

ALGORITHM FOR POSITIONING OF ROTARY ACTUATORS BASED ON SHAPE MEMORY Cu-Al-Ni TENSILE FORCE ELEMENTS

A. Priadko^{1*}, S. Pulnev¹, O. Kovalev^{2,3}, I. Ilin²

¹Ioffe Institute, Polytechnicheskaya 26, St. Petersburg, 194021, Russian Federation

²Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya str. 29, St. Petersburg, 195251, Russian Federation

³Turner Scientific Research Institute for Children's Orthopedics, Parkovaya str. 64-68, Pushkin, St. Petersburg, 196603, Russian Federation

*e-mail: aiprdko@mail.ru

Abstract. This paper considers positioning algorithms for rotary actuators based on shape memory Cu-Al-Ni crystals. The actuator function scheme is provided. An algorithm for positioning of the actuator based on an actual rotary angle has been developed. Experimental results on the control algorithm and the actuator are presented. The functional characteristics of the actuator (rotation speed and positioning accuracy) are considered.

Keywords: shape memory effect, Cu–Al–Ni single crystals, cyclic rotary actuator, positioning algorithms

1. Introduction

Actuators based on shape memory alloys (SMA) are characterized by a high power-to-weight ratio and silent operation [1]. These properties make them ideal candidates for applications in robotics [2-3]. Typically a Cu-Al-Ni wire, usually shaped into a helical spring, is used as a force element in rotary and linear SMA actuators [4-5]. Due to a small diameter and high electrical resistance, the SMA wire can be directly heated by passing an electrical current through it. Unfortunately, force elements of this type typically have a low power output. An alternative approach is to use SMA cylindrical rods as force elements. In this case, the SMA force element has to be heated externally by a dedicated heater, but the developed force is substantially higher compared to that of a helical shaped force element. For example, a 3-mm-diameter SMA rod can develop a force up to 1500 N. In this paper we consider SMA actuators with rod-shaped force elements.

In our previous publications [6-12] we investigated the design of cyclic rotary and linear actuators based on the shape memory effect in relation to the properties of Cu-Al-Ni single crystals. This publication follows up on our earlier study of the design and control system for a cyclic rotary actuator [13] and describes the positioning system of such an actuator with rod-shaped force elements.

2. Actuator design

A detailed description and design of the cyclic rotary actuator used in this study can be found in Ref. [13]. Figure 1 shows the actuator scheme. The actuator consists of two Cu–Al–Ni force elements each having an individual electric heater (not shown in Fig. 1). The shaft is supported by two rolling bearings mounted in a supporting body. The rotation angle of the shaft is measured by a rotary transducer which is attached to one end of the shaft by a

coupling bushing. One end of each force element is hinged to the actuator body by means of a sleeve and a pin. Another end is connected by the sleeve to a lever, which is rigidly attached to the output shaft.

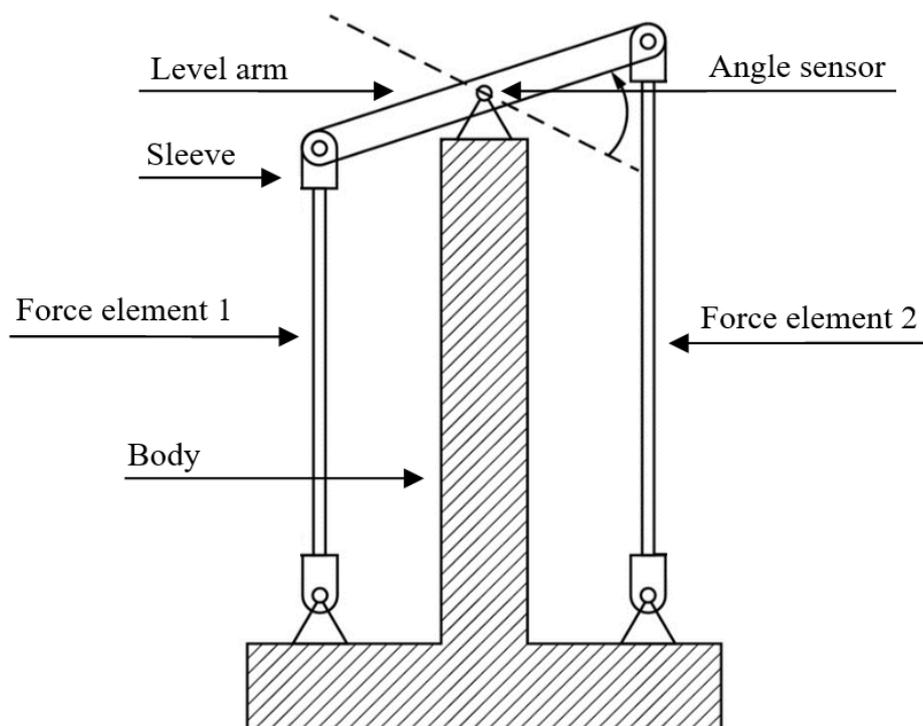


Fig. 1. Actuator scheme

Force elements are 148 mm in length and have a cylindrical section with a diameter of 3 mm. Both ends of the force element have an M6 male screw thread. Each force element has a dedicated heater consisting of a Ni-Cr alloy wire insulated with silica fiber and wound in coils around the force element. Temperatures of the force elements are measured by thermocouples placed between the coils of the heating wire. The end of the thermocouple is coated by thermal conductive grease in order to get good thermal contact with the force element.

The main parameters of the actuator are shown in Table 1.

Table 1. Actuator parameters

	Designation	Value	Units
Diameter of force element	d	3	mm
Length of undeformed force element	L	148	mm
Reversible deformations	ε_{SM}	0.08	
Heating element power	P	135	W
Operating temperature	T	60 - 200	°C
Type of thermocouple		Chromel-Alumel	

In this paper, we focus on an in-depth analysis of actuator performance characteristics in the positioning mode.

3. Logic scheme of an actuator control system

The actuator control system consists of the following elements: a personal computer, an Arduino microcontroller, a software for actuator control, a 270W power supply, a 5V DC–DC

stabilizer, two k-type thermocouples, two thermocouples signals amplifiers, and two high current transistors.

A functional diagram of the actuator control system is shown in Fig. 2. The controller collects the data from the sensors, i.e. the temperature of each force element and the angular position of the shaft and sends them to the PC. The control software on the PC analyzes the sensor data and input parameters set by a user ("input parameters" on Fig. 2) and adjusts heating/cooling accordingly. The output power of the heaters is controlled by pulse-width modulation (PWM) of the transistors in the power supply circuit. Also, the software displays reading from the sensors and plots the results in real-time ("output parameters" in Fig. 2).

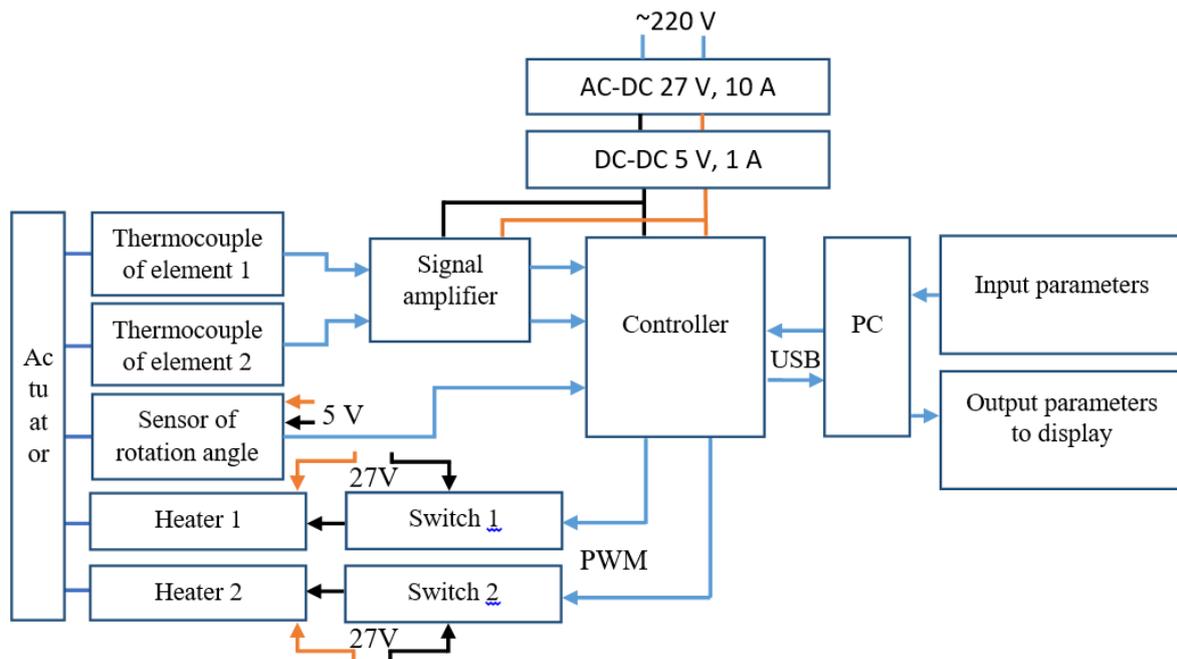


Fig. 2. Functional diagram of the actuator control system

4. A control algorithm

Realization of the control algorithm. The control algorithm was implemented using the MatLab software package. The Arduino Uno microcontroller was communicated via a Serial-USB port using the MatLab Support Package for Arduino Hardware.

In our prior work [13] we described the control algorithm for an actuator working in a cyclic mode. There MatLab script was used to calculate the desired temperature of each force element. The power supplied to each of the heaters was adjusted using a proportional-integral (PI) controller to achieve that temperature set point.

In this paper, we present an updated version of that algorithm. The key difference is the addition of the position feedback provided by the angular transducer. A proportional (P) controller is used to position the actuator shaft at the desired angle. The control diagram is shown in Fig. 3.

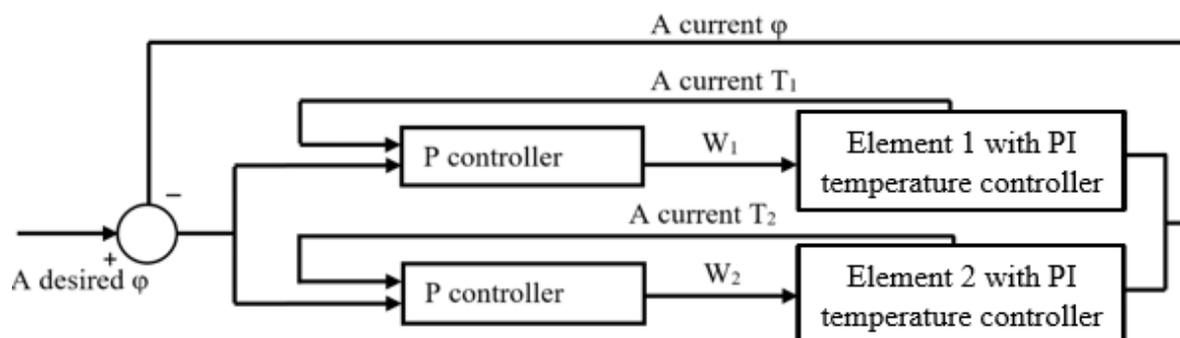


Fig. 3. Angle control diagram

The actuator positioning without a load. We conducted a series of experiments to test the actuator control algorithm and analyze the specifics of using shape memory elements in actuators.

The first experiment demonstrates the actuator performance when the shaft rotates from 0° to 60° and then back to 0° . Figure 4a shows the dependence of the angular position and temperature versus time. Figure 4b shows strain-temperature hysteresis loops for both force elements. As one can see the dependence of the angle versus time is nonlinear; the fastest motion is achieved in the range from 15° to 60° where the rotation speed is approximately constant and can be controlled. It is noteworthy that the heating of the first force element mirrors the cooling of the second force element and vice versa (Fig. 4a). This effect originates from the very logic of the temperature control algorithm. The hysteresis loops of thermomechanical behavior of elements almost coincide with each other. The regions of the curve in the vicinity of the start and end temperatures of the phase transformations are special in the sense that the temperature variation does not produce any significant displacement. These regions can be defined as 80°C - 120°C and 150°C - 160°C for the heating branch, and 150°C - 120°C and 100°C - 80°C for the cooling branch. Thus, we can conclude that the optimal stroke is about 50° (i.e. from 10° to 60°), which is 77% of maximum stroke.

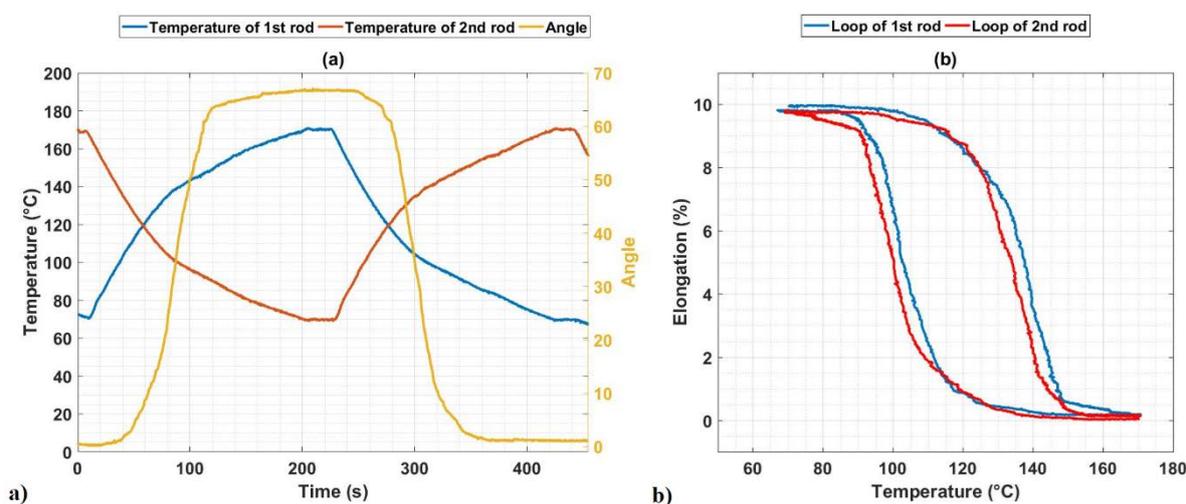


Fig. 4. Cyclic rotation: a) the actuator parameters diagram; b) hysteresis diagrams

The next experiment demonstrates the actuator performance going through the following consecutive motions: from 0° to 50° , then a rotation from this position to 30° , then from 30° to 27° , and finally from 27° to 26° (Fig. 5 and Fig 6). It can be seen that the P controller can achieve the desired angle position for small and large angular displacements. The investigation and analysis of the positioning limit will be given in the next works.

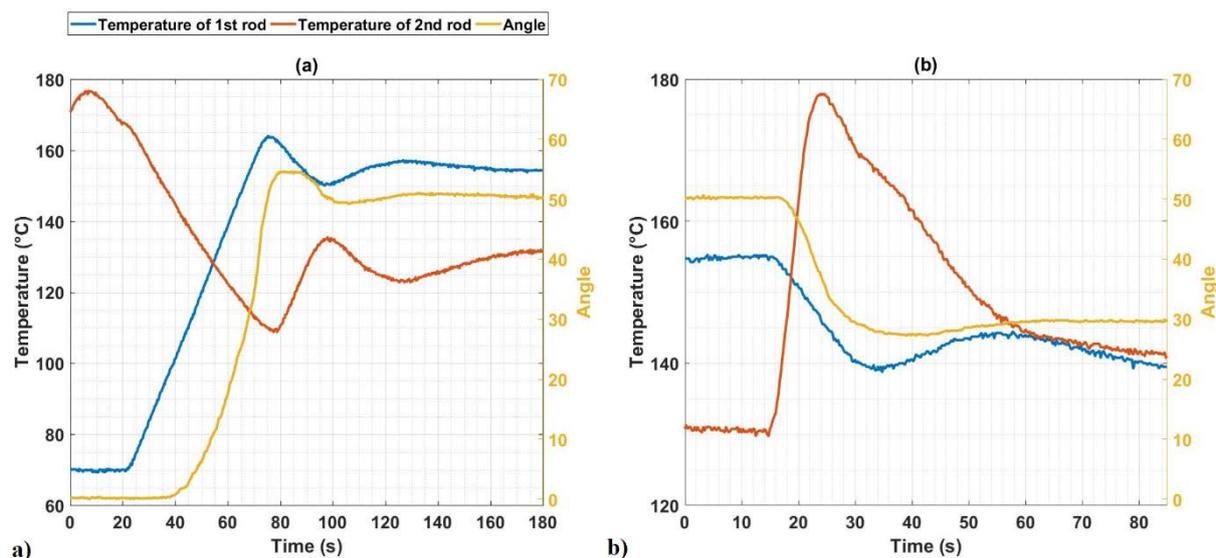


Fig. 5. Rotation from some angle totarget angle: a) from 0° to 50° b) from 50° to 30°

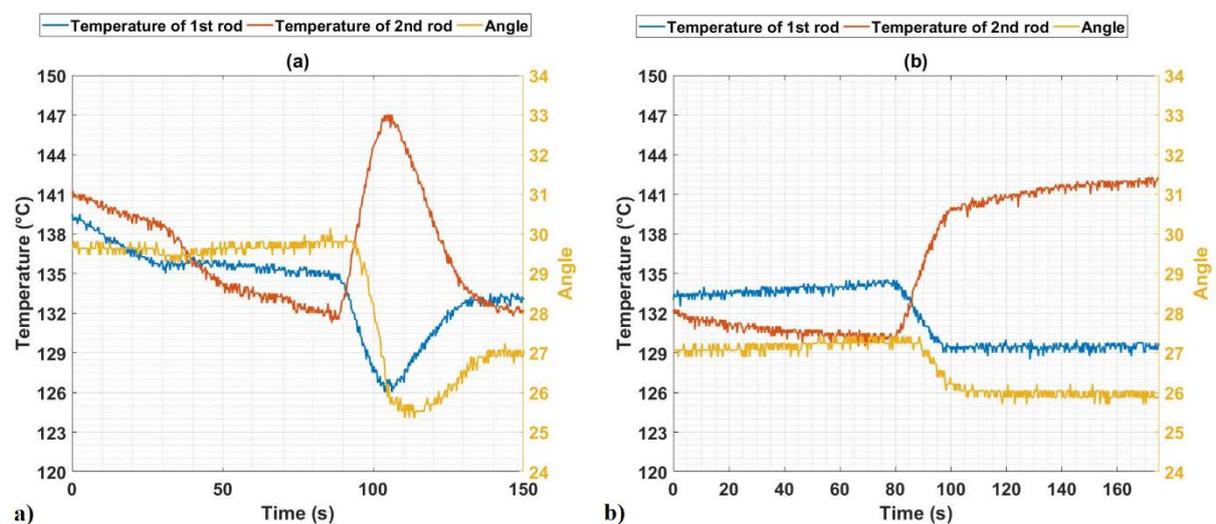


Fig. 6. Rotation from some angle to the desired angle: a) from 30° to 27° b) from 27° to 26°

In the next experiments we investigated how the actuator control algorithm copes with large and small changes of the angular position (Fig. 7). It can be seen that the difference between the starting position and the setpoint does have a significant impact on the rotation time. Typically the actuator can reach the target position in one or two oscillations.

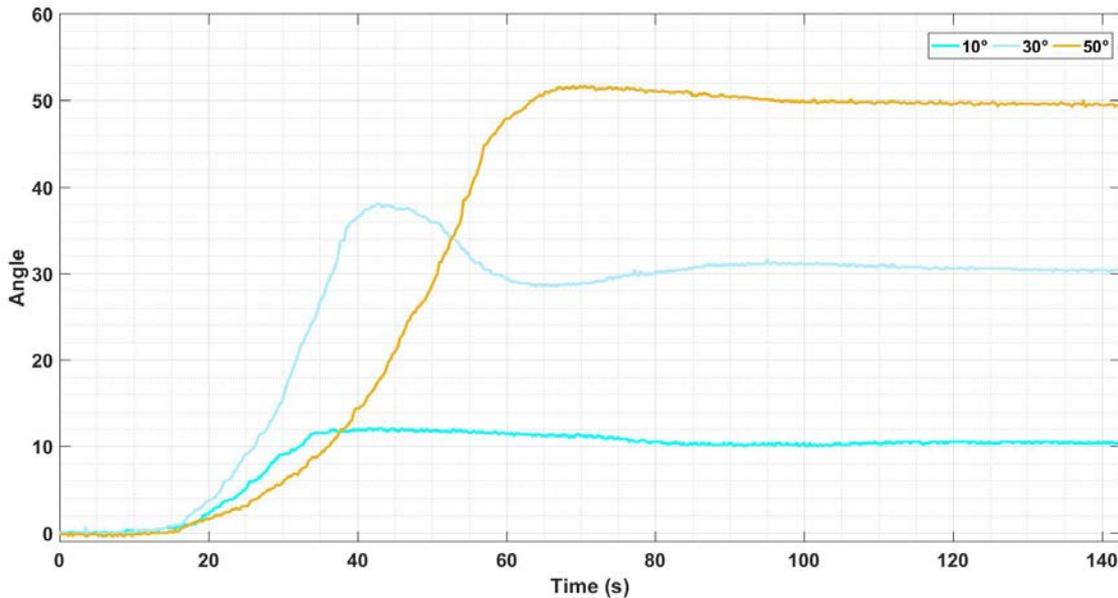


Fig. 7. Rotation from 0° to 10°, 30°, 50°

The conducted experiments yielded the following important conclusions:

- shape memory elements can be successfully employed in rotary cyclic actuators;
- precise control of actuator position can be achieved by the use of a P controller;
- the rotation angle difference does significantly impact the rotation time;
- the actuator can equally well cope with large and small angular displacements.

5. Conclusion

The actuator design and functional diagram are provided. An algorithm for positioning the actuator based on an actual angular position is designed. Experimental results on the performance of the control algorithm and the actuator are presented. The stabilization time is the same for large and small angular displacements. The positioning accuracy is better than 1°. It is sufficient to use P controller for angular position and PI controller for temperature. Further research should be aimed at the investigation of the actuator performance under load.

Acknowledgements. This work was supported by the Russian Science Foundation under Project 16–19–00129.

References

- [1] Robert BG, Russell RA. A novel differential shape memory alloy actuator for position Control. *Cambridge University Press*. 1995;13(4): 423-430.
- [2] Dutta SM, Ghorbel FH.. Differential hysteresis modeling of a shape memory alloy wire actuator. *IEEE/ASME Trans. Mechatronics*. 2005;10: 189-197.
- [3] Song G, Zhao J, Zhou X, Abreu-Garcia J. Tracking control of a piezoceramic actuator with hysteresis compensation using inverse Preisach model. *IEEE/ASME Trans. Mechatronics*. 2005;10: 198-209.
- [4] Sharma SV, Nayak MM, Dinesh NS, Umanand L. Micro Stepping Of Shape Memory Alloy Based Poly Phase Motor. In: *IEEE International Conference on Industrial Technology, Chengdu*. 2008. p.1-6.
- [5] Hisseine D. Modeling and control of shape memory actuator. *IFAC Proceedings Volumes*. 2006;39(16): 1059-1064.

- [6] Jani JM, Leary M, Subic A, Gibsone MA. A review of shape memory alloy research, applications and opportunities. *Materials and Design*. 2014;56: 1078-1113.
- [7] Pulnev SA, Nikolaev VI, Malygin GA, Kuzmin SL, Shpeizman VV, Nikanorov SP. Generation and relaxation of reactive stresses in Cu-Al-Ni shape-memory alloy. *Technical Physics*. 2006;51(8): 1004-1007.
- [8] Nikolaev VI, Pulnev SA, Malygin GA, Shpeizman VV, Nikanorov SP. Generation and relaxation of reactive stresses in a Cu-Al-Ni shape memory alloy upon cyclic temperature variation in the range 293-800 K. *Physics of the Solid State*. 2008;50(11): 2170-2174.
- [9] Nikolaev VI, Averkin AI, Egorov VM, Malygin GA, Pulnev SA. Influence of incomplete shape memory deformation on the generation of reactive stresses in single crystals of the Cu-Al-Ni alloy. *Physics of the Solid State*. 2014;56(3): 522-526.
- [10] Pulnev S, Nikolaev V, Priadko A, Rogov A, Viahhi I. Actuators and Drivers Based on CuAlNi Shape Memory Single Crystals. *Journal of Materials Engineering and Performance*. 2010;20: 497-499.
- [11] Priadko AI, Pulnev SA, Nikolaev VI, Rogov AV, Shmakov OA, Golyandin SN, Chikiryaka AV. Investigation of single crystal Cu-Al-Ni alloy bending force elements for linear motors. *Materials Physics and Mechanics*. 2016;29(2): 158-165.
- [12] Priadko AI, Nikolaev VI, Pulnev SA, Stepanov SI, Rogov AV, Chikiryaka AV, Shmakove OA. Shape memory Cu-Al-Ni single crystals for application in rotary actuators. *Materials Physics and Mechanics*. 2017;32(1): 83-87.
- [13] Priadko AI, Pulnev SA, Kovalev OO, Ilin IA. Rotary actuator control based on tensile force elements made of shape memory Cu-Al-Ni crystals when operated in a cyclic mode. *Materials Physics and Mechanics*. 2019;42(4): 407-414.