Investigation and development of an actuator based on an elastic element

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Abstract

The main purpose of this work is development and investigation of power-efficient actuator for transforming an applied force into translatory motion. An elastic element (which has the functioning principle based on the phenomenon of loss of stability) is used as an operating element of this device. In addition, there is made the analysis of the analogues of the proposed mechanism. In this paper we propose the actuator design and demonstrate the main components of the mechanism. Moreover, we have described the calculation of the mechanical properties and conditions for the applicability of a working link of the mechanism (an elastic element). Also this research is focused on the study of recuperation mechanisms which is used in actuators for partially restore of the spent energy.

1 Introduction

In the modern world one of the main functions of technology is the partial or complete replacement of a person production functions. Thus, the use of high-tech mechatronic devices allows to save a person from heavy physical activity (labouring job), routine and monotonous work, to eliminate the impact on personnel of harmful factors, and to liquidate the influence of the human factor during work that requires high accuracy, productivity and quality of tasks.

Currently, there are a large number of different types of actuators which are used in virtually all areas of robotics for energy transfer from the controlling object to the controlled object. Along with the most common types of actuators, such as mechanical, electrical, hydraulic and pneumatic, there are complex and "exotic" types of actuators, for example, pneumatic muscle, actuators based on electroactive polymers and metals with memory effect. However, these actuators are not always able to meet the demands for the design of complex mechatronic devices and sometimes designers have to solve the task of developing a new type of execution units. Thus, the main purpose of this work is development and investigation of power-efficient actuator for transforming an applied force into translatory motion.

Like any high-tech mechanisms, the actuator based on an elastic element is energy-dependent. For this reason, one of the central tasks to solve the problems of efficiency and productivity of such machines remains energy performance (energy efficiency).

As one of the solutions to this problem, it is possible to use the introduction of recuperation mechanisms that are aimed at partial restoration of the spent energy with the help of various actuating elements. The elements can be made in the form of elastic elements (for example, springs or elastic rods)[1].

2 Dynamics of recuperation mechanisms

Undoubtedly, a decrease in power consumption increases the time of autonomous operation of various mechanisms and actuators. Therefore, at the moment, various recuperation mechanisms are becoming widely used. The purpose of these mechanisms is partially restore of the spent energy (not only thermal and electrical but also mechanical) for reuse or its accumulation.

The present work is devoted to the investigation of recuperation mechanisms used to restore mechanical energy. We know two types of these devices.

The first type is recuperation mechanism of the executive device designed to convert the applied force into translational motion, where partial energy regeneration occurs due to the elastic properties of the working link in the process of restoring the initial form (further we will consider this mechanism in more detail).

The second type of recuperation mechanisms is a spring accumulator with an output rotary link used for rotational motion [2, 3]. The scheme of this device is shown in Fig. 1

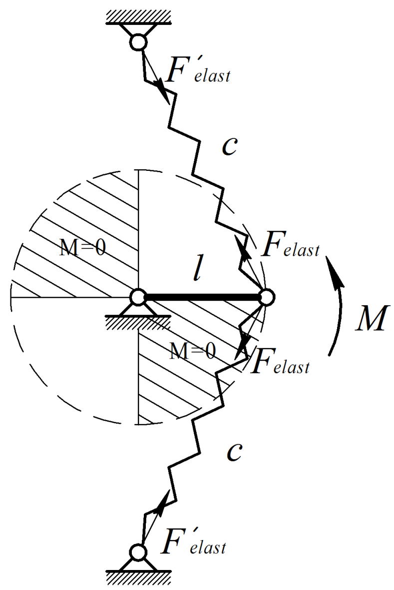

Figure 1: Scheme of the cyclic rotation mechanism with spring accumulator: l — length of the rotating crank; M — engine torque; F_{elast} and F'_{elast} — spring force; c — spring stiffness.

Consider the second device in more detail.

The mechanism is a rotating crank, to the free end of which are attached two springs of equal constant (spring force). The opposite ends of the spring are attached to the base, and are located on the same line and at the same distance from the axis of

the crank rotation. The initial length of these springs is assumed to be 0.1 m, also during the functioning of the mechanism, each of them is in a deformed (stretched) state and reaches the initial length only at the time when the other spring has the largest value of stretching. The described scheme allows the most effective use of a spring accumulator for energy recovery.
The working cycle of turning the mechanism, i.e. the complete turn of the working link about the rotation axis can be mentally divided into four parts (see Fig. 1). Unshaded areas correspond to the stage of "charging" the spring accumulator. Under the action of the drive torque, here takes place the rotational movement of the working link, which acts on the springs, shifts them from the balanced state, compressing one and stretching the other. In this part we should make some explanation: according to the theory of catastrophes and the theory of stability, this mechanism with a spring accumulator (consisting of two identical springs) has two stability positions, i.e. such conditions under which no vibrations of the working link are made, and the state and position of the springs do not change arbitrarily long. In our case at the initial moment of time the mechanism is in the first stable state equal to the zero deviation of the working link relative to the rotation axis. The second stable position is symmetric to it, i.e. it is located at the point of deviation equal to 180 deg. These two states are a kind of attractor for the right and left semicircles of the trajectory of movement of the worker, respectively.
The shaded areas of the trajectory of the working link correspond to the operation cycle of the spring accumulator. Here, the drive is disconnected and the motion is made only by the accumulated springs energy.

3 Modeling of recuperation mechanism

At the next stage of the work, a model of this mechanism was built using the SimMechanics/MATLAB environment (Fig. 2).
The Machine Environment and Ground (1,2) blocks specify the gravitational forces for the model and the mounting and positioning conditions of the machine parts, respectively. Revolute, Body - form the geometry of the rotating working link. Joint Actuator1 is a kinematic drive providing rotational motion. Joint Sensor is designed to obtain output characteristics of the working (actuating) link. Body Spring & Damper (1) perform the roles of non-linear springs. The Subsystem block specifies the input signal which is passed to the Joint Actuator1 drive. The Coulomb & Viscous Friction block is used to account for the effect of friction in the Revolute joint.
Let's talk in more detail about the modeling of friction in this mechanism.
If we take into account all theories of friction, it can be concluded that under friction processes it can be observed the following main effects: elastic deformation of surfaces, plastic deformation of surfaces, ploughing effect, shear of adhesion junctions [4].
This means that under modeling of the friction process, it is necessary to take into account both elastic and viscosity characteristics of friction surfaces.
In our model (Fig. 2) the input of the Coulomb & Viscous Friction block has a value of the body speed, the output has a value of the frictional force. The work basis of

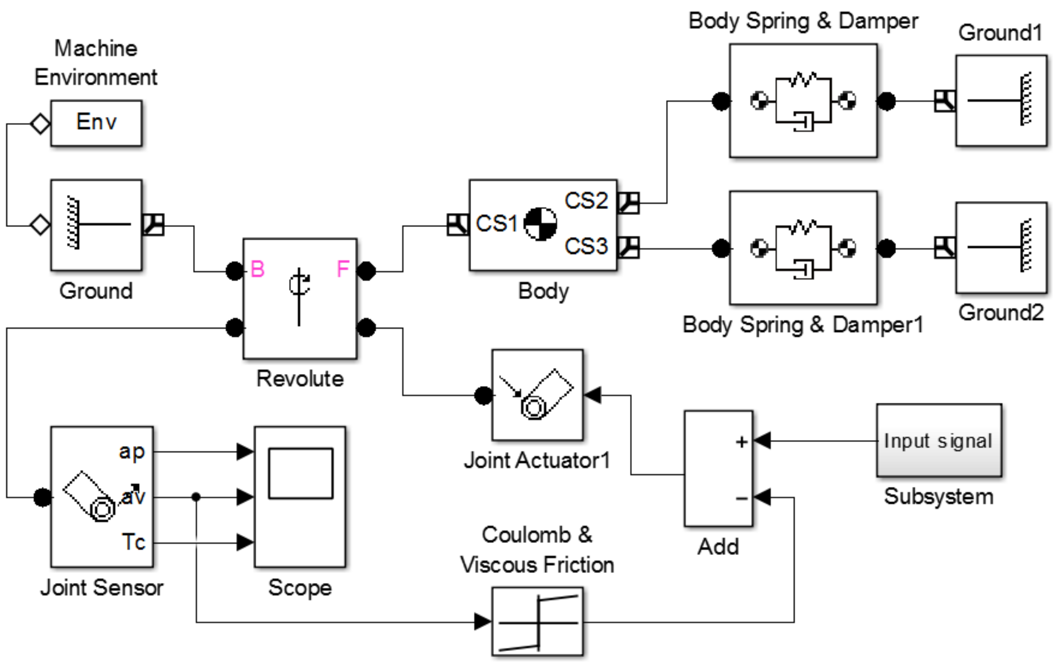

Figure 2: Model of recuperation mechanism with spring accumulator in SimMechanics.

the block is a well-known equation:

$$f = sign(v)(\mu|v| + \eta) \quad (1)$$

where f — friction coefficient; *sign* — function of variable sign determination; v — velocity; μ — coefficient of viscous friction; η — coefficient of dry friction.

At the next stage, experiments for evaluation of the recuperation properties of the resulting mechanism were conducted. As the initial (ideal) device, the mechanism was considered without the use of a spring accumulator. To compare the properties of the two devices, the same signal (corresponding to one complete turn of the actuator) was applied to their inputs of the drive blocks. After that, the data which are characterizing the angle of rotation of the actuator (Angle, deg.), the angular velocity of rotation (Angular velocity, degree/s) and the drive torque (Torque, N*m) were recorded. The obtained graphical results are shown in Fig. 3.

Analyzing the results obtained, it can be noticed that the use of a spring accumulator can significantly reduce the operating time of the drive. This accordingly leads to a reduction of power consumption (this can be seen when comparing the Torque/Time graphs). However, on the other hand, the use of elastic elements increases the frequency of vibrations of the working link, thereby increasing the runtime of the working cycle.

At conclusion, during the work with the application of the MATLAB application package and the SimMechanics library we were able to build a model of the recuperation mechanism and, on its example, show the expediency of using spring accumulators in cyclic rotational mechanisms for energy recovery.

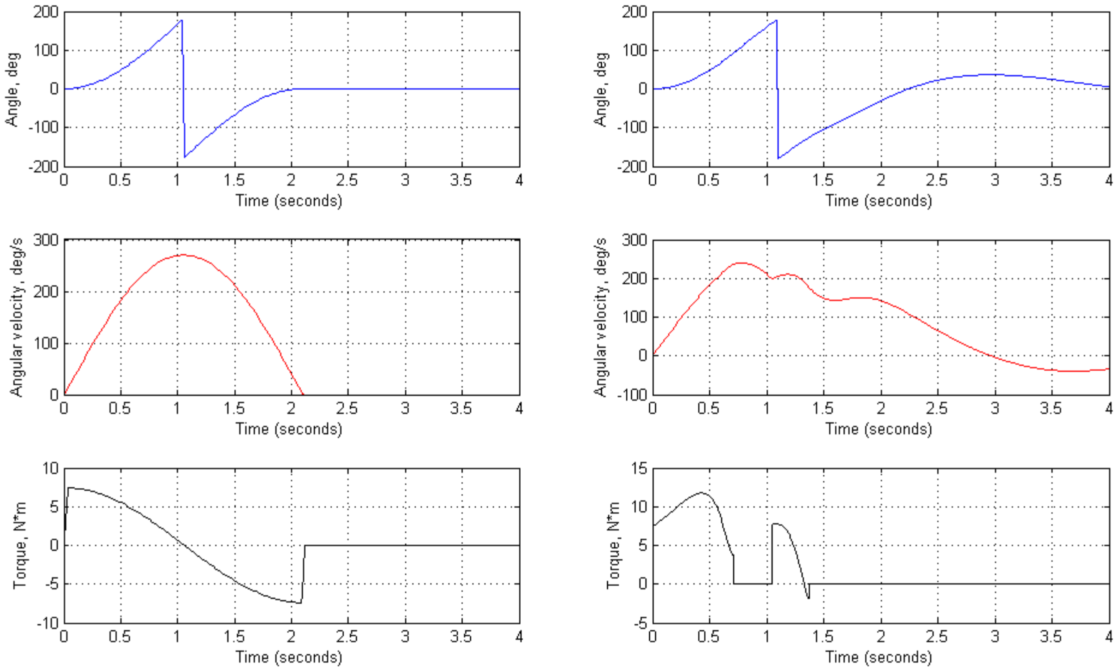

Figure 3: The obtained results for the ideal mechanism (left) and the mechanism with spring accumulator (right).

4 Design and investigation of the actuator based on an elastic element

4.1 Analogues

We know the next analogues. The first one is Mobile mechanism for converting the applied force into translational motion (Fig. 4).

The invention relates to a manpower walking mechanism. A travel mechanism is provided with a foreleg mechanism and a rear leg mechanism which are respectively hinged with a machine frame, the foreleg mechanism and the rear leg mechanism are of L-shaped cranks, unidirectional wheels are arranged at the bottom end of the cranks, the horizontal end heads of the cranks of the foreleg mechanism and the rear leg mechanism are respectively hinged and connected with a connected plate. The structure of the invention is simple and reasonable, the foreleg mechanism is designed into the L-shaped crank, through the hinging with the machine frame and the horizontal end head of the crank, only two point hinge is utilized to realize that the foreleg mechanism moves back and forth under the functions of the upper part pressure and the lower part pressure, thus a large quantity of parts are decreased, and the assembly and the regulation are convenient. Simultaneously, two connecting rod type cradle mechanisms are arranged at the upper parts of the foreleg mechanism and the rear leg mechanism, the power is directly exerted on the foreleg mechanism and the rear leg mechanism through a cradle to lead the mechanism to move smoothly, a pedal mechanism is connected with a drive mechanism, in

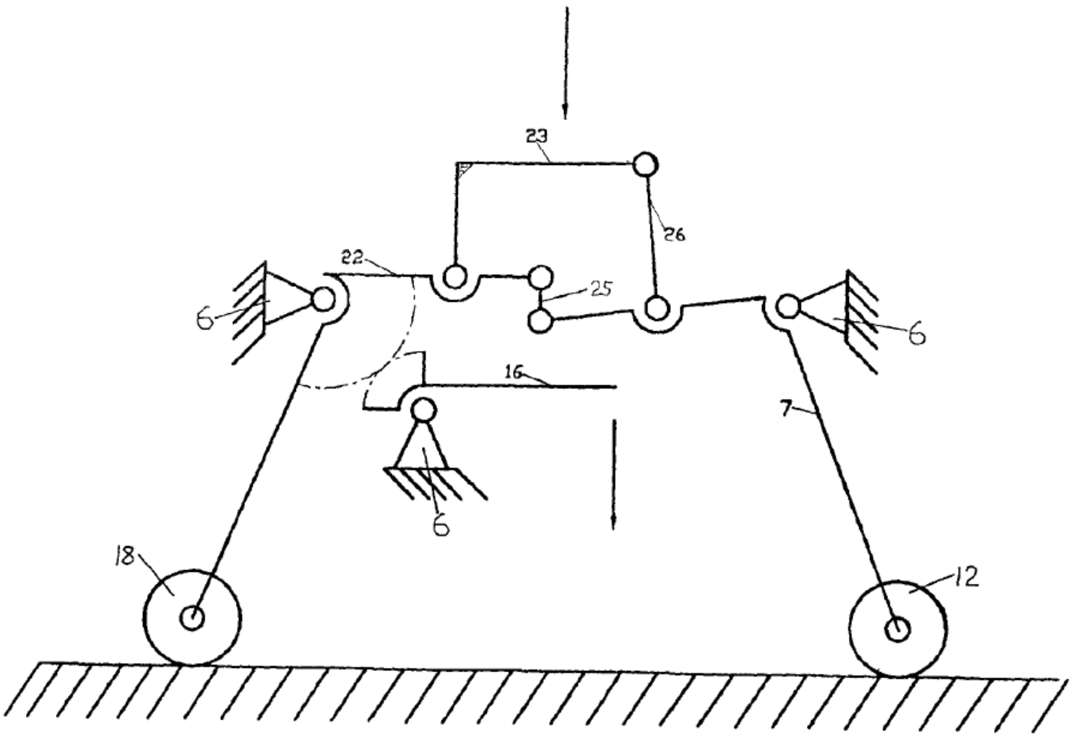

Figure 4: Mobile mechanism.

particular a gear drive mechanism or a lever drive mechanism, the guidance quality is good, and the connecting rod is arranged in a pressure spring frame, thus the position limit is accurate. The disadvantages of this device include the complexity of design and energy loss due to frictional resistance in kinematic nodes [5].

The second one is Bionic mechanical walking animal (Fig. 5).

The utility model provides a bionic mechanical walking animal, comprising a quadruped imitated outer shell, forelimbs with single direction rotating wheels, hind limbs with two-way rotating wheels, a cradle, pedals and a limb driving mechanism in the outer shell. The bionic mechanical walking animal is characterized in that the forelimbs and the hind limbs are respectively connected with the front and back ends of a cross beam through a rotation shaft, and the limb driving mechanism is hinged by the middle part of a front upper connecting rod and the middle part of the cross beam; the upper end of the front upper connecting rod is provided with the cradle, and the lower end of the front upper connecting rod is hinged with the connection shafts of the two forelimbs; a back upper connecting rod is also hinged with the middle part of the cross beam, and the other end of the back upper connecting rod is hinged with the connection shafts of the two hind limbs; one end of a front lower connecting rod is hinged together with one end of a back lower connecting rod, and the other end of the front lower connecting rod is hinged with the lower part of the front upper connecting rod; the other end of the back lower connecting rod is hinged with the lower part of the back upper connecting rod; the two pedals are respectively arranged at both ends of a horizontal connecting rod, and the middle part of the horizontal connecting rod is connected with the lower

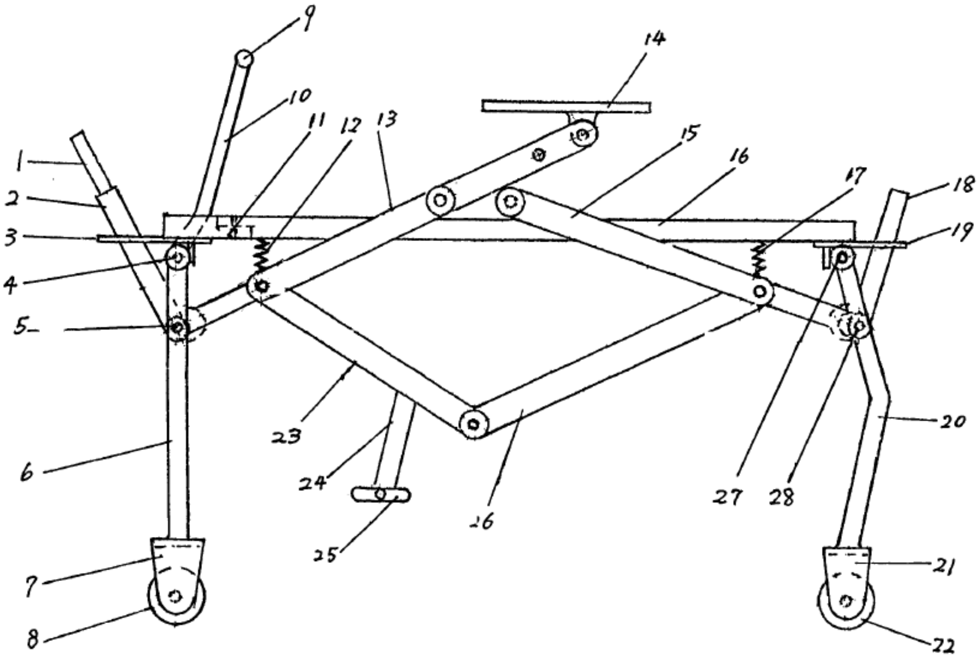

Figure 5: Bionic mechanical walking animal.

part of the front lower connecting rod or the back lower connecting rod via a vertical connecting rod. The bionic mechanical walking animal has simple structure, low cost, portable operation, safety and reliability. As the shortcomings of the above mechanism, we can distinguish: the complexity of the design, numerous connection joints that introduce significant friction resistance of the mechanism, as well as the dependence of the speed and distance of movement on the time and impulse of the applied force [6].

4.2 Modeling and operating peculiarities of the device

To eliminate the shortcomings of analogues and to solve the aforementioned problem, the mechanism was proposed and constructed (the scheme is shown in Fig. 6) [7]. The proposed device is a new type of energy-efficient actuators, where an elastic element is used as a working link. Its operation is based on the phenomenon of loss of stability under the action of the applied external force. The purpose of this mechanism is to demonstrate the properties and behavior of an elastic element whose design features can be used in the modeling of bionic systems.

It should be noted that the movable base (including frame 1 and mobile supports 3 in Fig. 6) is used only to demonstrate the force action that occurs under the process of buckling failure (loss of stability) of elastic element.

The principle of operation of the proposed mechanism is as follows: at the initial moment of time a force P (which is directed vertically downwards) is applied on the area of the conjugation of the motion platform for transferring the loading force 4 and the elastic element 5. When the applied force reaches a critical value, a loss of stability of the elastic element occurs, in other words the rectilinear shape of

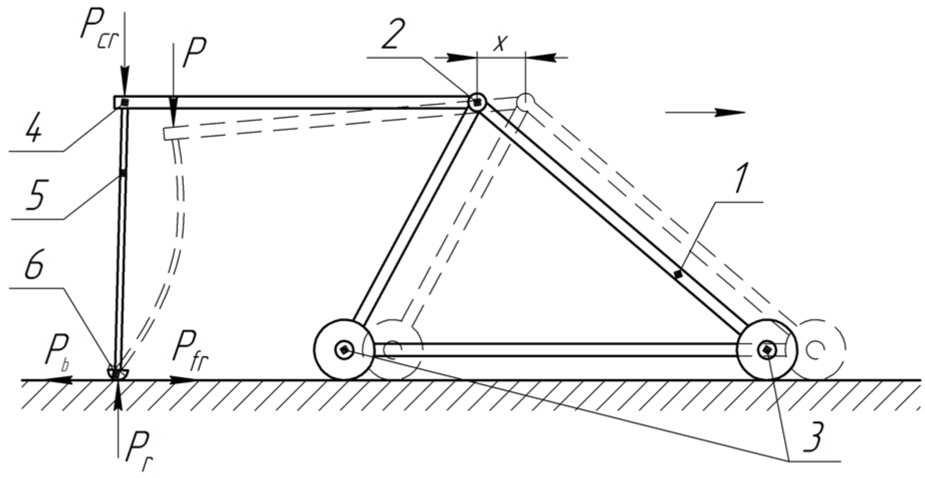

Figure 6: Proposed scheme of the actuator based on an elastic element: 1 — base; 2 — joint hinge; 3 — mobile supports (equipped with a ratchet mechanism); 4 — motion platform for transfer of the applied loading force P; 5 — elastic element; 6 — semicircular support tip; P_{cr} — the critical loading force; P_{fr} — the friction force; P_r — the support reaction force; P_b — the bending force; x — device displacement.

the elastic element changes under the action of the bending moment. Due to this phenomenon, the free end of the elastic element (in the present case, we consider that the free end is the lower edge of the elastic element with the semicircular support tip) will begin to deviate from the rectilinear steady state. However, under the condition of the appearance of frictional force P_{fr} (it is directed opposite to action of the bending force P_b) the entire energy of the elastic element (which was accumulated under process of loss of stability) is redistributed and reverses direction toward translational motion of the base of the actuator. When the applied force P is removed, an inverse process is occurring. The elastic element recovers an initial rectilinear shape, but the movable base (like the whole mechanism) will not change its position due to reaction of the ratchet mechanisms of the movable supports [8, 9, 10].

The whole process of moving the actuator can be divided into two cycles. The first cycle is a "loading cycle". Under the influence of the applied force, here is occurring the loading of elastic element that causes a change in the rectilinear shape, which in turn ensures the movement of the entire mechanism. The second cycle is "recuperation cycle". Here, on the condition that the value of the applied force is less than the critical value, the process of restoring the original shape of the elastic element takes place by virtue of the stored energy in the process of loss of stability.

4.3 Selection of the device working link and the way of functions

In the next step, an elastic element is selected. The selection of a suitable working link is expedient to begin with the calculation of elastic properties, the selection of

suitable materials and forms.
In general, the proposed device can be designed in a wide range of the size range — from millimeters to several tens of centimeters. The overall dimensions of the device (in particular, the linear dimensions of the elastic element) directly affect on the properties of the operating link and, consequently, on the technical characteristics of the entire mechanism. This feature allows us to expand an application area of the proposed actuator.
When making a selection of a material for the elastic element, attention should be paid to the following parameters: high elastic properties, durability, endurance range, and also its mechanical characteristics have to be stability over time.
In this work, as an example of parameters calculation of elastic element were used solid rods of rectangular cross section with dimensions of 5x10 and 7x10 mm, and 70 mm length. As materials for manufacturing, the following were selected: high-quality carbon steel (65), manganese steel (65G), silicium steel (60S2) and chromium-vanadium steel (50HFA).
To determine the mechanical properties of an elastic element, let us consider it as a rectilinear rod which is fixed one end and being under the influence of pressure force, that directed along the longitudinal axis of the rod and acting on its free end (see Fig. 7) [4].

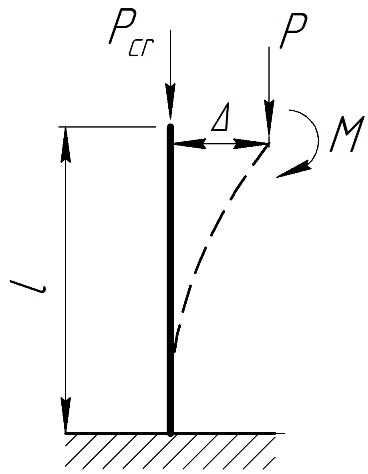

Figure 7: The process of changing a shape of the rod under action of force: P — load force, P_{cr} — critical force, M — bending moment, Δ — deviation of the rod end, l — length of the elastic rod.

For $P < P_{cr}$ only the central compression of the rod occurs. For $P > P_{cr}$ the rod operates on the joint action of compression and bending. Even with a small excess of the critical load, the deflections of the rod end and the occurred flexural stress are quite significant. To determine P_{cr}, we used the following expression:

$$P_{cr} = \frac{\pi^2 EJ}{\mu l^2} \qquad (2)$$

where EJ — flexural stiffness, which is determined as a product of the Young's modulus of material elasticity E and the moment of inertia of the cross-sectional

J; μ — factor depending on the end conditions of the rod (in our case $\mu = 2$); l — length of the elastic rod [11].
The loss of stability of the rod occurs until the critical longitudinal compressive stress of the rod is reached which is equal to a yield stress or a proof strength for ductile materials, or ultimate compressive strength for brittle materials [12].
The peculiarity of the loss of stability lies in the fact that it occurs suddenly and at low stress values, when the strength of the material is nowhere near exhausted [13].
From the foregoing, it can be concluded that for deviation of the free end of the rod (as a consequence, the displacement of the movable base of the actuator), it is necessary to apply a force which is greater than the critical value, but the magnitude of this applied force should be less than the value at which the rod reaches the critical longitudinal compressive stress. Therefore, in this paper, only the rods of great flexibility are considered, i.e. those for which Euler's formula is valid.
Thus, it is possible to compose a system of equations describing the application condition of an elastic element:

$$P_{cr} = \frac{\pi^2 EJ}{(\mu l)^2} \leq P \tag{3}$$

$$\sigma_{cr} = \frac{\pi^2 E}{\lambda^2} = \frac{\pi^2 EJ_{min}}{(\mu l)^2 A} < \sigma_T \tag{4}$$

$$\lambda = \frac{\mu l}{i_{min}} \geq \lambda_s = \sqrt{\frac{\pi^2 E}{\sigma_p}} \tag{5}$$

where P — the applied force; σ_{cr} — the critical longitudinal compressive stress; λ — the slenderness ratio of a rod; $P\Theta$ — the cross-section area; σ_T — the yield stress; i_{min} — the minimum cross section radius of inertia; λ_s — the limit slenderness ratio of a rod; σ_p — the proportional elastic limit.
Using the conditions of application of the elastic element that were described above, we can complete a table in which all the mechanical properties and features of the elastic rods for some materials are displayed (see Table 1). The materials, which for their properties are most suitable in the manufacture of elastic elements, were listed in this table as examples.

5 Conclusions

In conclusion we have researched recuperation mechanisms which is used in actuators for partially restore of the spent energy. In the course of the work, we have designed the recuperation mechanism of an energy-efficient actuator based on an elastic element and have selected and calculated parameters of the working link which was made in the form of an elastic solid steel rod of rectangular cross-section. This mechanism has a simpler construction in comparison with the studied analogues due to reducing of connecting nodes and kinematic pairs number. The proposed device can find its application in many areas of mechanical engineering, especially under designing of various actuated parts of machines and mechanisms which have a purpose to convert an applied force into translational motion. Also, this actuator can be used in robotechnics area as a new type of energy efficient mechanism.

Table 8: The calculated parameters of the elastic rod.

Material	Cross-section dimension, mm x mm	Length of elastic rod, mm	Critical force P_{cr}, N	Applied (loading) force P_f', N	Deflection of the rod end, mm	Bending force, N
Steel 65	5 x 1	70	1.2	43.01	43.1	0.006
			4		44	0.019
			6.9		46.15	0.033
	7 x 1	70	1.4	60.21	60.3	0.005
			5.8		61.7	0.02
			6.9		62.4	0.024
Steel 65G	5 x 1	70	1.2	45.12	45.2	0.006
			4.9		46.7	0.023
			6.7		48.2	0.032
	7 x 1	70	1	63.15	63.2	0.004
			5.4		64.5	0.018
			7.7		66	0.026
Steel 60S2	5 x 1	70	0.59	44.48	44.5	0.003
			5.1		46.2	0.024
			7.2		48	0.034
	7 x 1	70	0.59	62.27	62.3	0.003
			2.9		63	0.014
			6.6		66.4	0.031
Steel 50HFA	5 x 1	70	0.98	45.74	45.8	0.005
			3.4		46.5	0.016
			5.7		48	0.027
	7 x 1	70	0.87	64.03	64.1	0.004
			4.6		66	0.022
			6.4		68	0.03

References

[1] K.A. Nuzhdin. System issues of a creation of actuators based on elastic // Journal of Instrument Engineering, 61, 2018, pp. 148–153.

[2] V.M. Musalimov, K.A. Nuzhdin. Study and design of the actuator based on elastic element // Week of Science SPbPU: Proceedings of a scientific conference with international participation. Institute of Metallurgy, Mechanical Engineering and Transport, 2017, pp. 32–35.

[3] D.S. Pelupessi, M.V. Zhavner, Spring-Loaded Accumulators with the Output Rotary Link for Step Movements // Proceedings of Higher Educational Institutions. PЁPөchine Building, 679, 2016, pp. 9–17.

[4] V.M. Musalimov, K. Nuzhdin. The experimental determination of bifurcation components of friction // Procedia Engineering, 199, 2017, pp. 1478–1483.

[5] Nie Wenlong, Mobile mechanism // CN Patent 101172203B.

[6] Sheng Ming Yi, Bionic mechanical walking animal // CN Patent 2734289Y.

[7] V.M. Musalimov, K.A. Nuzhdin, The actuator based on an elastic element // RU Patent 172799.

[8] I.V. Kragelsky, M.N. Dobychin, V.S. Kombalov // Principles calculations on friction and wear, 1977, p. 526.

[9] V.M. Musalimov. Bifurcation component of sliding friction // Journal of Instrument Engineering, 60, 2017, pp. 793–796.

[10] V.M. Musalimov, K.A. Nuzhdin, A.E. Tyurin. Modeling of external dynamic of the friction engagement // Book of papers. 24th International Congress of Theoretical and Applied Mechanics, 2016, pp. 1802–1803.

[11] J.M.T. Thompson // Instabilities and Catastrophes in Science and Engineering, 1985, p. 254.

[12] R. Gilmor // Applied theory of catastrophes, 1984, p. 350.

[13] Y. Panovko // Fundamentals of applied theory of vibrations and shock, 1976, p. 320.

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