

UDC 621.646.4

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## SYNTHESIS OF PRESSURE REDUCING VALVE WITH ENHANCED FUNCTIONALITY

*I.I. Сидоренко, О.В. Корольов, Чжан Йхен.* Синтез редукційного клапана з розширеними функціональними можливостями. Редукційні клапани знаходять широке застосування в промисловості. Підвищення вимог до точності регулювання тиску в промислових гідравлічних і пневматичних системах, а також автоматизація регулювання тиску при максимальній автономності та енергонезалежності таких операцій вимагають реалізації нових конструкторських рішень. **Мета:** Метою роботи є апробація методики аналізу і синтезу механічних систем на основі модифікації їх моделей, представлених у вигляді кінематичних графів, на прикладі розробки нової конструкції редукційного клапана з розширеними функціональними можливостями. **Матеріали і методи:** В якості базового пристрою прийнято прямий редукційний клапан РД-120. Для досягнення поставленої мети розглянуто використання методики аналізу і синтезу керованих механічних систем, яка заснована на модифікації моделей цих систем у вигляді кінематичних графів. Враховуючи, що при вирішенні задачі синтезу виявлено декілька рішень, в роботі запропоновано визначити оптимальне рішення шляхом розрахунку енергії кінематичного графа. **Результати:** Розроблено принципово новий пристрій – пасивний керований прямий редукційний клапан. Показано, що модель у вигляді модифікованого кінематичного графа, яка визначає деякий пристрій як пристрій з механічно змінними характеристиками, повинна мати як мінімум три цикли, два з яких визначають основну функціональну взаємодію елементів пристрою, а третій – їх зміну. Представлено конструкторську реалізацію розробленого пристрою.

*Ключові слова:* редукційний клапан, модифікований кінематичний граф, механічна система керування.

*I.I. Sydorenko, O.V. Korolyov, Zhang Yi Heng.* Synthesis of pressure reducing valve with enhanced functionality. Reduction valves are widely used in industry. Increasing requirements for accuracy of pressure adjustment in industrial hydraulic or pneumatic systems, as well as automation with maximum autonomy of these operations require the implementation of new design solutions. **Aim:** The aim of the research is to test the methods of analysis and synthesis of mechanical systems based on the modification of their models presented in the form of kinematic graphs, for example, the development of a new design of pressure reducing valve with extended functionality. **Materials and Methods:** The pressure reducing valve RD-120 is considered as the basic device. To achieve research aim, the method of analysis and synthesis of mechanical systems based on the modification of their models presented in the form of kinematic graphs is applied. Taking into account of multivariance of solutions during the synthesis of a device based on modified kinematic graphs, it was suggested to search for the optimal solution by calculating the energy of the kinematic graph. **Results:** A fundamentally new device was synthesized in the form of a passive controlled pressure reducing valve. It was found that the model in the form of a modified kinematic graph that defines a certain device as a device with mechanically variable characteristics must have at least three cycles, two of which determine the main functional interaction of the elements of the device, and the remaining – their modification. The design realization of the synthesized device is presented.

*Keywords:* pressure reducing valve, modified kinematic graph, mechanical control system.

**Introduction.** In industrial hydraulic or pneumatic systems, the pressure reducing valves are most often used as regulators whose task is to regulate the pressure under conditions when the pressure behind the regulator valve is less than half the operating pressure at the input [1].

Increasing requirements for accuracy of pressure adjustment in industrial hydraulic or pneumatic systems, as well as automation with maximum autonomy of these operations require the implementation of new design solutions. In particular, a specialized pressure reducing valve is required to solve the problem of increasing the functional reliability of the reactor core cooling system (RCCS) in nuclear power engineering [2]. According to B320 project, there should not be any valves on the primary circuit of the reactor, the closure of which violates the natural circulation in the event of an accident. However, to improve the functional reliability of the existing scheme of RCCS requires some refinement. For example, *Fisenko V.* [3] proposed to install a “leak stop” in a pipe connecting the pressure compensator to the main circulation circuit, in the form of a specialized reduction valve. Theoretical studies show that this device, having excluded leakage from the pressure compensator in the event of a major accident, will significantly reduce its negative consequences.

DOI 10.15276/opu.1.51.2017.06

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Therefore, the development of new designs of passive reducing valves with enhanced functionality that allow to implement the required (objective) reduction characteristic with the smallest deviation is an actual scientific and applied problem.

**The aim** of the research is to test the methods of analysis and synthesis of mechanical systems based on the modification of their models presented in the form of kinematic graphs, for example, the development of a new design of pressure reducing valve with extended functionality.

**Materials and Methods.** The operating principle of the pressure reducing valve is based on the throttling of the operating environment passing through the high pressure cavity into the low pressure cavity through the gap formed by the valve seat and plate [1]. Automatic maintenance of the flow area is carried out by balancing the adjustable elastic element (spring) with the reduced pressure acting through the sensing element – drive component (diaphragm or piston).

The analysis of existing reducing valves' designs showed that up to 70 % of the valves have a single block design with an integrated sensing element: diaphragm/piston, and adjustment element – spring [1, 4].

In this paper we will consider the pressure regulator RD-120, the schematic diagram of which is shown in Fig. 1. The device is oriented in the pipeline by flanges located in the lower part of the main body 0, thereby determining the input and output of the transported medium. From the cavity I, formed by the lower and middle parts of the main body 0, the transported medium flows into its lower part through a slot formed by a seat fixed to the body and a valve plate fixed to the movable rod 1, then proceeding to the outlet. The control system that determines the adjustment for the pressure change is located in the cavity II, formed by the middle part and the housing cover 0. It consists of three main elements: the comparison element (sensor) – membrane; the master element – spring; the regulating element – screw 2. The comparison element (membrane) divides the cavity II into two parts, and in the lower part of the cavity it contacts the transmitted medium coming through the cylindrical channel in the middle part of the body 0. The change in the pressure of the transferred medium leads to a deformation of the membrane, which in turn is transferred to the rod 1 in the form of movement. The action of the adjusting screw 2 on the spring makes it possible to correct the movements of the associated rod 1 as a function of the pressure. Variations in the displacement of the rod, on which the size of the gap between the valve plate and the seat fixed on it, depends on the self-control of the device presented.

The application of this type of pressure reducing valves is possible only in the case of systems autonomy, as well as the absence of interrelating parameters in the systems. The reason for this is the low sensitivity of the devices of this design because the membrane performs two different functions – sensing element and control drive.

To achieve research aim, we applied the method proposed and tested during analysis and synthesis of elastic [5] and dissipative [6] systems.

As the basic device, the functionality of which is supposed to be expanded, the known pressure reducing valve RV-120 (Fig. 2, a) is investigated. At the initial stage, it is advisable to pass from the actual construction of the device to its kinematic scheme (Fig. 2, b). Such step allows us to simply obtain a kinematic graph of the basic device (Fig. 2, c). Modeling is carried out under the condition that the mechanism under consideration is flat;  $p_i$  is the vertex of the graph from the vertex set  $p$  that determines the  $i$ -th element of the device with the corresponding numbering;  $q_5$  is the edge of the graph that determines the functional contact interaction between the two elements of the device and corresponds to the kinematic pair of the 5<sup>th</sup> class. For more detailed structuring of the model, possible types of the given edge of the graph are accepted, which correspond to the rotational or translational kinematic pair ( $q_{R5}$  and  $q_{T5}$ , respectively). With this in mind, the resulting kinematic graph is put in

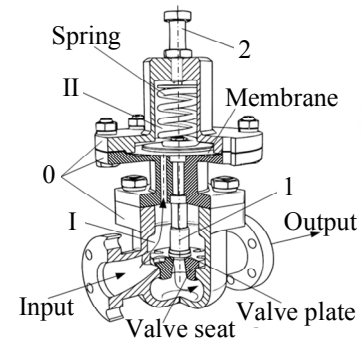


Fig. 1. Pressure reducing valve

correspondence with the so-called “assembly matrix” (analogue of the incident matrix), which has the form:

$$M = \begin{array}{c|ccc} & p_0 & p_1 & p_2 \\ \hline p_0 & 0 & q_{T5}^* & q_{T5}^* \\ p_1 & q_{T5}^* & 0 & 0 \\ p_2 & q_{T5}^* & 0 & 0 \end{array} \quad (1)$$

The characteristic of the model of the basic device in the form of a kinematic graph with respect to the mobility index is calculated by the following formula

$$W=3(p-1)-2q_{5(T,R)}-q_4=3(3-1)-2\cdot 2-0=2. \quad (2)$$

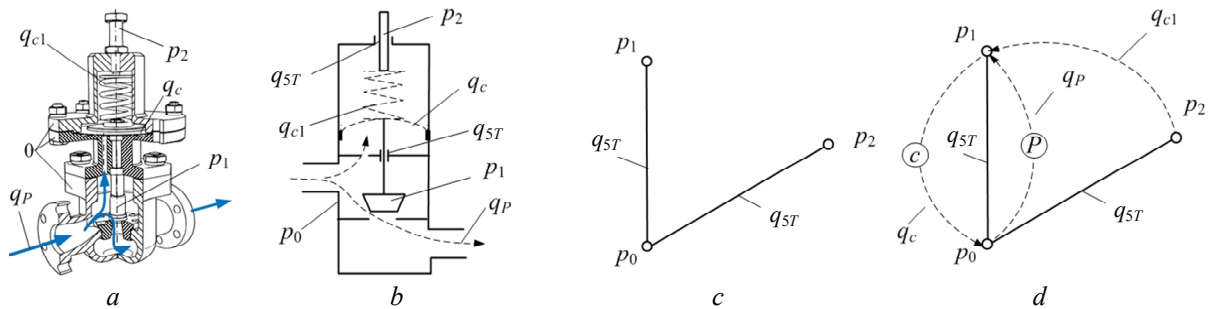


Fig. 2. The model of pressure reducing valve: key diagram (a); kinematic scheme (b); kinematic graph (c); modified kinematic graph (d)

This result indicates that the model determines the mechanism with excessive mobility. As an excessive mobility there is an adjusting screw (vertex  $p_2$ ). According to the definition of excessive mobility, this element does not affect the kinematic of the mechanism, but is introduced into its structure for constructive reasons [7]. In our case, the adjusting screw serves to change a certain non-kinematic parameter – displacement. The movement determines the stiffness of the sensor (membrane) by pressing the spring in contact with it.

The nature of the kinematic control of a device when simulating it using a kinematic graph can be judged by using the indicator in the form of a cyclomatic number. The cyclomatic number of the basic device can be calculated by the formula:

$$\sigma=q-p+1=2-3+1=0. \quad (3)$$

This result indicates the absence of any cycles in the kinematic graph, which is typical for mechanical devices with the complete absence of a kinematic control system.

From the above analysis, it follows that the kinematic graph does not allow one to trace the relationship between the kinematic of the device and the change in its other characteristics, other than mechanical ones. However, the advantage of the kinematic graph is that it allows to combine the physically connected parameters of a simulated system of different nature for elastic systems. It is this fact that underlies the method of modifying the kinematic graph (MKG) proposed below. According to this method, all the functional interactions between the elements of the modeled flat device that do not lead to the formation of kinematic pairs are initially represented in the form of labeled edges analogous to kinematic pairs of the 4<sup>th</sup> class. It was found that the model in the MKG form for a device whose characteristics can be changed by kinematic should be a multigraph [5].

The modification of the kinematic graph defining the basic device is accomplished by adding to its composition additional “labeled” edges  $q_L$ :  $q_b$  – determining the controlled parameter in the form of pressure;  $q_c$  – stiffness of the membrane;  $q_{c1}$  – determining the spring stiffness (Fig. 2, d).

The cyclomatic number for the model of the basic device in the MKG form can be calculated by the formula:

$$\sigma = q - p + 1 = 5 - 3 + 1 = 3. \quad (4)$$

Let us consider the MKG cycles corresponding to certain functional interactions of the elements of the simulated device, and also verify their adequacy to the equilibrium equation determining the operability of the device. We write the equation of equilibrium in the following form

$$PS - cx = c_1(x_{1p} + x_1), \quad (5)$$

where  $S$  – area of the membrane;

$c$  – stiffness of the membrane;

$c_1$  – spring stiffness;

$x$  – deformation of the membrane under the pressure of the medium;

$x_{1p}$  – pre-compression of the spring when installed in the device;

$x_1$  – adjusting spring compression when adjusting the device.

Taking into account that the order of the vertices for the edges  $q_P$  and  $q_c$  is different, then the existing pair of cycles with common edge  $q_{5T}$  ( $p_0 - q_{5T}^* - p_1 - q_c$  and  $p_0 - q_{5T}^* - p_1 - q_P$ ) determines the oriented graph [8]. This graph shows that the pressure change (edge  $q_P$ ) causing the translational motion (edge  $q_{5T}^*$ ) of the movable rod (vertex  $p_1$ ) on one side will be compensated by the elastic membrane resistance (vertex  $p_c$ ) on the rod (vertex  $p_1$ ), whose value is determined by the same translational motion (edge  $q_{5T}^*$ ). Consequently, the presented part of the MKG describes the basic functional interaction between the elements of the basic device that are main, and is adequate to the left side of equation (5).

The cycle  $p_0 - q_{5T} - p_2 - q_c - p_1 - q_{5T}^*$  in this case shows the functional interaction between the main ( $p_0, p_1$ ) and additional (vertex  $p_2$ ) elements of the basic device. This interaction determines the change in the properties of the device and is adequate to the right side of equation (5).

This result suggests that MKG of device with variable characteristics should have at least three cycles, two of which determine the main functional interaction of the elements of the device, and the remaining – their modification.

It should be noted that the calculation of the motion freedom of the MKG model under the assumptions initially adopted, made by the formula

$$W = 3(p-1) - 2q_{5(T,R)} - q_4 - q_L = 3(3-1) - 2 \cdot 2 - 0 - 3 = -1,$$

is not correct and needs to be corrected. To do this, we use the assembly matrix of this model

$$M = \begin{array}{c|ccc} & p_0 & p_1 & p_2 \\ \hline p_0 & 0 & q_{T5}^*, q_P, q_c & q_{T5} \\ \hline p_1 & q_{T5}^*, q_P, q_c & 0 & q_c \\ \hline p_2 & q_{T5} & q_c & 0 \end{array}. \quad (6)$$

It is not difficult to see that in the contiguity between the poles (vertices)  $p_0$  and  $p_1$  there are edges  $q_{5T}^*$  defining the pair of the 5<sup>th</sup> class,  $q_c$  and  $q_P$  defining virtual pairs of the 4<sup>th</sup> class.

Obviously, with this neighborhood the motion freedom can be determined only by the kinematic pair of the 5<sup>th</sup> class. Thus, the calculation of the motion freedom should be carried out as follows

$$W = 3(p-1) - 2q_{5(T,R)} - q_4 - q_L = 3(3-1) - 2 \cdot 2 - 0 - 1 = 1. \quad (7)$$

The result of this calculation shows that the simulated system will be self-controlled. Changing the controlled parameter in it, causing a certain movement, leads to kinematic coupling of all elements of the device without exception.

**Results.** Based on the analysis, a model of the basic device in the form of an MKG, the corresponding assembly matrix (6), and two conditions in the form of expressions for calculating the cyclomatic number (4) and motion freedom (7) of the model are obtained. Further, using the obtained data, a new construction design with a mechanical control system is synthesized.

When synthesizing a new construction design, it is quite natural to obtain a solution by replacing virtual kinematic pairs of the 4<sup>th</sup> class with real kinematic pairs of the same class (Fig. 3, a). However, conditions (4) and (7) determine the multivariance of the solution (Fig. 3, b).

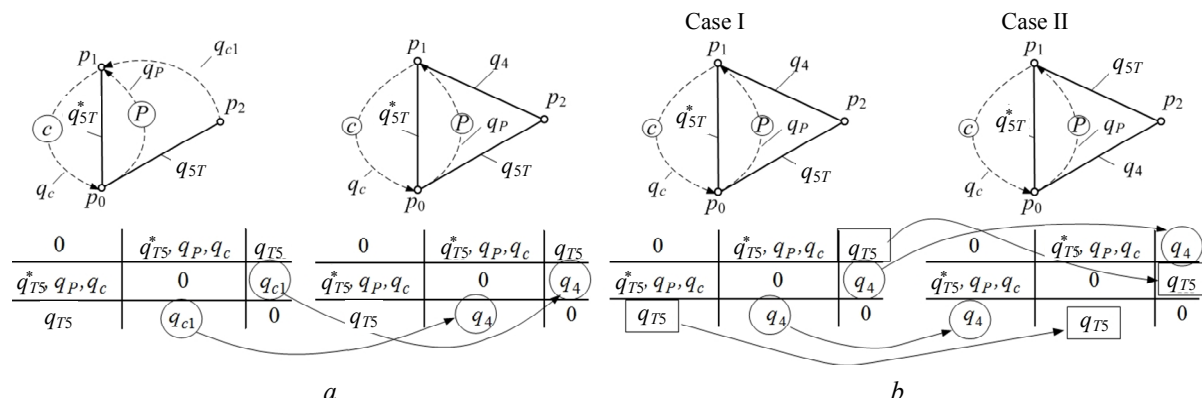


Fig. 3. Modified kinematic graphs and assembly matrices: search for solutions (a); identification of the multivariance of solutions (b)

In order to choose the optimal solution from cases I and II, it is suggested to assign the weight coefficients to the edges of the corresponding MKGs, and to calculate the energy of the graph in order to determine the graph whose energy is minimal, according to the expression

$$E(M) = \sum_{i=1}^n \lambda_i, \quad (8)$$

where  $\lambda_i$  – eigen values of the adjacency matrix (assembly matrix).

This approach is based on the principle of minimum energy of the optimal mechanical system, which is determined by the graph [6].

For solutions of cases I and II of the characteristic polynomials corresponding to the assembly matrices

$$P_{I,II}(\lambda) = \lambda^4 - 4\lambda^2 = 0, \quad (9)$$

we obtained the roots for each of the matrices

$$\lambda_{11}=-1.41; \lambda_{12}=-1.41; \lambda_{13}=1.41; \\ \lambda_{111}=-2; \lambda_{112}=-0.00018; \lambda_{113}=0.00018.$$

The energy values of the graphs for the corresponding assembly matrices, calculated from expression (8), are

$$E(M_I) = 4.23; \\ E(M_{II}) = 2.00036. \quad (10)$$

The obtained values of energies indicate that the optimal solution is the solution of case II. The subsequent analysis of the assembly matrix and MKG of this case allows us to proceed to the development of the kinematic scheme of the synthesized device (Fig. 4, a).

The design implementation of the obtained kinematic scheme in the form of a 3D-model of the device was performed using the *Autodesk Inventor Series* software package (Fig. 4, b). Checking the kinematics of the developed device, carried out by this software package, showed that the change in the flow area has a close relationship with the geometric parameters of the elements determining the kinematic pair of the 4<sup>th</sup> class. The implementation of the kinematic pair in the form of a camshaft mechanism with a kinematic closure suggests that it is possible to realize a synthesized design of the reduction characteristics of a different form of nonlinearity. Moreover, the form of nonlinearity will be closely related to the nonlinearity of the cam, which in this case sets the control algorithm.

An important role in the synthesis of the new mechanism and its design implementation is played by solid-state modeling of the device elements in order to create a prototype. In this case, additive 3D-printing manufacturing were applied (Fig. 5, a). The presence of solid constituent elements allowed carrying out the choice of material for each of them, to clarify their shaping, as well as to clarify the

nomenclature of standard products that can be used in the design of the device being synthesized. Data on the material and the shaping of the components of the device along with the expected input parameters (nominal pressure, range of its changes, and diameter of the pipeline) allowed, in turn, to calculate structural strength using the *SolidWorks* software. Using the *CAM*-software from *Autodesk Inventor Series* package, we have obtained the appropriate control programs for the CNC machine tools required to manufacture the complete product part list. Computer simulation of assembly operations and their parallel testing on a solid model allowed to create a complete technological map of the assembly of this device and to develop recommendations for the appropriate technological equipment (Fig. 5, b).

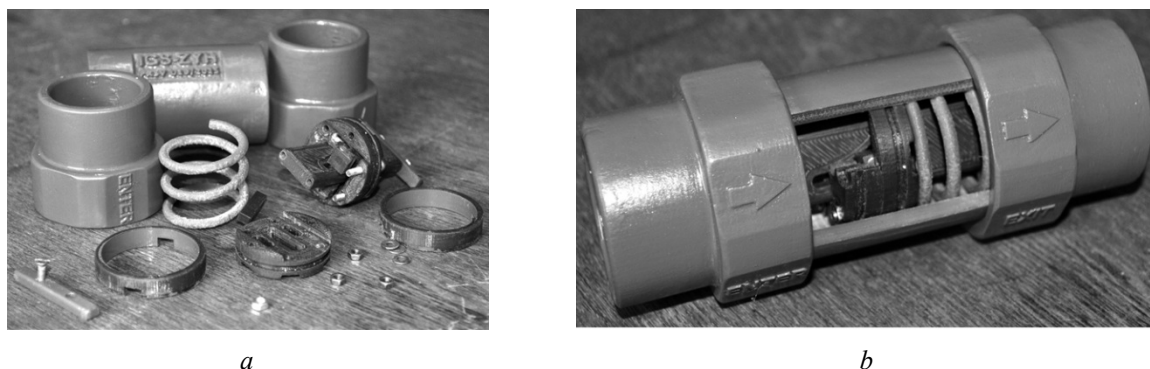


Fig. 4. Modeling using additive 3D-printing technologies: solid-state components of the device (a); assembled solid-state device model (b)

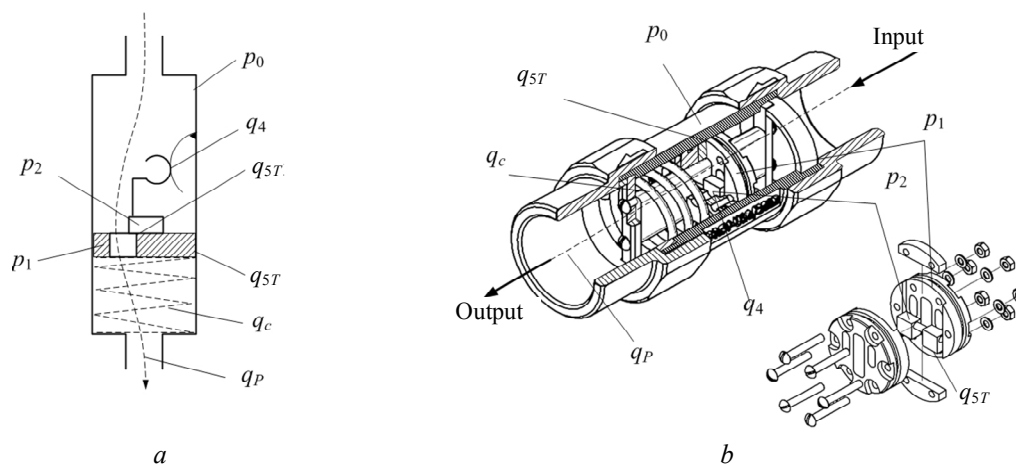


Fig. 5. Synthesis of pressure reducing valve with mechanical control system: kinematic scheme (a); design implementation (b)

**Conclusions.** As a result of the studies, a fundamentally new device was synthesized in the form of a passive controlled pressure reducing valve. The presence in the structure of the device of an additional mechanical structure that determines the camshaft mechanism with a kinematic closure makes it possible to significantly expand its functional capabilities.

It was found that:

– expansion of the structure of the known reducing valve by additional mechanical structures is appropriate, because it allows to realize a fundamentally new way of controlling its reduction characteristic;

- model in the form of a modified kinematic graph that defines a certain device as a device with mechanically variable characteristics must have at least three cycles, two of which determine the main functional interaction of the elements of the device, and the remaining – their modification;
- in the case of multivariance of solutions during the synthesis of a device based on modified kinematic graphs, it is expedient to select the optimal solution based on calculating the graph energy.

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Received January 20, 2017

Accepted March 7, 2017