STRUCTURAL OPTIMIZATION OF PIPELINE SYSTEMS DURING THEIR DESIGN AND RECONSTRUCTION

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ABSTRACT

The study considers peculiarities of structural optimization of pipeline transport systems that help to ensure the required level of their resistance to development of the process of progressive blocking of nodes. It is shown that the highest level of resistance of network structures to consistently increasing risks of damage is achieved in systems with the largest composition of the subset G1 (source to consumer links), under the condition of high valence of the source node of the target product. The valence of an individual system node is a number of pipelines converging into it, and the linear elements connecting directly the source and consumers of the product are considered to belong to the subset G1.

The established regularities allow solving the problems of searching for optimal network structures that are resistant to development of emergency situations, by the mechanism of progressive blocking of nodes in design and reconstruction of pipeline transport systems.

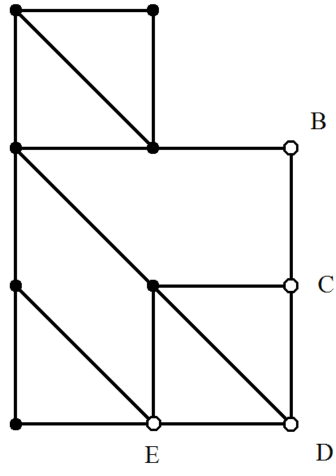
Keywords: *transport, system, pipeline, structure, optimization, damage.*

Background. *Pipeline transport systems are widely used in various branches of industrial production for delivery of various substances and materials to consumers [1, 2]. The technological capabilities of such systems depend to a large extent on their structure, the choice of which is an independent engineering and technical task.*

Designed solutions determine not only the operational properties of systems, but also their behavior in the context of development of extraordinary situations. Thus, transition to the state of inoperability of one or several pipelines may lead to restrictions or complete cessation of the delivery of the target product to individual consumers. In these conditions, the most dangerous is the process of damage to the system's nodal elements, in which the delivery of the product through the blocked node becomes impossible.

Objective. *The objective of the author is to consider structural optimization of pipeline systems during their design and reconstruction focused on their resistance to development of the process of progressive blocking of nodes.*

Methods. *The author uses general scientific and engineering methods, graph construction, simulation method, structural synthesis methods.*



Pic. 1. A network object with a specified location of nodes-consumers of the target product.

Results. *In essence, blocking of a node means a momentary transition to a state of inoperability of all pipelines converging to this node. If the process of blocking occurs in a random sequence, then such an emergency scenario is called progressive blocking [3].*

Progressive damage through blocking of transport nodes is an extremely dangerous scenario, causing rapid degradation of the properties of the system with the subsequent disconnection of all consumers of the product from the source. The ability of the system to withstand the development of processes of progressive blockage is characterized by an index of resistance F_x. It is the average fraction of nodes whose lock-up in a random sequence results in disconnection of all consumers of the target product from the source.

The value $0 \leq F_x \leq 1$ depends on the structure of the pipeline system and is established using the simulation method [3]. The closer is the value of the indicator of resistance to unity, the greater is resistance of the structure of the pipeline system to progressive blocking of nodes.

Structural synthesis of pipeline systems should be carried out from the point of view of optimality, i.e. search for the best or the nearest solution to it from the existing set of alternatives [6].

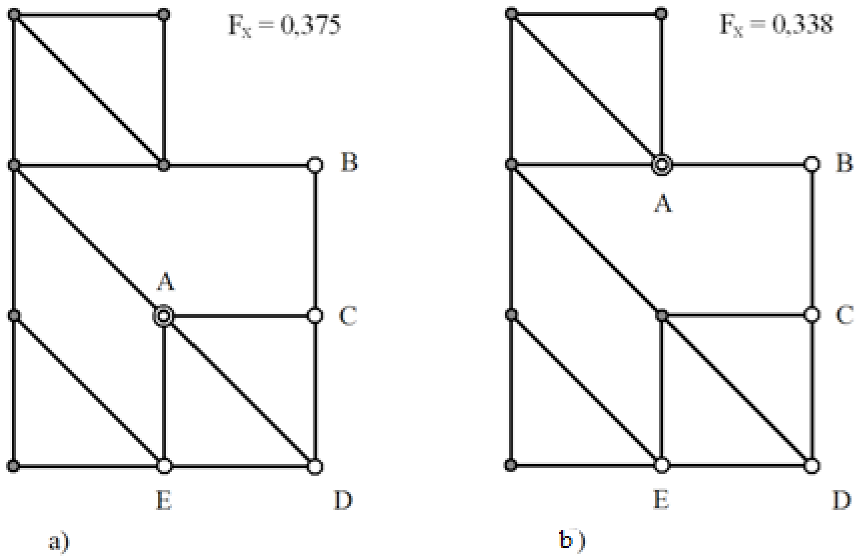
In this connection, let us consider the most common variants of the formulation of typical design problems and the corresponding methods for their solution.

Formulation of the problem. *For a given network structure with a known location of the nodes-consumers of the target product, it is required to select the position of the source node. The synthesized object should be as close as possible to the optimal, providing the highest (or close to it) level of the system's resistance to development of the process of progressive blocking of nodes.*

Let us consider the object shown in Pic. 1. It is a given network with a fixed location of the nodes-consumers B, C, D and E.

It is required to establish the location of the source node, at which the highest level of system resistance to development of the process of progressive blocking of nodes is achieved. In this formulation, the problem can be solved using the above recommendations.

Thus, Pic. 2a shows the solution that allows obtaining the highest value of the index of resistance F_x. This is due to the fact that the source of the product is located in the node with the highest valence 4 in the system (valence is the total number of pipelines



Pic. 2. Alternative variants of structural schemes with different arrangement of the source node.

converging into the node). In addition, three of four linear elements converging to the node A belong to the subset G1[1]*.*

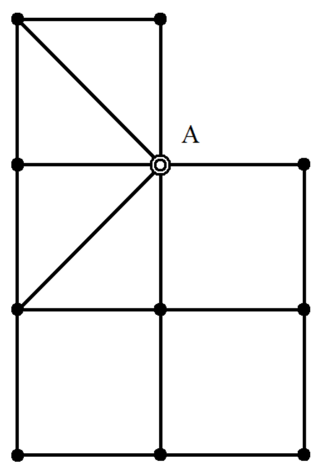
In Pic. 2b, an alternative solution is given in which the source of the product is also in a node with a valence 4. However, of four linear elements converging to this node, only one belongs to the subset G1.

In view of these structural features, the first variant of solution of the problem should be evaluated as the preferred one. The results of determining the values of F_x for each of these two cases are shown in Pic. 2. It can be seen, that the value of the indicator of resistance for the first option is greater than for the second variant, approximately by 1,11 times. Thus, the problem of choosing the location of the source is solved so that the node used for this purpose has a high valence, and the linear elements converging to it, if possible, belong to the subset G1. If there are several alternatives to such conditions, then for a final decision, the value of F_x for each of them should be clarified.

Let us now consider the features of the procedure of structural synthesis, which involves searching for location of consumers of the target product.

Formulation of the problem. *For a given network structure with a constant position of the source node, it is necessary to select the locations of consumers of the target product. The network object synthesized in this case must have high resistance to development of the process of progressive blocking of nodes.*

Let us consider in this connection the structural diagram of the pipeline system, shown in Pic. 3. Let us suppose that it is required to enter into its structure five consumers of the target product. The source node of the system under analysis has a valence 6. Since the network object needs to include five consumers,



Pic. 3. Source network object with a fixed location of the source node A.

the greatest positive effect will be achieved if each consumer is connected directly to the source of the product.

One of the solutions to this problem is shown in Pic. 4a. The number of elements of the subset G1 in this case is the largest. If the consumers of the target product are located as shown in Pic. 4b, then the number of elements of the subset G1 in the object under consideration turns out to be the smallest.

In this connection, we can assume that the first of the considered solutions of the problem has better properties. The results of calculating the values of resistance to the process of progressive blocking of nodes are shown in Pic. 4. It can be seen that the value of F_x, established for the first variant is greater than for the second one, approximately by 1,12 times,

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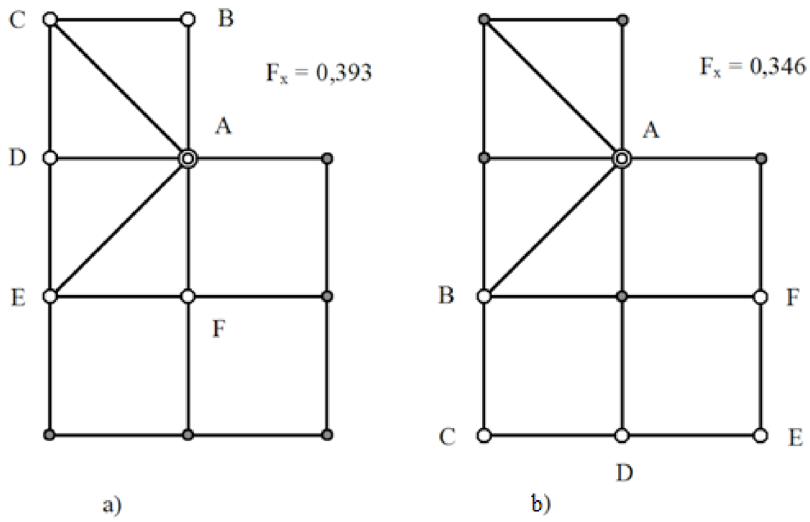
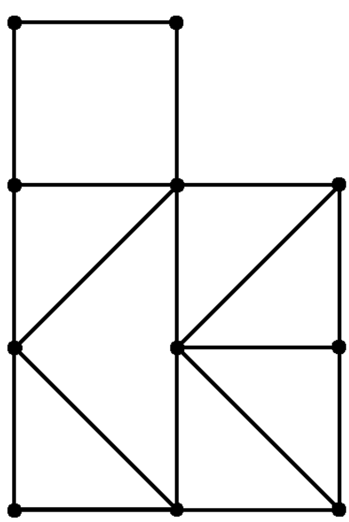
[1] The author uses the following subsets: G1 source – consumer, G2 consumer – consumer, G3 consumer – distribution node, G4 distribution node – distribution node, G5 source – distribution node.



Pic. 4. Alternative variants of block diagrams with different arrangement of nodes-consumers B, C, D, E and F.



Pic. 5. The initial graph as a basis for editing a structural diagram of the pipeline transport system.

which confirms the above assumption about the expected properties of the analyzed objects.

In this formulation of the problem, the choice of location of nodes-consumers is done in such a way that each of them is as far as possible connected with the source directly. If several alternatives meet these requirements, then to determine the final decision, the value of the resistance index F_x for each of them should be clarified.

Let us now consider the features of the procedure of structural synthesis in the case when only the topology of the network object is specified.

Formulation of the problem. *For a network object with a given set of links between point elements, it is required to determine the position of the source node and nodes-consumers of the target product, ensuring that the values of the resistance index F_x are greatest or close to them.*

Let's suppose that the original topology of the object is described by the graph shown in Pic. 5. It is required to select the location of the source and five consumers of the product in such a way as to provide the greatest F_x value or the value which is the nearest to it. Since there are nodes with a valency 5 in the structure under consideration, they should be used when selecting the position of the source node. Thus, Pic. 6a shows implementation of this solution, and nodes-consumers are arranged so that the composition of the subset G1 is the largest.

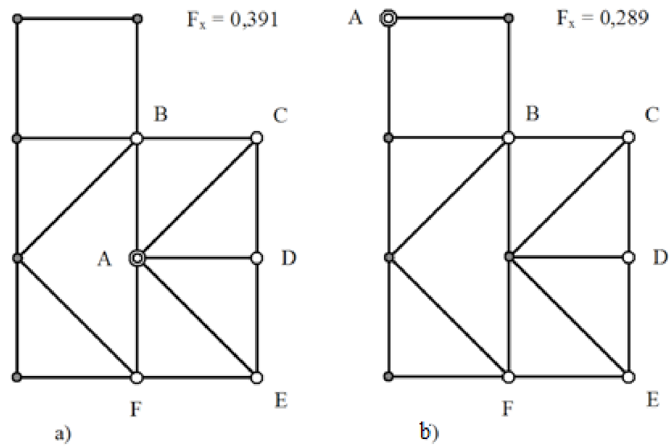
The alternative solution shown in Pic. 6b, is characterized by a low valency of the source node, in which only 2 elements of the subset G5 converge. The results of calculating the resistance of the analyzed objects to development of the process of progressive blocking of nodes are also shown in Pic. 6. It can be seen that the value of F_x for the first variant is greater than for the second variant, by 1,35 times. That is, the block diagram shown in Pic. 6a should be considered as a solution of the synthesis problem.

The problem of choosing rational network structures also arises in reconstruction of existing pipeline transport systems [7, 8].

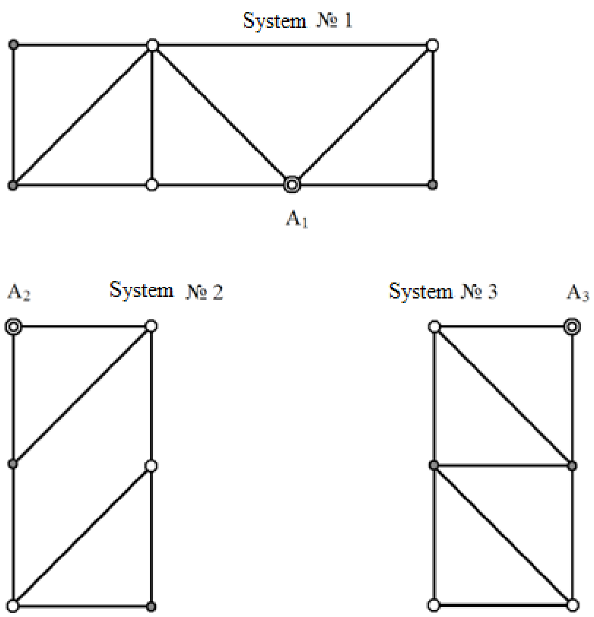
Formulation of the problem. *Reconstruction of nearby pipeline systems requires expansion of their technological capabilities due to inclusion in a unified transport network. The structural synthesis of the new system is connected both with introduction of additional linear elements and with the choice of location of the source of the target product on the basis of one of the operating source nodes of the systems being combined.*

The solution of such a problem should ensure formation of a new network object with a high level of resistance to development of the process of progressive blocking of nodal elements.

Let's suppose that the planned reconstruction work involves unification of three independently functioning pipeline systems, the structural diagrams of which are shown in Pic. 7. The combination of systems will require introduction of at least two additional linear elements, as well as the choice of the



Pic. 6. Alternative variants of the structural diagrams of the pipeline transport system.



Pic. 7. Diagram of mutual arrangement of three functioning pipeline systems prior to commencement of the procedure for their unification.

location of the source node, capable of performing its functions under new conditions.

A possible solution to the problem is shown in Pic. 8. It can be seen that in the new system the source node A, which belonged to system No. 1 earlier, retained its position and purpose, and the remaining source nodes of systems No. 2 and No. 3 began to act as distribution nodes.

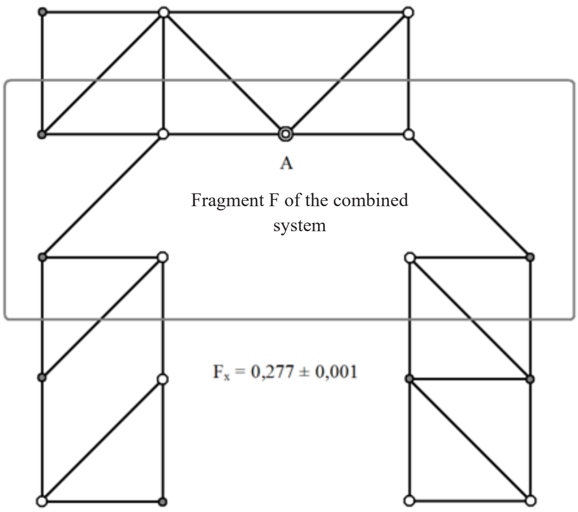
This variant of combining three original pipeline systems is further considered as the base-case variant.

Formation of alternative network structures in search for other design solutions can be perceived as a result of transformation of this basic option. All planned changes in composition of the base object should be limited to the established boundaries of the fragment F, shown in Pic. 8.

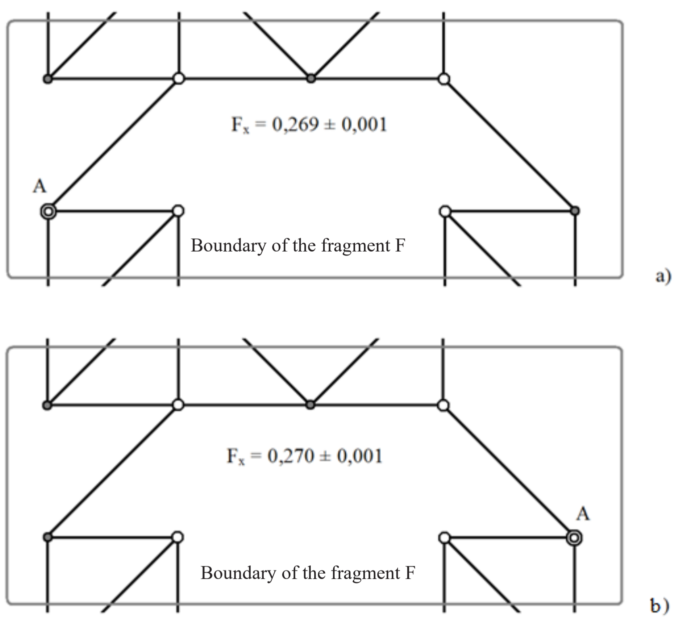
Let us consider formation of an integrated system that is different from the base-case, choosing other options for locating the source node within F, as shown in Pic. 9a and 9b. The advantage of these solutions is the possibility of further use of existing infrastructure and equipment that ensure functioning of the source nodes of the combined systems.

However, the listed options for solving the problem of structural synthesis are not able to provide a high level of values of the indicator of resistance:

1. The valence of the source node of the base structure exceeds the valence of the source nodes in the presented alternative solutions.



Pic. 8. Structural diagram of the base pipeline system and location of the fragment F.



Pic. 9. Alternative variants of location of the source node within the boundaries of the fragment F of the combined system.

2. Four pipelines belonging to the subset G1 converge to the source node of the base structure, and only two elements from the composition of the specified subset are assigned to the source node of each of the alternative structures.

In this connection, it should be assumed that, from three options for forming the network structure, the base-case model has the best properties.

The values of F_x set for each of these options are shown in Pic. 9. It can be seen that the above assumption is justified, and the basic scheme is just one of the best options for solving the problem.

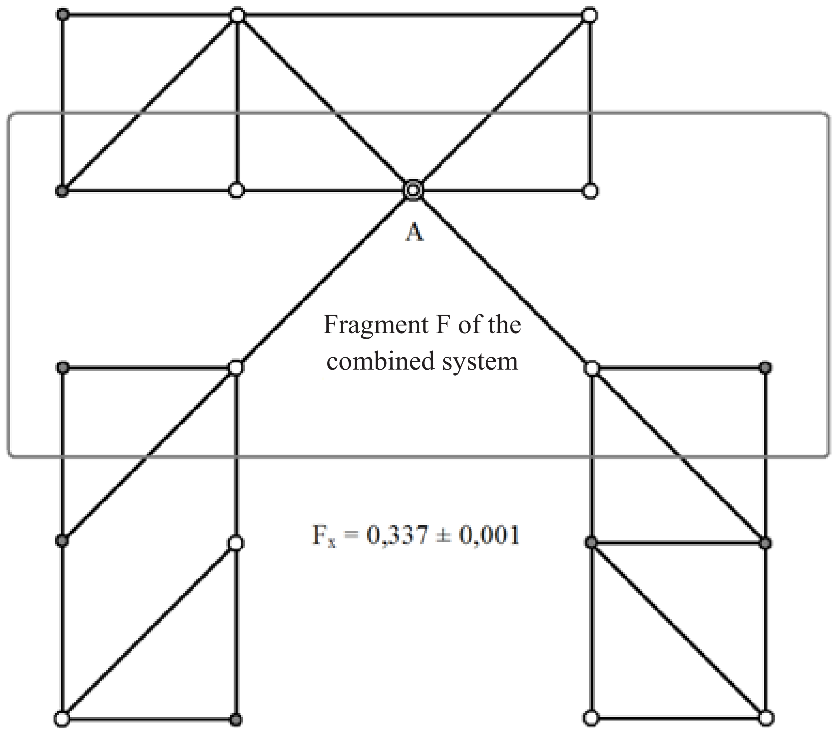
At the same time, it should be noted that the properties of the base object can be significantly improved if the valence of the node A is increased by two units, as shown in Pic. 10.

When implementing such a solution, the increase in valence of the source node occurs due to addition of elements of the subset G1 that converge to this point element. Since the scheme of the pipeline system, shown in Pic. 10, is characterized by the highest value of the resistance index, then it should be considered as the solution of the formulated optimization problem of structural synthesis.

Thus, the solution of the problems of structural optimization of network objects should be performed on the basis of the developed methods and recommendations, taking into account the established patterns of development of the processes of progressive damage to the nodal elements of transport systems.

Conclusions.

1. The highest level of resistance of network structures to development of the process of



Pic. 10. Structural diagram of the pipeline system with valence 6 of the source node.

progressive blocking of transport nodes is achieved in systems with the largest quantitative composition of the subset G1, and also under condition of high valence of the source node of the target product.

2. The choice of location of the source in the given network structure with the known arrangement of the nodes-consumers is carried out in such a way that the used node has a high valence, and the elements converging to this node belong, if possible, to the subset G1.

3. The choice of the location of nodes-consumers in a given network structure with a known source position is implemented so that each consumer is as far as possible connected to the source of the product directly.

4. The choice of mutual location of the source and consumers of the product in the structure of the given topology should be carried out in such a way that the greatest value of the index of resistance F_x is provided.

5. Structural optimization of existing pipeline systems under conditions of their integration during reconstruction is carried out so that with a minimum number of additional linear elements to ensure a high level of values of the index of resistance F_x.

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