MODELLING AND SIMULATION OF THE THERMOELASTIC NYLON ACTUATOR

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1. Introduction

Like actuators and sensors, artificial muscles are needed for diverse applications, ranging from humanoid robots, prosthetic limbs, exoskeletons and other mechatronic applications. There are several material options for making them and each has specific properties and features [1-2]. One option is the low-cost high-strength polyethylene and the nylon fibers, most commonly used in fishing line. The polymer fibers are twisted to make them chiral, which enables them to function as torsional and tensile muscle. A tensile stroke is greatly amplified by inserting such a large amount of twist that some twist converted to fiber coiling. By completely coiling, tensile contractions exceeding the maximum in vivo stroke of human skeletal muscles are obtained. Immediately after coiling adjacent coils are in contact, limiting contraction during actuation, and must be separated by increasing load or reducing twist. When adjacent coils contact, due to insufficient applied load or excessive twist, the muscle-direction thermal expansion becomes positive. When adjacent coils do not contact due to applied load, the muscle-direction thermal expansion is negative and the muscle performs mechanical work [3]. In the paper, which is a continuation of our work [4], the like von Mises structure actuator that is made of two nylon springs is proposed. The main purpose of the paper is modelling and simulation of the actuator concerning the elastostatic and thermoelastic analysis. The results obtained by analytical method are presented and discussed.

2. Geometric and material parameters of the nylon von Mises actuator

In design of the electro-thermo-mechanical systems, like sensors and actuators, the von Mises structure, consisting of two straight bars, is very often used - see Fig. 1a. Due to the excellent properties of the nylon springs, their using in the design of such system is straightforward as shown in Fig. 1b. Its action, the force or displacement, is activated by heat through water, air or electric current.

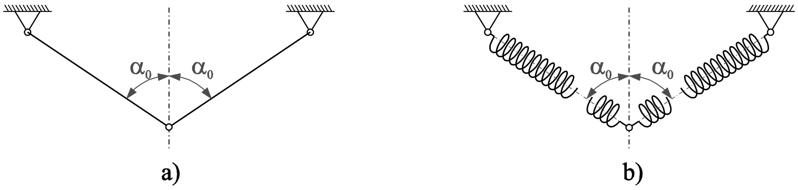

Fig.1: *The von-Mises type actuator*

In our case, following parameters of the actuator and the competent prestressed nylon springs are considered: $l_0 = 135$ mm is the active length of the spring; $n = 155$ is the number of coils; $d = 0.87$ mm is the nylon line diameter after torsion application on the fishing line (Sufix, Suple Link, Finland) of initial diameter equal to 0.8 mm to the state when coiling begin; $R = 0.79$ mm is the middle radius of the coil; $k = 0.082$ N/mm is the measured spring constant;

$\alpha_0 = 78^\circ$ is the initial angle of breakage of the springs. Other measured properties are [4]: $G = 795.5$ MPa is the shear modulus of the twisted line to the state when coiling begin; $k_t = -0.325$ mm/^{0}C is the thermal spring constants; $F_p = 2.3$ N is the prestress force in the springs. The actuator is firstly loaded by the vertical force $F = 0.981$ N acting at point C. Subsequently, the constant tempereature rise Δt is applied on the actuator. In the next chapter, elastic and thermo-elastic mechanical and mathematical model is established by which the resultant thermo-elastic deformation of the actuator is calculated.

3. Mechanical and mathematical model of the actuator for its thermo-elastic analysis

After the load *F* application, the point C moves vertically from the unloaded configuration in its deformed ones - Fig. 2. In the unloaded configuration, the coils are in contact caused by the prestress force F_p. The vertical load *F* elongates the springs above the value $\delta_m = \left(N_c - F_p\right) / k$ to the length $l_m = l_0 + \delta_m$.

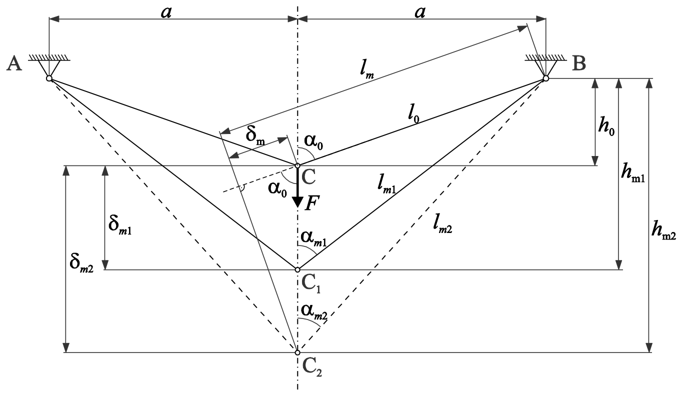

Fig. 2: *Elastic deformation of the actuator*

The new position of the point C caused by vertical load *F* can be calculated analytically by two methods. By the first one, the elongated spring is rotated around the point A to the position C_1 while $l_{m1} = l_m$. The vertical position of the point C_1 is $h_{m1} = \sqrt{l_{m1}^2 - a^2}$ and $a = l_0 \sin\alpha_0$. Then, the vertical displacement of the point C is $\delta_{m1} = h_{m1} - h_0$ while $h_0 = l_0 \cos\alpha_0$. The angle $\alpha_{m1} = \arcsin\left(a / l_{m1}\right)$.

By the second approach, the new position of the point C is obtained by perpendicular projection of the end point of the length l_m to the position C_2. Then, the vertical displacement of the point C is $\delta_{m2} = \delta_m / \cos\alpha_0$ while $h_0 = l_0 \cos\alpha_0$. The new length of the spring is $l_{m2} = \sqrt{a^2 + + h_{m2}^2}$ and the angle $\alpha_{m2} = \arcsin\left(a / l_{m2}\right)$.

For the thermo-elastic analysis the physical model of the actuator is shown in Fig. 3. It is assumed, that the position of the point C in the deformed state is known - particularly the position C_1 or C_2 (see Fig. 2). In the state, the springs are heated by a constant temperature difference Δt and the negative thermal constant of the sprigs k_t is obtained by measurement [4]. Then, the thermal shortening of the spring is $\delta_t = k_t \Delta t$. New position of the point C, namely C_t, can be calculated by similar way as above the elastic deformation is calculated. For short space point of view, the second approach, according the Fig. 3, is described in this chapter. According to it, the vertical shortening $\delta_{t2} = \delta_t / \cos\alpha_{m2}$ and $h_{t2} = h_{m2} - \delta_{t2}$ Again, $l_t = \sqrt{\left(h_{m2} - \delta_{t2}\right)^2 + a^2}$ and $\alpha_{t2} = \arcsin\left(a / l_t\right)$. But the calculation results are shown in Tab. 2 and Fig. 4 for both the approaches (δ_{t1} and δ_{t2}).

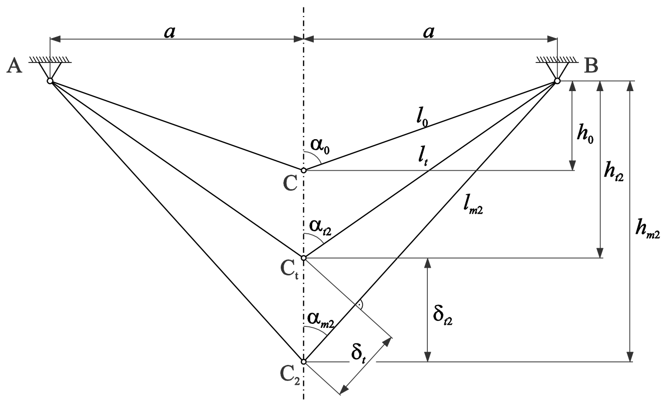

Fig.3: Thermo-elastic deformation of the actuator

4. Numerical experiments

In the chapter, results of the von Mises type actuator elastic (Tab. 1) and thermo-elastic (Tab.2) analysis by the above approaches are presented.

Tab. 1. *Results for elastic analysis.*

$2\alpha_0\,[^\circ]$	$\alpha_{m1}\,[^\circ]$	α_{m2} [mm]	h_{m1} [mm]	h_{m2} [mm]	δ_{m1} [mm]	δ_{m2} [mm]
162	66.68	57.10	57.45	86.25	36.33	65.13
161	68.41	61.62	52.68	71.92	30.40	49.64
160	70.09	65.60	48.14	60.29	24.70	36.84
159	71.74	69.05	43.78	50.80	19.18	26.20
158	73.37	72.00	39.56	43.05	13.80	17.29
157	75.00	74.48	35.44	36.72	8.52	9.80
156	76.64	76.57	31.35	31.53	3.29	3.47

The results in Tab. 1 show strong dependence of the vertical displacement of the point C on the angle α_0. The results also show marginal difference according the used two approaches. Therefore, an experimental verification of the calculated results has to be done. The results from Tab.1 are drawn in Fig. 4. The values denoted by index 1 should be of higher accuracy, because the first proposed model agree better with the reality, for the large displacements.

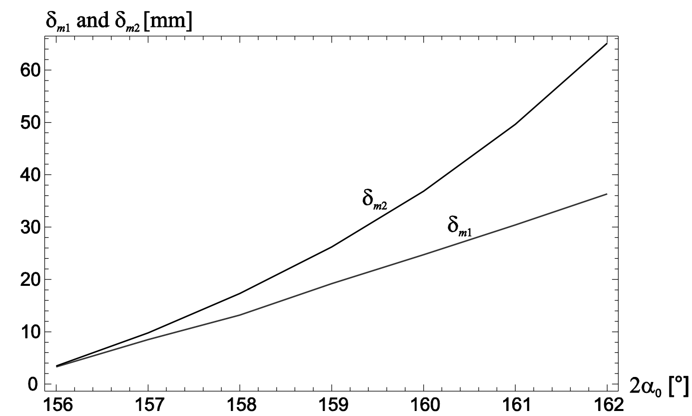

Fig.4: Result for elastic analysis.

Tab. 2 shows results of the thermo-elastic analysis of the actuator. A dependence of the vertical displacements of the points C_1 / C_2 on the temperature rise Δt for several angles α_0 and the two approaches is presented.

Tab. 2. *Vertical displacement for thermo-elastic analysis.*

$\Delta t\left[{}^\circ C\right]/2\alpha_0\left[{}^\circ\right]$	156	157	158	159	160	161	162
2	2.9/2.8	2.6/2.4	2.3/2.1	2.1/1.8	1.9/1.6	1.8/1.4	1.7/1.2
4	6.2/5.6	5.4/4.8	4.8/4.2	4.3/3.6	3.9/3.1	3.6/2.7	3.4/2.4
6	9.9/8.4	8.5/7.3	7.5/6.3	6.7/5.4	6.1/4.7	5.5/4.1	5.1/3.6
8	14.5/11.2	11.9/9.7	10.3/8.4	9.2/7.3	8.3/6.3	7.5/5.5	6.9/4.8
10	20.8/14.0	16.0/12.1	13.5/10.5	11.8/9.1	10.6/7.9	9.6/6.8	8.8/6.0
12	-	21.2/14.6	17.2/12.6	14.7/10.9	13.0/9.4	11.8/8.2	10.7/7.2

The results in Tab. 2 show that the vertical displacement of the point C decreases with increasing of the angle α_0. At the left side of symbol "/" the displacements for the first approach and at the right side the displacements for the second approach are displayed. The results from Tab. 2 are drawn in Fig. 5. Similarly to the previous case, some differences occur between the obtained results that are caused by different geometric model for the deformed actuator.

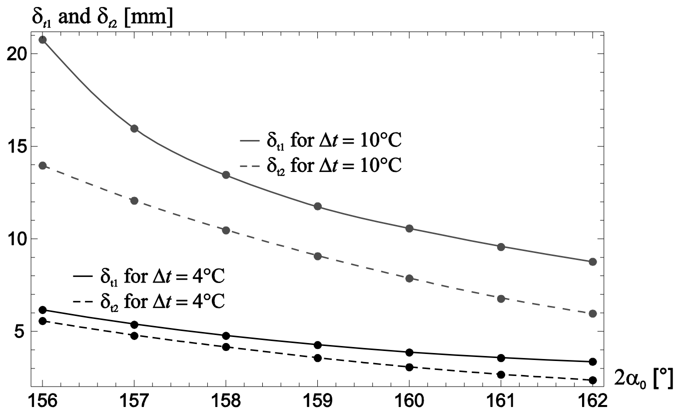

Fig.5: Result for thermo-elastic analysis.

5. Conclusions

In the paper, a mechanical and mathematical model of the von Mises type actuator in a form of two prestressed nylon springs (artificial muscles) made of a fishing line is originally proposed. Elastostatic and thermoelastic analyses are made using an analytical method based on the statics of the simple truss systems. Elastic and thermoelastic properties of the nylon springs are obtained by experimental measurement. Results of the analyses are evaluated and discussed. It is found that the vertical displacement of the acting point of the actuator, loaded by vertical force, non-linear increases with increase the initial angle of breakage of the springs. On the other side, the thermoelastic vertical shortening of the actuator decreases with increase of the angle. This knowledge is needed for optimal design of the actuator in our future research.

Acknowledgement

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