2, Cambridge Univ. Press, 1999.

[13] G. Songa, N. Ma and H.-N. Li, “Applications of shape memory alloys in civil structures,” Engineering Structures, vol. 28, pp. 1266–1274, 2006.

[14] D. Mandru, I. Lungu, S. Noveanu, and O. Tatar, “Aapplications of shape memory alloy actuators in biomedical engineering,” Annals of the Oradea University, vol. VII, pp. 922–927, 2008.

[15] T. Anson, “Shape memory alloys – Medical applications,” Materials World, Vol. 7, No. 12, pp 745-747, December 1999.

[16] L.G. Machado and M.A. Savi, “Medical applications of shape memory alloys”, Brazilian Journal of Medical and Biological Research, vol.36, pp. 683-691, 2003.

[17] S. Degeratu, L. Alboteanu, S. Rizescu, D. Coman, N. G. Bizdoaca, C. Caramida, “Active Solar Panel Tracking System Actuated by Shape Memory Alloy Springs,” Proceedings of the International Conference on Applied and Theoretical Electricity-ICATE, October 23-25, 2014, Craiova, Romania, publisher IEEE, pp.: 5.

[18] N. Bizdoaca, S. Degeratu, “Robotic Finger Actuated with Shape-Memory Alloy Tendon,” WSEAS Proceedings of Soft Computing, Optimization, Simulation & Manufacturing Systems, Malta, pp. 897-906, 2003.

[19] S. Degeratu, P. Rotaru, S. Rizescu, N. G.Bîzdoacă, “Thermal study of a shape memory alloy (SMA) spring actuator designed to insure the motion of a barrier structure,” Journal of Thermal Analysis and Calorimetry, February 2013, vol. 111, Issue 2, pp. 1255-1262.

[20] S. Degeratu, S. Rizescu, N.G. Bizdoaca, C. Caramida, V. Degeratu, “Analyzing and Modeling Performance of a New SMA Actuator-based Barrier Structure,” Proceedings of 7th International Conference on Electrical and Electronics Engineering, ELECO 2011, Bursa, Turkey, 1-4 December, 2011, vol. 2, pp. 110-114.

[21] S.Degeratu, N.G. Bizdoaca, S. Rizescu, P. Rotaru, V. Degeratu, and G. Tont, “Barrier structures using shape memory alloy springs,” Proceedings of WSEAS International Conference DEEE, 2010, Tenerife, December 29-October 2, pp. 367372.

[22] http://www.velleman.eu/products/view/?country=be&lang=en&id=350526.

[23] www.adelaida.ro

[24] http://www.industry.siemens.nl/automation/nl/nl/industriele-automatisering/industrial-automation/simatic-controller/logica-module-logo/logo-modulair-uitbreidingsmodules/Documents/e20001-a1120-p271-x-7600_20-21.pdf.

[25] http://w3.siemens.com/mcms/power-supply-sitop/en/logo-power/Pages/default.aspx.

[26] Jameco electronics catalog. 2012;625. p. 61. ftp://ftp.jameco.com/Archive/PreviousCatalogs/624catalog.pdf