Application of an actuator made of a material with a shape memory effect for a transformable space structure

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Abstract. Increase in the operational functionality of space technology leads to the necessity of creating large-sized transformable systems. The development of adequate models which are used in computational experiments to simulate the opening of transformable space structures is of great importance. Significant progress has been made in the field of creating large-sized transformable space antennas: the ratio of the mass of the reflector to its working area has decreased to 0.5–1.5 kg/m^2. Despite the significant progress achieved in the design of such structures, the task of ensuring smooth and reliable deployment of large-sized transformable space structures, while ensuring their subsequent functioning, remains important. An important area of applied research in the field of shape memory materials is the creation of thermomechanical force actuators that deploy large-sized space structures. Actuators with shape memory effect makes the opening process easy to control, ensuring its shock-free nature. As an active element of the force actuator, it is proposed to use a wire made of titanium nickelide material with a shape memory effect. To develop a functional model of the actuator's active element made of a shape memory material, a series of experimental and theoretical studies was carried out.

1 Introduction

The complication of design schemes and the increase in the dimensions of modern large space structures due to the increase in their operational functionality leads to the necessity of creating systems with different configurations in transport and operating states (figure 1).

When the required parameters of working orbits are reached, the process of deploying or transformation of large space structures is carried out [1]. The procedure of opening such space systems occurs under the influence of force actuators, which, generally, use various kinds of springs and electric motors. To date, in the field of space systems, many variants of opening large structures have been developed [2–5]. Shock-loads occur when the operating state is fixed after the completion of the structural transformation process in orbit [6].

In recent years, materials with shape memory effect (SME) are widely used in space technology [7, 8]. It is possible to create large space structures in orbit that use force actuators for their deployment, the active elements of which are made of materials with SME [9–13]. Active elements that use a change in temperature to control their deformation will allow for controlled slow deployment of large space structures. The defining relations for materials with SME, which represent the stress-strain dependences, temperature, and the fraction of

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(a) (b)

Figure 1. Large-sized transformable space antennas: (a) umbrella-type antenna reflector with a diameter of 12 m; (b) petal-type antenna with a diameter of 10 m

phase composition, are essentially nonlinear. This causes great mathematical difficulties in calculating the force characteristics (force-displacement relations) of active elements of actuators made of materials with SME [14]. Also, along with the problem of deformation of active elements, it becomes necessary to solve the problem of thermal conductivity [15, 16]. Therefore, the main role in creating such force actuators is currently played by experimental methods [17].

2 Experimental studies

In a force actuator, it is proposed to use a wire made of titanium nickelide material as an active element, which is heated during operation by passing an electric current through it (figure 2).

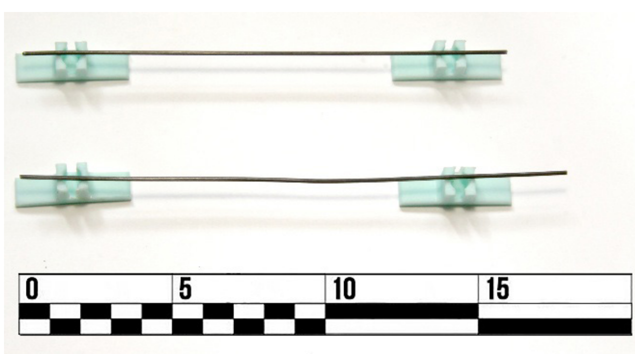


Figure 2. Active elements made of titanium nickelide material

The main characteristics of the active element of a force actuator made of SME material are: developed force, actuation time, maximum displacement or working stroke. To study the main characteristics of active elements, a large series of experimental studies were conducted. In the course of these experimental studies, the following parameters were measured: temperature of active element, electrical resistance, operating stroke, actuation time, and generated force.

The active elements of the force actuator (a wire made of titanium nickelide material with a diameter of 1.5 mm) were previously subjected to various types of heat treatment. Length of the samples was 160 mm. Heat treatment was performed to eliminate possible internal stresses. Then the samples of active elements were preliminarily stretched (deformed) to a relative elongation of about 10% and fixed in this state, the maximum external force was 1.2 kN. After removing the fixation, their length decreased by 1.0–1.2% of the new length. Then the active elements were heated. When the temperature of the beginning of the reverse martensitic transformation was reached, the active elements decreased their length by 4–5%. This decrease in the length of active elements ceased at the temperature of the end of the reverse martensitic transformation. During the repeated test cycle, the active elements were stretched to a relative elongation of about 7% and fixed in this state, while the external force was 1.15 kN. After removing the fixation, their length decreased by 1.2–1.4% of the new length. Further, the active elements were reheated and they reduced their length by 5%.

In the next cycle, the active elements were stretched to a relative elongation of about 7%, with an external force of 1.25 kN. After removing the fixation, their length decreased by 1.4–1.7% of the new length (figure 3).

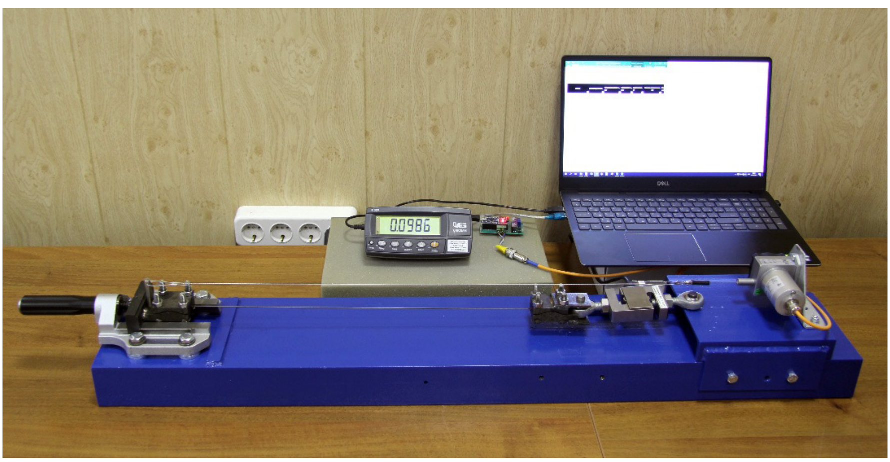


Figure 3. Experimental setup for preliminary deformation of active elements

Then the active elements were heated again and they reduced their length by 5%. The length of the samples after three test cycles was approximately 170 mm. When heated, they developed a longitudinal force of about 0.8–0.9 kN. Tests of active elements of the force actuator made of material with SME were carried out on the experimental setup shown in figure 4.

These tests were carried out to assess the stability of the main characteristics of the active elements of the force actuator, such as the working stroke (reduction of the relative elongation of the active element), the developed force (force generated by the active element) and the actuation time. Figure 5 shows the results of the conducted experimental studies.

Two methods were used to measure the temperature of the active element: contact and non-contact. In the contact method, a set of thermocouple sensors placed along the length of the active element was used. For non-contact measurement, a thermal imager was used that measures the radiation of the active element in the IR range. Using a digital multimeter operating in the ammeter mode, the current was measured. The magnitude of the current changed due to changes in the resistivity of the active element during the test. To measure the force, developed by the active element, a digital dynamometer with an external strain gauge

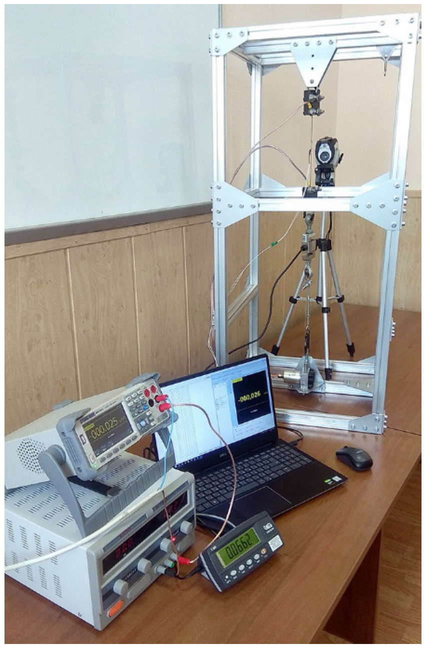
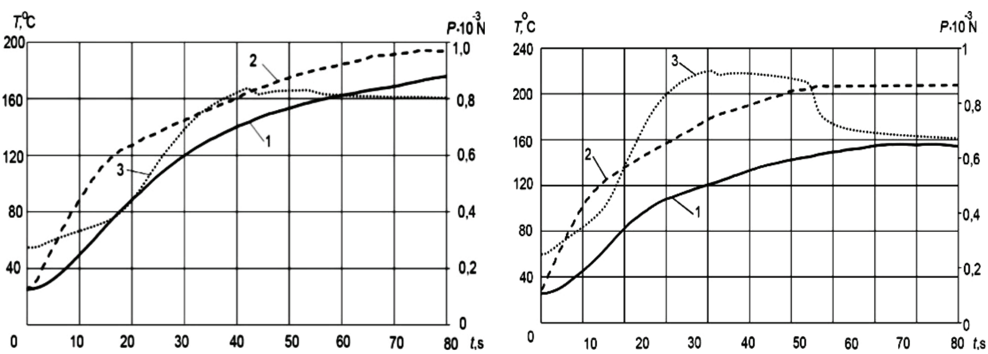


Figure 4. Experimental setup for determining the main characteristics of the active elements of the force actuator



(a) (b)

Figure 5. Experimental results: (a) active element with a length of 174 mm after the first deformation; (b) active element with a length of 180 mm after the second deformation; 1—temperature change when measured by thermocouple; 2—temperature change when measured by a thermal imager; 3—change in the force developed by the active element

was used. During the tests, the displacement of the active element was measured using a special cable sensor, the operation of which is based on the strain effect. This measurement made it possible to determine the change in the relative elongation (working stroke) of the active element with a fairly high accuracy.

When calculating the temperature change of the active elements of the force actuator in ground tests, the heat exchange coefficient was selected. When conducting a numerical experiment, the results obtained correlated well with the data of experimental studies. At the same time, the calculations took into account changes in the resistance and heat capacity of active elements during their heating.

3 Model of functioning of the active element of the force actuator

In the course of ground-based experimental studies, it can be assumed that the change in the thermal energy of the active elements of the force actuator is equal to the amount of heat received due to electrical energy minus heat losses from natural convection

$$cm\frac{dT}{dt} = RI_1^2 - \alpha S(T - T_a), \tag{1}$$

where c—specific heat capacity; m—mass of the active element; T—temperature of the active element; t—time; R—resistance of the active element; I_1—current in the active element during testing; α—heat exchange coefficient; S—heat exchange surface area; T_a—ambient temperature.

When operating in orbit, it can be assumed that the change in the thermal energy of the active element of the force actuator is equal to the amount of heat received due to electrical energy minus thermal losses from radiation in orbit

$$cm\frac{dT}{dt} = RI_2^2 - \varepsilon\sigma_0 T^4 S, \tag{2}$$

where I_2—current in the active element in orbit; ε—emissivity; σ_0—Stefan–Boltzmann constant. Find the equilibrium temperatures from (1) and (2) under the condition $dT/dt = 0$

$$\bar{T}_1 = \frac{RI_1^2}{\alpha S} + T_a, \quad \bar{T}_2 = \sqrt[4]{\frac{RI_2^2}{\varepsilon\sigma_0 S}}. \tag{3}$$

The power supply voltage is determined by the formula

$$U = RI.$$

Then the relation (3) can be represented as

$$\bar{T}_1 = \frac{U_1^2}{\alpha S R} + T_a, \quad \bar{T}_2 = \sqrt[4]{\frac{U_2^2}{\varepsilon\sigma_0 S R}}, \tag{4}$$

where U_1, U_2 is the voltage of power sources on earth and in space accordingly.

To ensure an approximate similarity of processes during ground tests and in orbit, it is necessary that

$$\bar{T}_1 = \bar{T}_2. \tag{5}$$

Then from (5) we obtain

$$\frac{U_1^2}{\alpha S R} + T_a = \sqrt[4]{\frac{U_2^2}{\varepsilon\sigma_0 S R}}. \tag{6}$$

Convert (6) to the form

$$U_2 = \sqrt{\varepsilon\sigma_0 S R}\left(\frac{U_1^2}{\alpha S R} + T_a\right)^2. \tag{7}$$

In the course of conducting experimental studies in ground conditions, the initial length of the active element of the force actuator was equal to 174 mm, the power supply voltage was 2.2 V. The resistance of the active element of the force actuator, obtained during the tests, was 0.09 Ohms. Substituting these values in formula (7), we obtain an approximate value of the power supply voltage U_2 in orbit, which is necessary to fulfill condition (5),

$$U_2 \approx 1.77 \text{ V}.$$

The following values included in relation (7) were used in the calculation:

$$\alpha = 50 \,\frac{\text{W}}{\text{m}^2\,\text{K}}, \quad S = 8.19 \cdot 10^{-4}\ \text{m}^2, \quad T_a = 298 \text{ K},$$
$$\varepsilon = 0.66, \quad \sigma_0 = 5.67 \cdot 10^{-8}\,\frac{\text{W}}{\text{m}^2\,\text{K}^4}.$$

4 Conclusion

The proposed actuator uses an active element, made of a wire of titanium nickelide material with SME, which is heated during operation by passing an electric current through it. As a result of experimental studies, the strain-force characteristics of active elements operating under uniaxial compression were studied. It has been determined that force actuators with active elements made of titanium nickelide material with SME have the advantages of generating significant forces, low weight and low power consumption.

The change in the relative elongation and the force generated by the active element of the force actuator occurred smoothly during experimental studies. When varying the amount of voltage supplied to the active element of the force actuator, the time of its operation varied greatly. However, it is worth noting that despite the significant difference in the actuation speed of the force actuator, the working stroke of the active element remained constant.

In the course of quantitative and qualitative studies of the active elements of the force actuator, it was established that it ensures very slow movements, which are necessary for a smooth shock-free transformation of large space structures in orbit. The main characteristics of these force actuators will ensure reliable opening of promising transformable space structures.

The development of a model of the functioning of the active element of the force actuator will allow to obtain its main characteristics (developed force, actuation time, working stroke), as well as the power and voltage of the power source. If necessary, using the model, it will be possible to adjust the design parameters of the active element (length, shape and dimensions of its cross-section) and the conditions of its heating.

References

[1] N.V. Banichuk, I.I. Karpov, D.M. Klimov et al., *Mechanics of large space structures* (Factorial, Moscow, 1997)

[2] A.V. Lopatin, M.A. Rutkovskaya, *Review of the designs of modern transformed space antennas (Part 1)*, Bulletin of the Siberian State Aerospace University named after academician M.F. Reshetnev, **2**, 51 (2007)

[3] V. Hasanzade, S.H. Sedighy, M. Shahravi, *Compact deployable umbrella antenna design with optimum communication properties*, J. Spacecr. Rockets, **54(3)**, 782 (2017)

[4] F. Zheng, *Affordable system conceptual structure design of new deployable spaceborne antenna*, in 33rd AIAA International Communications Satellite Systems Conference and Exhibition, 7–10 September 2015, Queensland, Australia (2015)

[5] S.V. Ponomarev, *Transformable reflectors of spacecraft antennas*, Bulletin of the Tomsk State University. Mathematics and Mechanics, **4(12)**, 110 (2011)

[6] V.N. Zimin., Z. Zikun, A.V. Krylov, S.A. Churilin, *Mathematical modelling of the deployment of a large transformable space structure*, AIP Conf. Proc., **2171**, 030002 (2019)

[7] L.W.Y. Feng, P. Martinez, *MEDUSA—Mechanism for Entrapment of Debris Using Shape Memory Alloy*, in 67th International Astronautical Congress, 26–30 September 2016, Guadalajara, Mexico (2016)

[8] E. Im, M. Thomson, H. Fang, J. Pearson, J. Moore, J. Lin, *Prospects of large deployable reflector antennas for a new generation of geostationary Doppler weather radar satellites*, in AIAA SPACE Conference & Exposition, 18–20 September 2007, Long Beach, California, USA (2007)

[9] K.J. De Laurentis, A. Fisch, J. Nikitczuk, C. Mavroidis, *Optimal design of shape memory alloy wire bundle actuators*, in Proceedings 2002 IEEE International Conference on Robotics and Automation, **3**, 2363 (2002)

[10] F. Schiedeck, T. Hemsel, J. Wallaschek, *The use of shape memory alloy wires in actuators*, Solid state Phenomena, **113**, 195 (2006)

[11] C. Liang, C.A. Rogers, *Design of shape memory alloy Actuators*, J. Intell. Mater. Syst. Struct., **8(4)**, 303 (1997)

[12] V.A. Likhachev, A.I. Razov, A.G. Cherniavsky, Yu.D. Kravchenko, S.N. Trusov, *Truss mounting in space by shape memory alloys*, in The First International Conference on Shape Memory and Superelastic Technologies, 7–10 March 1994, California, USA (1994)

[13] A. Riad, A. Ainamany, M. Benzohra, *The shape memory alloy actuator controlled by the Sun's radiation*, Materials Research Express, **4(7)**, 075701 (2017)

[14] I.V. Mishustin, *Three-level model of a shape memory alloy and its application to the description of the effect of reversible shape memory*, Mech. Compos. Mater. Struct., **18(4)**, 463 (2012)

[15] V.A. Barvinok, V.I. Bogdanovich, O.V. Lomovsky et al., *Development of reversible power drives from materials with the effect of memory of form for devices, applied in the knots of check off of space vehicles*, Izvestia of Samara Scientific Center of the Russian Academy of Sciences, **13(4-2)**, 301 (2011)

[16] V.A. Barvinok, V.I. Bogdanovich, A.A. Groshev et al., *Design method of power drives from material shape memory effect for rocket and space technology*, Izvestia of Samara Scientific Center of the Russian Academy of Sciences, **15(6)**, 272 (2013)

[17] V.N. Zimin, A.V. Krylov, A.O. Shakhverdov, *Development of the mathematical model of the force actuator for deployment of large-sized space structures*, J. Phys.: Conf. Ser., **1902(1)**, 012115 (2021)