Design of Emergency Switch Based on Flexible Elastic Element

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***Abstract*—Modern vacuum technology requires the creation of robots that do not fill the working area with micro-particles of wear and friction between the elements. It is necessary to control the temperature of the area, reduce external friction, which adversely affects the quality of the product. It should be recognized that even a slight friction leads to filling the working environment of vacuum robots with microparticles of wear. Temperature changes affect the properties of materials used in production. Temperature control during production is an important task. The mechanisms with a flexible elastic thin-walled element with any shape of the axis is used as a working element are considered. The moving of an element is carried out at submission of pressure in a cavity of an element. The given task is nonlinear and are reduced to the second regional task Cauchy. For the decision the method of discrete continuation on parameter in a combination to a method multisegment shooting is used. The technique allows to pick up under the given law of moving the geometric parameters of the flexible element used for the creation of emergency switch.**

***Index Terms*— flexible elastic, thin-walled element, working characteristic, discrete moving, working body**

I. Introduction

Modern technologies can not be imagined without automated systems that are widely used vacuum technology [1]. Vacuum technology has its own characteristics [2, 3] and assigns high requirements to the composition of the surrounding area. In a vacuum it is necessary to control the parameters of the working environment. It is necessary to control the temperature of the area, reduce external friction, which adversely affects the quality of the product [4]. It should be recognized that even a slight friction leads to filling the working environment of vacuum robots with microparticles of wear [5, 6].

It is especially important to maintain a clean working environment. In this case, external friction should be excluded. This has a negative impact on the quality of the process. Various devices and devices are used to control the temperature [5, 7, 8]. Temperature changes affect the properties of materials used in production.

Different properties of the raw materials resulting in differences in product properties. This is usually unacceptable. It is important to ensure the quality of the product with prompt notification of changes in temperature, pressure or other parameter. If the controlled parameter has a value exceeding the permissible value, it is necessary to quickly stop the production process.

It is possible to control the temperature indirectly, using special mixtures or fillers, which, when the temperature rises, sharply increase the volume. This increases the pressure. Obviously, the mixture in this case should be in a closed area.

Usually this work is performed by various emergency switches. Various robotic systems use switches of different designs. Switches on the design principles can be divided into two groups:

- Design with rigid elements,
- Design with flexible elements.

Some examples of switches of the first group are shown in Fig. 1. An example of a device with flexible elements is a computer keyboard.

Figure 1. The some models of emergency switches: (a) emergency stop button, (b) danger warning buttons, (c) automatic switch.

II. Characteristics and Advantages of Flexible Elastic Elements

In terms of operation, switches in the production of an important parameter of the device is the working characteristic [5, 9, 10]. Regardless of the specific design parameters, the working characteristic describes the movement of a feature point depending on the applied load. The load can be force, pressure, temperature and so on.

The working characteristic can be presented in the form of a graph, table or analytical dependence. A graphical view of the working characteristic is shown in Fig. 2. It can be linear (a) or nonlinear (b), (c).

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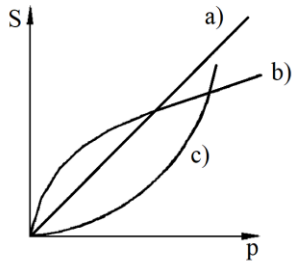

Figure 2. The types of working characteristic: (a) linear characteristic, (b) nonlinear damped (rigid), (c) increasing non-linear (soft).

It is possible to apply to elimination of external friction mechanisms, in which the moving of the executive body is carried out thanking deformation of a flexible elastic thin-walled element at submission of pressure in a cavity of an element. When pressure is applied to the inner cavity of the flexible element, it deforms and moves the working body of the robot.

The use of a flexible elastic element in the design of robots eliminates friction between the working parts [11].

The practical interest represents reception of the working characteristic. Depending on the type of elastic element, any point can be selected as a characteristic point. Typically, a characteristic point is assigned with the highest expected displacements during the deformation process.

Depending on parameters of an element and character loading the occurrence of effect bifurkation, allowing by jump to change the form of an element and, due to this is possible, to provide discrete moving of a working body. In connection with wide use of elastic thin-walled elements the research of elements with various geometrical parameters is necessary.

Flexible element having a plane of symmetry are considered. The cross section of the element has two axes of symmetry. It is assumed that the length of the element along the axis perpendicular to the cross-sectional plane is significantly larger than the cross-sectional dimensions. In this case, we can assume that all cross sections are deformed equally. The influence of the end effects on the deformation of the element at these proportions of the geometric parameters is negligible.

Due to the above assumptions, we consider a rod model that describes the geometry of the quarter section, that is, only the part of the section that is located between the axes of symmetry. During the deformation of the element, additional restrictions on displacements, forces and moments are recorded for the characteristic points of the section. These limitations explain the preservation of cross-section symmetry during deformation.

III. An Algorithm for Reducing a Nonlinear Boundary Value Problem to a System of Nonlinear Equations and the Cauchy Problem

Various variants of relations describing the behavior of flexible curvilinear rods are known. In the numerical study, the equations presented in a convenient form for the algorithm are used. The system of the nonlinear differential equations concerning basic unknown is used.

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Various variants of relations describing the behavior of flexible curvilinear rods are known. In the numerical study, the equations presented in a convenient form for the algorithm are used. The system of the nonlinear differential equations concerning basic unknown is used. Vector basic unknown in current section of a core enters the name as X^T axes are determined by the equation 1.

$$X^T=\{X,Y,\psi,N,Q,M\} \tag{1}$$

where X,Y - coordinates of the current point on an axis of a core; ψ - corner of an inclination toucher in a considered point; N,Q - longitudinal and cross force; M - bending moment.

For a large number of practical problems, methods based on the reduction, in general, of a two-dimensional problem to a boundary value problem for a system of ordinary equations have proved to be effective methods of solving. The obtained system is solved by means of its reduction to the system of nonlinear equations and the Cauchy problem for the initial vector [1, 12]. For one-dimensional problems, of course, the first stage of this approach is absent, which greatly simplifies the study.

Under the resolving system of equations in the case of a one-dimensional nonlinear boundary value problem, we mean a system of relations:

$$\frac{d\mathbf{X}}{ds}=\mathbf{f}(s,\mathbf{X},\mathbf{Z},\mathbf{Q}) \tag{2a}$$

$$\mathbf{g}_0\left(\mathbf{X}_0,\mathbf{Q}\right)=\mathbf{0},$$
$$\mathbf{g}_1\left(\mathbf{X}_1,\mathbf{Q}\right)=\mathbf{0}. \tag{2b}$$

Here s is an independent variable, $\mathbf{X}$ is a vector of internal parameters of the system, whose components are under the sign of ordinary derivatives. To simplify the algorithm in the formulation of relations, except for the vector $\mathbf{X}$, it is convenient to introduce a vector of additional variables $\mathbf{Z}$, formed by unknown quantities not included under the sign of the derivative. We consider a special case of a nonlinear problem that allows us to explicitly find the dependence of the derivative of the vector of variables $\mathbf{X}$ on the vector itself, the value of the independent coordinate s and some vector of the "external" parameters $\mathbf{Q}$.

Following the works [1, 8, 12], we call the components of the vector $\mathbf{X}_i$ (i=1,2,...m) - "basic" unknowns, and the components of the vector $\mathbf{Z}_j$ (j=1,2,...mz) - "auxiliary". The auxiliary unknown is expressed in the principal variables with, in General, nonlinear correlations not containing differentiation.

$$\mathbf{F}_z(s, \mathbf{X}, \mathbf{Z}, \mathbf{Q}) = \mathbf{0} \quad (3)$$

Note that under numerical implementation, the relations (30) it is not necessary to have analytical expressions. It is important that the researcher had a method or algorithm for the numerical determination of auxiliary unknowns through the main unknowns.

Consider a nonlinear two-point boundary value problem for a system of ordinary differential equations with respect to a vector function $\mathbf{X}$ containing only the basic unknowns as components.

The system of differential equations is supplemented by boundary conditions (2b), the number of which corresponds to the order of the system - *m*. In the case of a two-point boundary value problem, the boundary conditions are formulated separately at points s_0 and s_1.

Using the capabilities of the computer it is possible to numerically find the relationship between the components of the vectors $\mathbf{X}_0$ and $\mathbf{X}_1$ of the main variables specified in the start and end points of the integration interval s - $\left[s_0, s_1\right]$.

$$\mathbf{X}_1 = \mathbf{F}(\mathbf{X}_0) \quad (4)$$

The boundary conditions in this case can be interpreted as a nonlinear vector function depending on the vector of the main variables specified only in one of the boundary points of the problem, for example, at the beginning of the integration segment – $\mathbf{X}_0$.

$$\mathbf{g}_1(\mathbf{F}(\mathbf{X}_0), \mathbf{Q}) = \mathbf{r}(\mathbf{X}_0, \mathbf{Q}) = \mathbf{0} \quad (5)$$

Thus, the nonlinear boundary value problem for a system of differential equations is reduced to the solution of a system of nonlinear equations (5) with respect to the vector $\mathbf{X}_0$, and the Cauchy problem for the system (2a) under the initial condition $\mathbf{X}(s_0) = \mathbf{X}_0$.

It should be emphasized that the system (5) may be not defined explicitly, but are defined only algorithmically, i.e., a well-known algorithm for the numerical implementation, which allows to calculate a vector $\mathbf{r}$, called in what follows "the vector of residuals", for specific values of $\mathbf{X}_0$ and $\mathbf{Q}$.

In those tasks where the system integration (5) along the whole interval of integration $\left[s_0, s_1\right]$ is technically difficult or impossible because of the instability of numerical accounts is a useful application of the technique of dividing the interval of integration into separate segments with followed by docking them to each other [10, 12, 13].

Let *ns* = the total number of segments. Let's consider some partition of the integration interval

$$s_0 = a_1 \le a_2 \le \ldots \le a_{is} \le \ldots a_{ns} \le a_{ns+1} = s_1 \quad (6)$$

in which the position of the intermediate points a_{is}, *is* - [2, ... , *ns*], selected according to the integration features of the system of equations (2a). This means that a_{is} points should be aligned with the boundaries of abrupt changes in geometry, edges, points of application of concentrated loads, as well as concentrated in those areas of the interval where the system is particularly difficult to integrate, for example, in the zones of the boundary effect. Note that the right-hand side view of the equations (2a) may be different for each of the segments.

We denote the vector function of dimension - *m* of the principal unknowns for the is-this segment by $\mathbf{X}_{\mathbf{is}}$, where $\left[a_{is} \le \mathbf{X}_{\mathbf{is}} \le a_{is+1}\right]$. As the unknown initial parameters of the Cauchy problem, we take the values of the vectors $\mathbf{X}_{\mathbf{iso}}$ at the initial points of all segments

$$\mathbf{X}_{\mathbf{iso}} = \mathbf{X}_{\mathbf{is}}(a_{is}), \quad is = 1, 2, 3, \ldots, ns \quad (7)$$

The total number of unknowns to be determined in this case is $m \times n$, and the vector of unknown initial parameters of the Cauchy problem takes the form:

$$\left\{\mathbf{X}_{\mathbf{o}}\right\} = \left\{\mathbf{X}_{10}, \mathbf{X}_{20}, \ldots, \mathbf{X}_{is0}, \ldots, \mathbf{X}_{ns0}\right\}^T \quad (8)$$

System (2a) can be written as follows:

$$\begin{cases} \ldots\ldots\ldots\ldots\ldots \\ \dfrac{d\mathbf{X}_{is}}{ds_{is}} = f_{is}\left(s_{is}, \mathbf{X}_{is}, \mathbf{Q}_{is}\right), is = 1, 2, \ldots, ns \\ \ldots\ldots\ldots\ldots\ldots \end{cases} \quad (9)$$

Here the vector $\mathbf{Q}_{is}$ is a sub-vector for the generalized vector of "external" parameters of the problem $\mathbf{Q}^T = \left\{\mathbf{Q}_1^T, \mathbf{Q}_2^T, \ldots, \mathbf{Q}_{is}^T, \ldots, \mathbf{Q}_{ns}^T\right\}$.

The issues associated with the introduction of the procedure of account of the vector $\mathbf{Q}$ will be discussed next. For the one-parameter problem we consider the relations (4). At its core, the two-point nonlinear boundary value problem is reduced to a particular version of the multipoint.

Additional $m \times (ns-1)$ of the conditions follow from the conditions of joining segments. As in the case of the two-point problem, using the capabilities of numerical calculation, the components of the vectors $\mathbf{X}_{is1}$ at the end points of the segments can be determined through the values of the vectors $\mathbf{X}_{is0}$ at the initial points. The docking conditions will be written in the form:

$$\mathbf{X}_{is+1,0} = \left[\mathbf{A}_{is}\left(\mathbf{X}_{is1}, \mathbf{Q}_{is}\right)\right]\mathbf{X}_{is1}, is = 1,\ 2,\ ...,\ n \qquad (10)$$

where $\mathbf{X}_{is1} = \mathbf{X}_{is1}\left(\mathbf{X}_{is0}, \mathbf{Q}_{is}\right)$ is a vector of unknowns at the end of the segment number - is determined by numerical integration; $\left[\mathbf{A}_{is}\right]$ is a matrix transition function determined based on the features of the docking *(is)* and *(is+1)* segments. In the simplest case, based on the continuity of the components of the vector of the main unknowns, it follows that

$$\left[\mathbf{A}_{is}\right] = \left[E\right] \qquad (11)$$

where $\left[E\right]$ is a unit matrix of size $m \times m$.

We write the relations for the condition residual vectors in the form:

$$\mathbf{r}_{is}\left(\mathbf{X}_{is0}, \mathbf{X}_{is1}, \mathbf{Q}_{is}\right) = 0, \quad is = 1,2,3,...,ns \qquad (12)$$

The initial boundary conditions correspond to the relations:

$$\begin{aligned} &\mathbf{r}_{1}\left(\mathbf{X}_{10}, \mathbf{Q}_{1}\right) = 0, \\ &\mathbf{r}_{m}\left(\mathbf{X}_{m0}, \mathbf{Q}_{m}\right) = 0 \end{aligned} \qquad (13)$$

Note that each of the vector functions of residuals $\mathbf{r}_{is}$ in the relations (12) is of order - *m*, whereas the vector of residuals in the ratio (13) provide the order *m* in total.

System (12 - 13) is not explicitly given, so an efficient numerical algorithm is required to solve it, allowing to calculate the residual vector for the analyzed values of $\mathbf{X}_0$ and $\mathbf{Q}$.

Thus, as in the case of a two-point problem, the problem is reduced to solving a system of nonlinear operator equations (12 - 13) with respect to the vector (8), and the Cauchy problem for the system (9) under initial conditions

$$\mathbf{X}_{iso} = \mathbf{X}_{is}(a_{is}), \quad is = 1,2,3,...,ns \qquad (14)$$

The segmentation method allows generalization for multipoint boundary value problems with a multi-connected or tree-like integration interval. We note the similarity of the algorithm with the finite element analysis algorithm [14, 15]. Of course, the method described in this article is not directly related to the FEM. The proposed concept of "segment" (some part of the structure) in a certain way is similar to the concept of "finite element". The numerical procedure, by solving the Cauchy problem, determining the relationship of the vector of the main unknowns given at the beginning of the segment with the same vector at the end of the segment, is similar to the numerical procedure for constructing the stiffness matrix of the finite element. Preparation of docking conditions is similar to the procedure of assembling the stiffness matrices of individual elements into the stiffness matrix of the entire system. All this makes it possible to successfully apply a number of techniques, well-developed in the FEM [16, 17], in the numerical implementation of the considered method. The vector of the principal unknowns $\mathbf{X}$ can be defined in both local and global coordinates. For example, the vector of the main unknown problem can be represented both in the coordinate system associated with the deformed segment configuration, i.e. in the local coordinate system, and in the global system used to specify the initial configuration of the whole system.

In the case of multivariable interval of integration, it is convenient to use the numbering of the segments $\left(is = 1,2,3,...,ns\right)$ and the numbering of the docking points of segments or nodal points $\left(ip = 1,2,3,...,np\right)$. When describing the topology of the segment, its start and end node points are specified, the order of the node numbers determines the direction of integration.

When drawing up the conditions of docking, all segments converging at the considered nodal point are considered. In the case of solving one-dimensional problems (flat bending of rods and axisymmetric deformation of shells), for each nodal point three equilibrium equations and $3 \times (kp-1)$ geometric relations are formed, where kp is the number of meridians converging at the considered nodal point. By analogy with the above, boundary conditions and docking conditions can be written using the vector residual function

$$\mathbf{r}\left(\mathbf{X}, \mathbf{Q}\right) = 0, \qquad (15)$$

The order of which is $m \times ns$ corresponds to the dimension of the vector of initial parameters $\mathbf{X}_0$, whose sub - vectors $\mathbf{X}_{is0}$ are used as initial vectors in solving the Cauchy problem sequentially for each of the segments.

As a result of the calculation it is necessary to obtain the working characteristic of a flexible elastic element. The working characteristic allows to estimate quality and efficiency of work of an elastic element, and also to estimate possibilities of use of an elastic element in a design of the machine. The presence of a section of nonlinear deformation of the elastic characteristic allows to increase its efficiency. Different quality of nonlinearity allows to design fundamentally different elements [18, 19], devices and devices [20, 21] including actuators and vibration generators [13, 22, 23].

IV. Results of Researching

The rod model was used for the numerical decision of a practical task - analysis of process nonlinear deformation of the emergency switch shown in a Fig. 3. As already mentioned, a flexible element with a symmetrical cross section is considered. The rod model describes only a quarter of the section. The characteristic point is the point C for which the greatest vertical displacements are expected. It is assumed that the point C will not move horizontally. This assumption not only ensures the symmetry of the cross section during the deformation process.

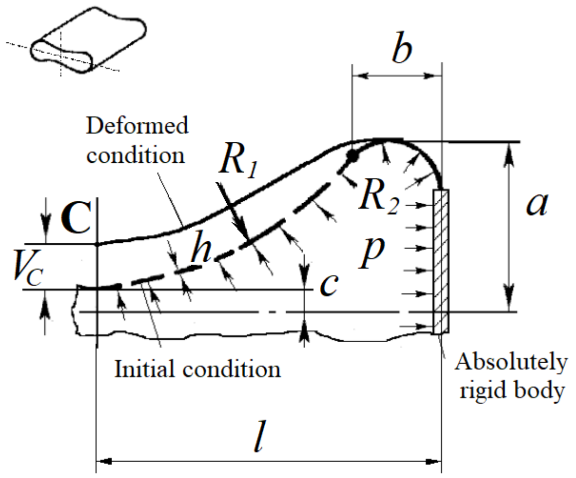

Figure 3. The settlement circuit of the emergency switch.

The need for research and creation of the presented element is dictated by the needs of modern technology. The task of creating alarm elements that are triggered by an increase in pressure above the permissible limit, with an increase in temperature and other operating parameters is relevant to modern technology.

Using the technique described in the article, the researchers of the process of deformation of flexible elastic elements are carried out. Different cross-sectional shapes with different geometric parameters are researched. Various forms of cross-section were studied, flexible elements with areas with different thicknesses were considered. The obtained working characteristics had areas of low nonlinearity.

Numerous studies have shown that the working characteristic of an element with a large nonlinearity can be obtained if the element has a rigid segment, as shown in Fig. 3. The results of this part of the study are not given in the article, as they do not contain scientific novelty.

Different forms of cross-section with a rigid segment are studied. The thickness of the flexible elastic element is selected. The basic geometrical parameters of initial settlement elements are given in the Table I.

TABLE I. Geometrical Parameters (mm) of Cross Section of the Switch

№ of switch	Geometrical parameter			
	a	***b***	***R1***	***R2***
1	2,0	2,56	4,65	1,5
2	2,5	1,71	6,85	1,0
3	3,0	1,28	8,81	0,75
4	4,0	0,80	3,76	0,4

Note. c =0,2 mm; h =0,1 mm; l =8,0 mm.

The obtained performance characteristics had areas of low nonlinearity. Numerous studies have shown that the performance of an element with a large nonlinearity can be obtained if the element has a rigid segment only. The results of account of a flexible element of variable thickness with the various form of cross section are given in a Fig. 4.

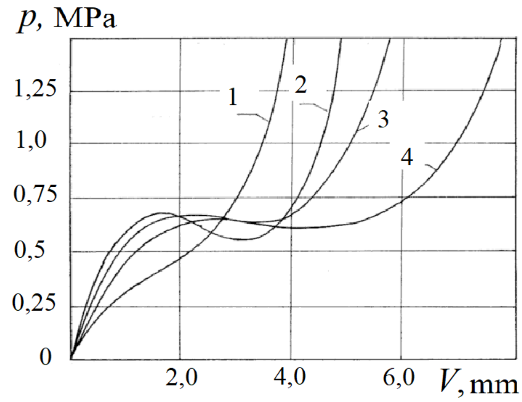

Figure 4. Working characteristics of the switch.

The results are the performance working characteristics of the elastic elements researched – dependence of vertical moving V_c of a point C from internal pressure. The material is characterized by the module of elasticity of the first sort E=0, 2 ·1012 Pa (Pascal) and coefficient of Poisson ν=0,3.

The analysis of the received working characteristics shows, that at various geometrical parameters of the switch it is possible to receive zones leaps. The area of the jump transition from one equilibrium situation to another provides discrete operation of the switch.

For element 1 (curve 1) is an area of significant nonlinearity. There is an area on the performance in which a slight increase in internal pressure leads to significant displacements (curve 1). Depending on the requirements, similar elastic elements can be used as sensing elements of devices.

For elements 3 and 4 (curve 3 and 4), the performance characteristics have zones of high nonlinearity, moreover, for elements 3 and 4, an jump transition becomes possible.

During the study, it was possible to choose the shape and geometric parameters of element 2, which provides a jump from one position to another. The displacement of the characteristic point of this flexible element will be observed as a jump with increasing pressure, and when it decreases.

The rod model presented in the article allows to develop further the design of the emergency switch for vacuum technologies. For example, if we consider the tubular manometric element, the cross section of which can be described in the first approximation by the considered rod model. The developed technique made it possible to choose the shape of the cross section of the tubular manometric element. Studies by numerical methods based on shell theory [24, 25] or using the finite element method [14, 15] are significantly more complex and take longer.

At designing mechanisms, which working bodies realize the given moving, it is recommended to use the considered flexible elastic elements. The advantages are: simple design; high technology; easy operation; small size; high maintainability. A significant advantage of the described flexible element is the preservation of its efficiency when used repeatedly.

The use of flexible elastic elements of discrete action allows not only to simplify the design of mechanisms, but also to increase the speed of work; to increase the efficiency of the robot; to reduce energy consumption.

The main advantage of the proposed type of emergency switch is maintaining the cleanliness of the working environment. This requirement is dictated not only by the properties of the vacuum technology, but also by the attention to environmental safety.

V. Conclusions

1. An algorithm for solving the boundary value problem for the deformation process of flexible elastic elements is presented.
2. The flexible elastic element of the emergency switch of multiple operation is considered.
3. The working characteristics of elements with different geometric parameters, providing fundamentally different types of motion: linear and nonlinear.
4. A model of a flexible shell element based on the results of the research of a flexible rod.
5. For the emergency switch, the geometric parameters of the emergency switch of the shell type of discrete action are obtained

VI. Perspective of Researches

It is possible to hold a row of researches, aimed to:

1. Determination of strength and analysis of stresses in elements.
2. Design of emergency switch constructions for different mechanisms.
3. Calculation of natural frequencies for proposed constructions.
4. Development of recommendations and demands for design and exploitation of appliances and devices with this switches.

Conflict of Interest

Author declares no conflict of interest.

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