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Structural and parametric models of hydro-aerodynamic systems for increasing the efficiency of energy infrastructure facilities

Vasyl A. Arsirii[1)]
ORCID: https://orcid.org/0000-0003-3617-8487; vasyly.arsiriy@gmail.com. Scopus Author ID 54419479400
Olena O. Arsirii[2)]
ORCID: https://orcid.org/0000-0001-8130-9613; e.arsiriy@gmail.com. Scopus Author ID. 54419480900
Oleg V. Kravchenko[3)]
ORCID: http://orcid.org/0000-0001-9765-2344; sir.kravchenko777@gmail.com. Scopus Author ID 57204660061
Petro M. Ryabokon[1)]
ORCID: https://orcid.org/0000-0002-3006-8757; Petr070567@gmail.com
Oleksandr V. Kroshka[1)]
ORCID: https://orcid.org/0000-0003-0975-3079; Kolvi@epg-kolvi.com
[1)] Odessa State Academy of Civil Engineering and Architecture, 4, Didrikson Str. Odessa, 65029, Ukraine
[2)] Odessa Polytechnic National University, 1, Shevchenko Ave. Odessa, 65044, Ukraine
[3)] National University "Odessa Maritime Academy", 8, Didrikson Str. Odessa, 65052, Ukraine

ABSTRACT

An analysis of the energy consumption structure in Ukraine shows that it is necessary to take into account the current global trends in energy efficiency during the post-war restoration of such key energy infrastructure facilities as heat and electricity generation heat hydro-aerodynamic systems and water supply ventilation air conditioning. etc. However the analysis of existing information technology for computer-aided design of energy facilities which are based on hydro-aerodynamic systems. Showed that the models and methods of structural and parametric synthesis of components of hydro-aerodynamic systems (generating energetically active basic elements and network energetically passive auxiliary elements) do not fully take into account the influence of the state of real hydro-aerodynamic processes in the formation of a base of typical design solutions of elements. This leads to a decrease up to 40% of the energy efficiency of the designed infrastructure facilities. Therefore the development of structural-parametric models of energy-efficient hydro-aerodynamic systems and the creation on their basis of an appropriate information technology integrated in engineering computer-aided design is especially relevant during the post-war restoration of Ukraine energy infrastructure facilities. When developing structural-parametric models of energy-efficient hydro-aerodynamic systems. The following tasks were solved: based on a comparative analysis of the possibilities of structural. Parametric and structural-parametric synthesis of energy-efficient hydro-aerodynamic systems to create information technologies integrated in machine-building and engineering computer-aided design systems. a structural parameter was reasonably chosen; structural-parametric models of an energy-efficient hydro-aerodynamic system and its components (network and generating parts) have been developed; a logical-numerical model for generating technical proposals for the structural-parametric synthesis of energy-saving hydro-aerodynamic systems taking into account the advantages of using the topological properties of graph models in the space-time domain has been developed; the definition of additional target parameters of the structural-parametric model of the hydro-aerodynamic system is proposed. The developed models were used to create an information technology for the structural-parametric synthesis of energy-saving hydro-aerodynamic systems integrated in computer-aided design. Approbation of the proposed information technology showed that the reduction of hydro-aerodynamic resistance in the network part of hydro-aerodynamic systems made it possible to increase the energy efficiency of the synthesized hydro-aerodynamic systems from 25 to 45%. This was performed by reducing the energy expended to provide the specified consumption of the working fluid created by the main elements such as feed pumps blow fans and smoke exhausters.

Keywords: Information technology integrated in computer-aided design; structural-parametric synthesis; graph models; hydro-aerodynamic processes; energy efficiency; energy infrastructure

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INTRODUCTION

During the period of post-war restoration of energy infrastructure facilities in Ukraine it is necessary to take into account the current global trends in efficient energy consumption in the systems of thermal and electrical generation heat. Hydro-aerodynamic systems and water supply ventilation air conditioning etc. The analysis performed proved that the desired energy efficiency indicators can be achieved through energy saving in hydro-aerodynamic systems (HAS) which provide hydro-aerodynamic processes (HAP) of lifting compressing expanding and transporting liquids and HASes and therefore are the main consumers of electrical energy for the so-called own needs [1, 2]. Therefore new modern requirements for energy saving in HAS should be taken into account already during their design and creation of appropriate information technologies in machine-building and engineering computer-aided design (CAD) systems.

However the analysis of existing information technologies for computer-aided design of HAS showed that *models and methods of structural and parametric synthesis of HAS components* (generating energetically active main elements and network energetically passive auxiliary elements) do not fully take into account the influence of the state of real HAPs when forming a base of typical design solutions (templates) of the elements. And the *models and methods of structural synthesis of the network part of HAS* implemented in engineering CAD use exactly such templates with unreasonably high values of hydro-aerodynamic resistances. The situation is complicated by the fact that the *models and methods of parametric synthesis of HAS* implemented in CAD take into account the total pressure losses in auxiliary elements as a limiting parameter when choosing the capacity of the main generating element in the designed HAS. In this case the value of the limiting parameter is unreasonably large so it is formed on the basis of overestimated hydro-aerodynamic resistance in the selected auxiliary elements. In the final decision on the design of HAS only the value of the coefficient of efficiency of the selected main element is taken into account. Studies show that the above problems lead to energy losses of up to 40% in HAS designed with the help of implemented information technologies in mechanical engineering and engineering CAD [3, 6].

Thus the development of structural and parametric models of energy-efficient HAS and the creation on their basis of appropriate information technology integrated in the engineering CAD is an actual scientific and technical task especially during the post-war restoration of energy infrastructure facilities in Ukraine.

ANALYSIS OF EXISTING RESEARCH AND PUBLICATIONS

Structural-parametric synthesis is the process by which the structure of an object is determined and the values of the parameters of its constituent elements are found in such a way as to satisfy the conditions of the technical specification. If the synthesized object is optimal (quasi-optimal) by any criterion(s) then the synthesis is also optimal (quasi-optimal) [7].

When automating the process of structural-parametric synthesis of energy-efficient HAS as a rule. the following three tasks are solved: development of complex system models definition of the target function (indicator criterion) and creation (selection) of synthesis method (algorithm) [8].

Analysis of the literature and the Internet showed that the existing machine-building and engineering CAD is implemented in sufficient detail the third task through the method of creating computer parametric models of HAS and their elements (MicroCAP, Microwave Office, ANSYS) [9, 10]. Therefore, let us formulate the content of the first two listed tasks of automation of structural-parametric synthesis in comparison with similar tasks of parametric synthesis.

Designing of a structural-parametric model of the system. It is known that during parametric synthesis and optimization of HAS the search for design solutions is performed in the space of element template parameters from the database of design data. Consequently in the parametric model of HAS only the parameters of these elements been changed. Which in turn are the components of the designed system structure? While the system structure itself in the process of parametric synthesis and optimization remains unchanged. In structural-parametric synthesis of HAS. The search for design solutions is carried out in the space of both structures and templates of elements of these structures. Consequently it is necessary to perform modeling not of a particular system but of a class of similar designed systems. Such a model is called a structural-parametric (universal) model and sets a restriction on the set of HAS structures in which the search for a design solution is organized [11]. The authors' comparison of the properties of parametric and structural-parametric models is given in Table 1.

There are two approaches in the development of structural-parametric models in order to create an information technology integrated in CAD-HAS:

– on the basis of “autonomous” models the solution of which will be the characteristics of the designed systems;

– on the basis of “morphological set models” the solution of which will be the specifications of the designed devices.

When implementing the first approach based on autonomous models it is necessary to perform the process of computer modeling for all proposed HAS

Table 1. **Comparative properties of parametric and structural-parametric synthesis models**

Properties of parametric models	Properties of structural-parametric models
The structure of the model is fixed and does not change during synthesis	The structure of the model is not known in advance and the model is generated automatically
Only the parameters (patterns of elements) are changed. The search is performed in the parameter space	Both structure and parameters are changed. The search is performed in the space of structures and parameters
The dimensionality of the parameter vector is fixed	The dimensionality of the parameter vector is unknown beforehand and can only be determined after the structure is determined

Source: **compiled by the authors**

structures their elements and parameters including formation and calculations. They can be implemented in the form of dynamically linked libraries (DLL). The advantages of such models are their efficiency. Since special methods of modeling systems of a narrow class (for example an algorithm for developing a forced-draft tract or a heat pipeline) can be used in their creation. Information technologies created on the basis of such models are autonomous and do not require other expensive software packages (like ANSYS). The disadvantage is the high labor intensity of their creation [7].

When implementing the second approach on the basis of morphological set models it is necessary to provide only the generation of specifications of structures of the class of designed systems. The advantage of such models is the simplicity of their creation in the presence of special linguistic support. In addition the separation of different types of knowledge – about the structure of the designed systems (in the morphological set model) and about the calculation of characteristics (in the external package of the computer modeling system) from the methodological point of view seems to be positive. The disadvantage is that CAD that uses such models requires external expensive computer simulation software packages. And they can only be used in conjunction with packages that have an input language compatible with the specifications generated by these models [8].

Target function definition. It is known that during parametric optimization only parameters of elements that make up the structure of the designed system are changed while the structure itself remains unchanged. At the same time in structural-parametric optimization both parameters and structure of the system are changing. Thus from the formal point of view the target function for each structure will be unique and an algorithm for its automatic formation is required. However in practice the synthesis of structures may require an additional target function. Reflecting the structural properties of the designed object and indicating the compliance of the selected structure with the conditions of the technical problem [11].

It should be emphasized that in the structural-parametric synthesis of systems. The designer gets more freedom in creating the target function which is a formalized synthesis problem. Thus in parametric synthesis the application of restrictions on the criteria is limited by the fact that for a given structure of the designed system the cumulative fulfillment of the restrictions may be unattainable. In structure-parametric synthesis there is no such problem if the algorithm is designed correctly the technical problem is correct and the morphological set contains a structure in which these constraints are satisfied.

The studies show that for the analysis to further take into account the state of HAP in the structural-parametric synthesis of models of energy-efficient HAS use the representation of parameters in the form of graphs and the corresponding adjacency and incident matrices.

Models in the form of graphs have become widespread in science and technology in particular in the creation of information technologies integrated in CAD. Due to the additional opportunities that appear with the geometric approach to the interpretation and solution of various processes in the field of design

production and management. This is due to the fact that in contrast to the Euclidean rectangular. Curvilinear and other spaces in the graph models the concepts of topological geometries and spaces are used [11, 12].

In the spatiotemporal domain a graph is a set of points and lines connecting these points. These connections can have many characteristics. Figuratively a graph is represented as a set of points on the plane called vertices (Fig. 1) and a set of directed segments connecting all or some of the vertices called arcs. Mathematically graph G is defined as a pair of these sets X and U: $G = \langle X.U \rangle$.

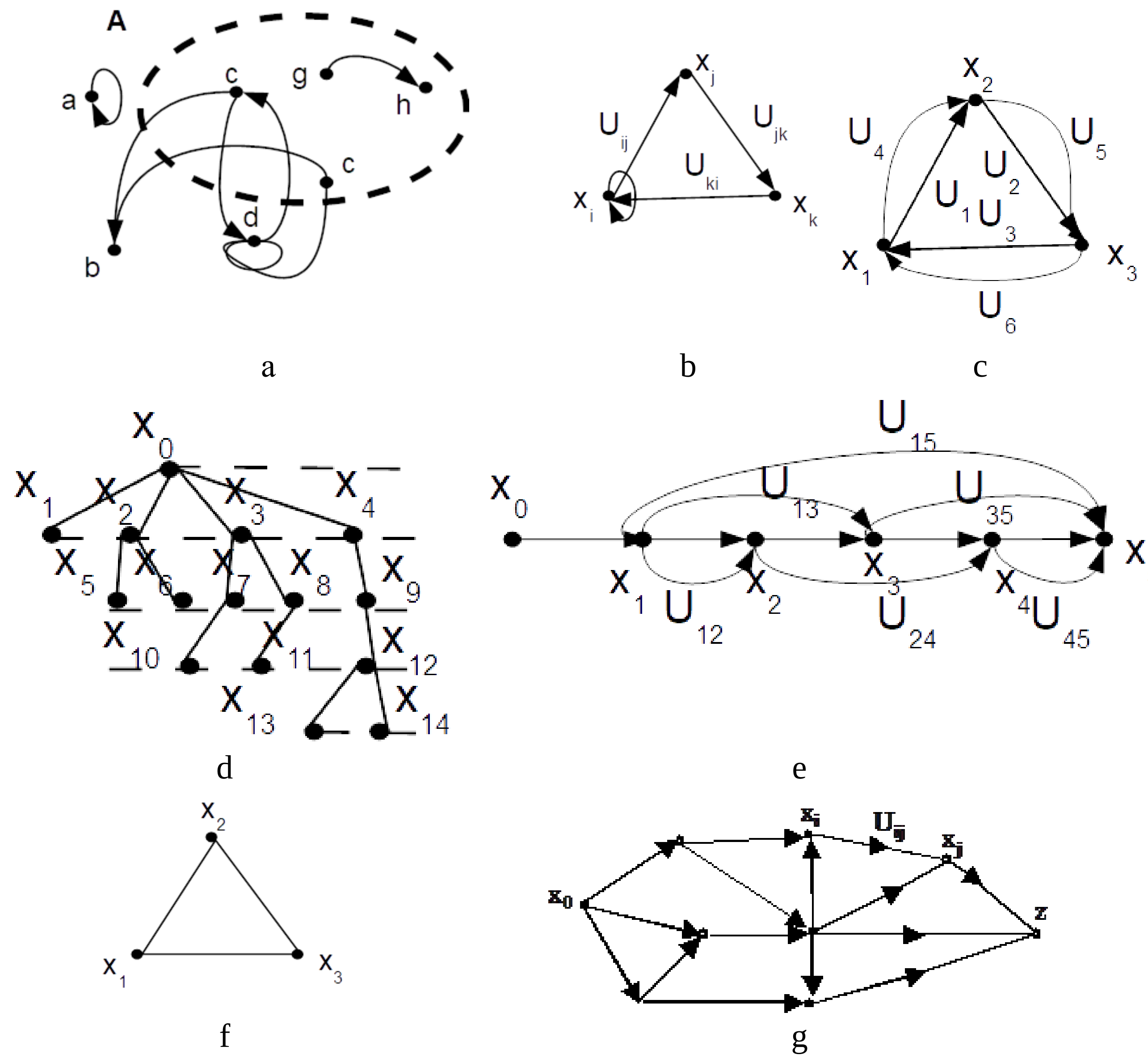


Fig. 1. **Examples of graph models:**
a - general view of graph; b - with loop; c - symmetric; d - as a tree; e - undirected; f - oriented; g - as a network
***Source:* compiled by the authors**

For example the vertices of the graph (Fig. 1a) are points $a.b.c.d.e.g.h$ and its arcs are segments $(a.a), (c.b), (c.d), (d.c), (d.d), (e.d), (g.h)$. If we assume that the set of directed arcs$U$, connecting elements of the set X, reflects this set in itself then a graph can be considered given if the given set of its vertices and the way of mapping Γ of the set X to X i.e, graph G is a pair $(X.\Gamma)$.

It consists of the set X and the mapping Γ defined on this set:

$$G = (X.\Gamma). \tag{1}$$

For the graph in Fig. 1a, the mapping Γ is defined as follows:

$$\Gamma a = a;\ \Gamma b = \varnothing;\ \Gamma c = \{b.d.e\} \tag{2}$$

$$\Gamma d = \{d.c\};\ \Gamma e = d;\ \Gamma h = \varnothing.$$

Here are some definitions. A graph is called complete if for any of its pairs of vertices x_i and x_j $x_i \neq x_j$ there exists an arc $(x_i.x_j)$ (Fig. 1b).

Let x_i be a subset of the vertices of the graph $G = (X_1.\Gamma_1)$. Then a graph $G_1 = (X_1.\Gamma_1)$ whose set of vertices coincides with $X \subseteq X$ and whose set of arcs $\Gamma_1 \subseteq \Gamma$ and whose set of arcs G_1⊆G includes all arcs of the set Γ with finite vertices only from the set X_1 is called a subgraph of graph G generated by the set X_1. A graph is called planar if it can be represented in the plane so that its edges intersect only the vertices. A subgraph G_A of graph $G = (X.\Gamma)$ is a graph which includes only a part of vertices of graph G forming set A together with arcs connecting these vertices.

$$G_A = (A.\Gamma_A) Z \subseteq X;\ \Gamma_{A^x} = (\Gamma_x) \cap A. \quad (3)$$

The adjacency characterizes the relationship between elements of sets of the same name X and Γ. Different vertices are called adjacent if they are connected by an arc (edge). Different arcs (edges) are called adjacent if they have a common finite vertex.

Incidentality characterizes the relation between elements of different names sets X and Γ. An arc and a vertex are incidental if the vertex for the arc is a finite vertex. The degree of vertex x_i ($\deg x_i$ or $\mathrm{d}\, x_i$) for an undirected graph is the number of edges incident to vertex x_i. If $\mathrm{d}\, x_1 = 1$ then the vertex is deadlocked and if $\mathrm{d}\, x_1 = 0$ then the vertex is isolated.

It is convenient to represent graphs in the form of some matrices. Particularly common are descriptions of graphs by means of adjacency and incidence matrices. Let us denote by $x_1. \dots . x_n$ the vertices of the graph and by $u_1. \dots . u_m$ its arcs.

Now introduce numbers:

$$r_{ij} = \begin{cases} 1.\ \text{if there is an arc between vertices } i \text{ and } j; \\ \quad 0.\ \text{if there is no such arc.} \end{cases} \quad (4)$$

A square matrix $R = \|r_{ij}\|$ of order $n \times n$ whose rows and columns correspond to vertices, is called the *adjacency matrix* of graph vertices. In the case of undirected graph, the matrix element is equal to the number of edges connecting vertices x_i and x_j.

An edge adjacency matrix is a matrix whose rows and columns correspond to graph edges and the element r_{ij} equals the number of vertices incident to two edges U_i and U_j.

Let us introduce further the numbers:

$$s_{ij} = \begin{cases} \quad +1.\ \text{if } u_j \text{ is out of } x_i; \\ \ -1.\ \text{if } u_j \text{ is within the } x_i; \\ 0.\ \text{if } u_j \text{ is not incidental to } x_i. \end{cases} \quad (5)$$

The matrix $S = \|s_{ij}\|$ of order $n \times m$ with rows is corresponding to vertices and columns corresponding to edges – is called the *incident matrix* for the graph arcs. For an undirected graph the element of the incident matrix S_{ij} is equals to 1 if a vertex is incident to an edge. Otherwise $S_{ij} = 0$.

The incidence matrices in the described form are applicable only to graphs without loops. If a graph has loops this matrix should be dissected into two half-matrices: positive and negative. Two graphs are called isomorphic if and only if there is a one-to-one correspondence between their vertices and edges while maintaining incident relations.

The described graph structures were used when developing models of structural-parametric synthesis of energy-saving HAS to formalize technical proposals when creating information technology integrated in CAD.

THE AIM AND OBJECTIVES OF THE RESEARCH

The aim of this study is to develop structural-parametric models of energy-efficient HAS and create on their basis an appropriate information technology integrated in the engineering CAD which is especially relevant during the post-war reconstruction of energy infrastructure facilities in Ukraine.

To achieve this goal the **tasks** were solved in the work:

1. A comparative analysis of structural parametric and structural-parametric synthesis capabilities of energy-efficient HAS using information technologies integrated in machine building and engineering CAD has been carried out.
2. Analyzed the advantages of using graph models when constructing a structural-parametric model of HAS in the spatial-temporal domain.
3. Structural-parametric models of energy-efficient hydro-aerodynamic system and its components (network and generating parts) have been developed.
4. A logical and numerical model of generation of technical proposals in the structural-parametric synthesis of energy-saving hydrodynamic aerodynamic system is developed.
5. The definition of additional target parameters of the structural-parametric model of HAS is proposed.
6. The method and information technology of structural-parametric synthesis of energy-saving HAS integrated in CAD is developed.

PRESENTATION OF THE MAIN RESEARCH MATERIAL

Development of a structural-parametric model of the hydro-aerodynamic system

During development of structural-parametric model (SPM) of energy-efficient HAS the definition of HAS as a system of elements providing technological processes of lifting compression and transportation of liquids and gases (hydro-aerodynamic processes – HAP) was introduced. For example systems for supplying fuel water air removal of flue waste gases. Structurally these systems consist of energetically active element and energetically passive technological and auxiliary elements.

To analyze the energy intensity in such systems it is proposed in the HAS structure to allocate the generating part which creates pressure due to the use of energy in the main energy active element (pump. fan. smoke exhauster) and the network part which spends the created pressure and consists of energy passive technological (filters, burners, heat exchangers) and auxiliary (turns, tees, collectors, latches) elements.

Thus when developing SPM of energy-saving HAS taking into account the existing design models and the influence of HAP state on the structural features of systems and elements. As well as the presence/absence of energy conversion process it is proposed to distinguish an energy-passive network part (*Network*) and energy-active generating part (*Generation*).

Then let's represent the SPM HAS as:

$$Sys_{H-A} = \langle Generation.Network \rangle. \qquad (6)$$

For the analysis of energy intensity in the network part *Network* the *Eminor* energy-passive components are highlighted such as inlet and outlet sections of pipes and channels equipment (parting pipes). Sections of pipes and channels with expansion or contraction of the section (washers. diaphragms. diffusers. confuse); change of the flow direction – turns (bends branching); merging or separation of flow (tees crosses distribution collectors); obstacles (nozzles grids meshes mesh layers); pipeline fittings and labyrinths (valves gate valves gates seals compensators) as well as technological elements of *Etechnolog* – different devices (purification devices. filters. heat exchangers).

In this case the technological elements *Etechnolog* are considered as units consisting of auxiliary elements.

To analyze the state of HAP in auxiliary elements and assess its efficiency it is proposed to use the coefficients of hydrodynamic resistances $R_{Eminor_i}.R_{Etechnolog_j}$ which are selected from the base of auxiliary elements.

The sum of the resistances of all elements of the network part is the hydrodynamic resistance R_{Net} of the network part of the HAS defined as:

$$R_{Net} = \sum_{i=1}^{n} R_{Eminor_i} + \sum_{j=1}^{m} R_{Etechnolog_j}, \qquad (7)$$

where $R_{Eminor_i}, R_{Etechnolog_j}$ is reference values of hydro-aerodynamic resistance of the i-th auxiliary element and the j-th technological element respectively.

In this case the number of elements is determined by the layout rules.

The theoretical calculation of hydrodynamic (hydraulic) resistances R_{Eminor_i} and $R_{Etechnolog_j}$ is possible only in the simplest cases (e.g. in noncontinuous flow around some well streamlined bodies or when the fluid flows along a straight cylindrical tube). Therefore in practice when forming the base of elements the hydraulic resistances are determined by empirical dependences on the similarity criteria obtained on the basis of numerous experimental studies.

In the works [4, 5] *hydro-aerodynamic resistance* is the resistance arising during the movement of the working fluid (liquid, gas) through pipes and channels. The energy or pressure of the moving working fluid spent on overcoming hydro-aerodynamic resistance is called the lost energy or *pressure loss* P_{Net} in the network part of HAS.

$$P_{Net} = R_{Net} Q_{Net}^2 = \left(\sum_{i=1}^{n} R_{Eminor_i} + \sum_{j=1}^{m} R_{Etechnolog_j} \right) (Q_{Net})^2, \qquad (8)$$

where R_{Net} is the sum of the resistances of all energetically passive network elements; Q_{Net} working fluid flow in the network.

At the same time $Q_{Net} = \rho d V_{cp}/2$, where V_{cp} is average speed of the working fluid before reaching the element under consideration; ρ is fluid density; d is diameter of the element under consideration.

Thus when developing technical proposals for the design of the network part of the HAS the necessary technological elements *Etechnolog* and auxiliary elements *Eminor* which are combined with each other and form a network structure in accordance with the selected layout rules are selected from the base of typical elements.

Taking into account (7) and (8) the network part of HAS is proposed to represent in the form of the following SPM:

$$Network = \bigcup_{i=1}^{n} [Rul_i]. \langle (Eminor_i.Etechnolog_i.Eminor_{i+1}).P_{Net}(R_{Net}.Q_{Net}) \rangle, \qquad (9)$$

where Rul_i is the rule of composition of the i-th energetically passive elements $i = \overline{1.n}$ defines the network part structure of the HAS; P_{Net} is function of pressure losses in the network which depend on the sum of resistances R_{Net} of all energy passive elements and losses of the working fluid in the network Q_{Net}.

With the help of the P_{Net} function the parameters of the network part of the HAS of a given structure are determined. In accordance with the SPM of the network part (9) the evaluation of the value of total pressure losses P_{Net} in the designed network part of the HAS is formalized for the given options of layout and working fluid flows Q_{Net}.

Major elements ($Emajor$) include elements that convert one type of energy into another. such as turbines engines boilers blowers and others.

For the analysis of energy intensity in the automation of generating part design of HAS *Generation* of particular interest are blowers (pumps. fans. compressors. smoke exhausters). In which the characteristics of hydro-aerodynamic process formed the space of parameters using the functions of total pressure $P_{Emajor}\left(Q_{Emajor}. n_{Rotor}\right)$ and energy consumption $N_{Emajor}(Q_{Emajor}. n_{Rotor})$.

Then the efficiency of the main element is defined as:

$$\eta_{Emajor} = \frac{P_{Emajor}Q_{Emajor}}{N_{Emajor}}. \qquad (10)$$

To construct the functions of pressure energy and efficiency the test data of the main element $Emajor$ on the manufacturer's experimental bench is used. These data contain information about the working fluid consumption Q_{Emajor} at a given number of motor revolutions n_{Rotor} of the main element. For the tests in order to build the space of analyzed functions [GOST 10921-90] the rules (schemes) Rul_{Emajor} of layout of the main generating element $Emajor$ and the $Econtrol$ element regulating the flow of working medium Q_{Emajor} by position of the guide vanes are defined. Thus the generating part of the HAS is tested together with the virtual network part the function of which is performed by the $Econtrol$ element.

In this case four possible rules are used:

– $Rul1_{Emajor}$ – free input and output i.e. no network part $P_{Net}^{in} = 0$ and $P_{Net}^{out} = 0$;

– $Rul2_{Emajor}$ – free input and output with pressure. i.e. the network part is located at the output section $P_{Net}^{in} = 0$ and $P_{Net}^{out} > 0$;

– $Rul3_{Emajor}$ – input with discharge and free output. i.e. the network part is located at the input section $P_{Net}^{in} > 0$ and $P_{Net}^{out} = 0$;

– $Rul4_{Emajor}$ – input with discharge and output with pressure, i.e., the network part is located on both sections $P_{Net}^{in} > 0$ and $P_{Net}^{out} > 0$.

The placement of the main $Emajor$ and the regulating $Econtrol$ elements determine the methodology of the experimental tests. The pressure losses at the input P_{Net}^{in} and output sections P_{Net}^{out} are modeled differently. As a rule only the parameters of the main element $Emajor$ are taken into account in the design. Therefore for modeling the parameters of both fans and smoke exhausters the composition $Rul4_{Emajor}$ is used as a unified one. In this case the input and output sections perform the role of stabilization of HAS parameters.

To analyze the influence of the HAP state on the projected energy characteristics of the HAS the so-called P-model is used (Fig. 2a) [16, 17].

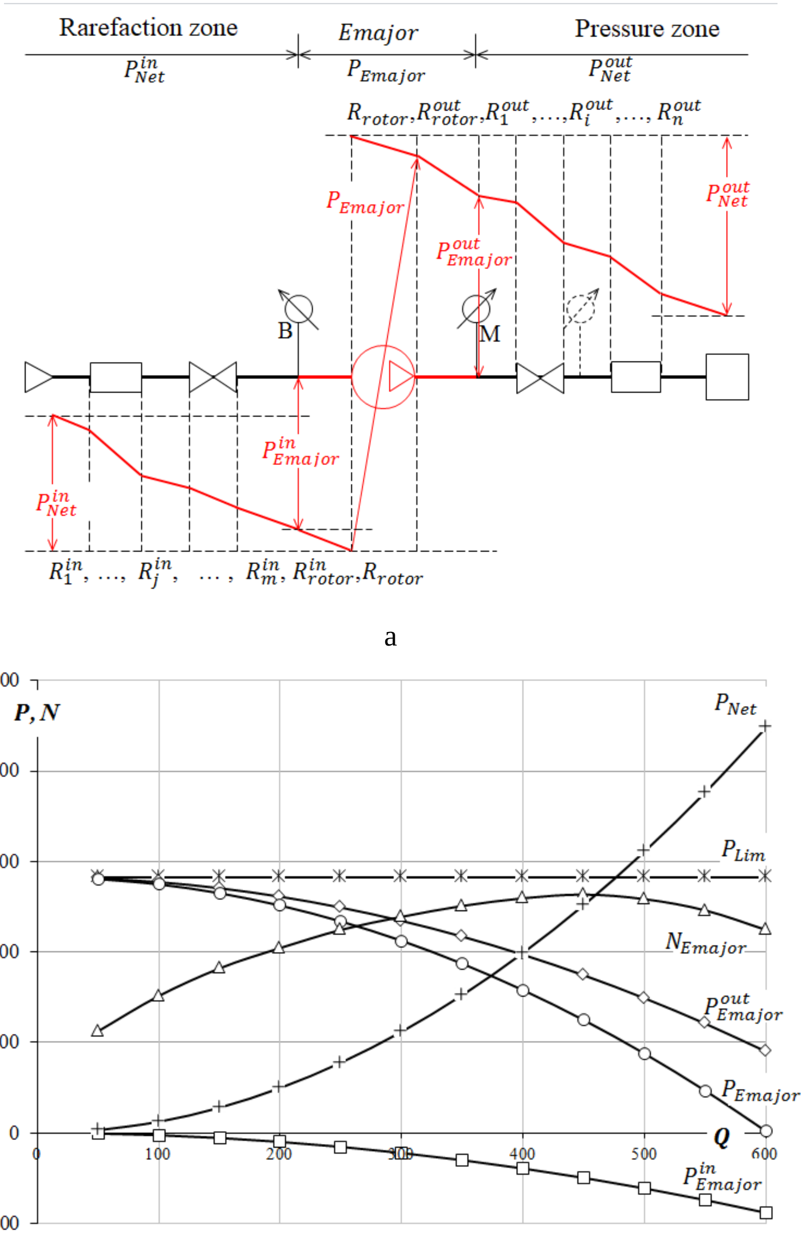
Based on the P-model (pressure model) a qualitative characteristic of the influence of the HAP state on the projected energy characteristics of the HAS is presented. The interaction of energy active element with the characteristics of pressure energy efficiency and energy passive elements and the characteristic of hydro-aerodynamic resistance is shown.

In the P-model all HAS elements are represented by the value of energy potential – pressure value P_{Net}^{out} (pressure zone) and discharge value P_{Net}^{in} (rarefaction zone). And all equipment is characterized by hydraulic resistance values R_j^{in} and R_i^{out} (including separate elements of blowers – input sections of the rarefaction zone from the place of vacuum gauge installation to the rotor wheel which diameter and number of rotations affect the increase in potential – pressure in HAS as well as pressure sections from the rotor wheel to the place of gauge installation.

An additional parameter of the P-model is the limiting pressure P_{Lim} calculated from the actual values of the blower rotor wheel diameter D_{rotor} and the number of rotations of the rotor wheel n_{rotor} (rpm).

$$P_{Lim} = ku^2 = k(\pi D_{rotor} n_{rotor})^2, \qquad (11)$$

where u is the peripheral rotation speed in the outlet cross-section of the blower rotor wheel.



a

b

Fig. 2. **Influence of the structure of the designed hydro-aerodynamic system on the parameters of the P-model:**
a – test scheme for the fourth rule; b – space of the characteristics of the hydro-aerodynamic processes in the analyzed hydro-aerodynamic system
Source: **compiled by the authors**

As noted above the main purpose of testing the main element on the manufacturer's experimental bench is to build a space of functions of pressure energy and efficiency depending on the flow of the working fluid at a given number of rotations of the electric motor of the main element (Fig. 2b).

According to the parameters obtained from the instrument readings (pressure loss and working fluid flow rate in the generating part). The hydro-aerodynamic resistance R_{rotor} of the flowing part of the main element is calculated using (8). The obtained values of pressure losses in the input and output sections of the main element can be used to calculate and build a pressure characteristic of the generating part of the HAS.

According to the P-model following pressure characteristics are constructed for the basic element:

1 – the limit pressure characteristic P_{Lim} . calculated by (11);

2 – characteristic of HAS input sections

rarefaction P_{Emajor}^{in} (rarefaction zone). The discharge value of this characteristic corresponds to the readings of the vacuum gauge installed in a given section of the generating part of the HAS;

3 – characteristic of the outlet section after the blower P_{Emajor}^{out} (pressure zone). The pressure value of this characteristic corresponds to the readings of the pressure gauge (or gauges) installed in a given section of the generating section of the HAS;

4 – generalized pressure characteristic of the generating part of the designed HAS.

Constructed according to the following expression:

$$P_{Emajor} = P_{Lim} - \left(P_{Emajor}^{in} + P_{Emajor}^{out}\right), \qquad (12)$$

where $\left(P_{Emajor}^{in} + P_{Emajor}^{out}\right)$ is pressure losses in the main element.

As the operating point PT. according to the P-model. Is selected the point defined by the cross-section of the pressure characteristic P_{Emajor} and pressure losses $\left(P_{Emajor}^{in} + P_{Emajor}^{out}\right)$.

To summarize the aforesaid to develop technical proposals for the choice placement and integration with the network of the main energy active element $Emajor$ based on the analysis of its experimental reference pressure characteristics $P_{Emajor}\left(Q_{Emajor} \cdot n_{Rotor}\right)$, energy consumption $N_{Emajor}\left(Q_{Emajor} \cdot n_{Rotor}\right)$, efficiency (KPI) $\eta_{Emajor}\left(P_{Emajor} \cdot Q_{Emajor} \cdot n_{Rotor} \cdot N_{Emajor}\right)$ and depending on the working fluid consumption Q_{Emajor} and the number of motor revolutions n_{Rotor} a structural-parametric model of the generating part of HAS is developed:

$$Generation = \left\langle \begin{array}{c} [Rul_{Emajor}] \bigcup (Econtrol.Emajor). \\ P_{Emajor}\left(Q_{Emajor} \cdot n_{Rotor}\right). N_{Emajor}\left(Q_{Emajor} \cdot n_{Rotor}\right). \\ \eta_{Emajor}\left(P_{Emajor} \cdot Q_{Emajor} \cdot n_{Rotor} \cdot N_{Emajor}\right) \end{array} \right\rangle \qquad (13)$$

where Rul_{Emajor} – rule of arrangement of the main generating element $Emajor$ and the element $Econtrol$ regulating the flow of the working fluid by the position of the guide vanes. Efficiency of the main element is determined at a given number of rotations of the electric motor n_{Rotor} as $\eta_{Emajor} = P_{Emajor} Q_{Emajor} / N_{Emajor}$.

Taking into account the structural-parametric models of the network part (9) and the generating part (13) of HAS. It is proposed to calculate the energy intensity indicator of the hydro-aerodynamic process as a characteristic of energy intensity in the designed system for the given working fluid consumption $Q_{Emajor} = Q_{Net} = Q_{Sys_{H-A}}^{*}$ and pressure$P_{Net} = P_{major}$:

$$K_{Sys_{H-A}} = \frac{N_{Emajor}}{Q_{Sys_{H-A}}}. \qquad (14)$$

Taking into account (6) and (14) the structural-parametric HAS model looks like:

$$Sys_{H-A} = \left\langle Generation. Network. K_{Sys_{H-A}} \right\rangle. \qquad (15)$$

Thus structural-parametric models of the generating and network parts of the HAS with simultaneous consideration of the layout rules and parameters of energy active and energy passive elements of the system were developed. Which allowed to formalize the development of technical proposals when creating information technology integrated in CAD.

Development of a logical and numerical model for the generation of technical proposals

In the structural-parametric synthesis of energy-saving HAS there is a problem of enumerating possible structural solutions based on the choice and calculation of parameters for each structural solution. Besides this problem is weakly formalized when solving it even with the use of computational capabilities of modern computers it is possible to check a small number of solutions. Therefore when creating information technology integrated in CAD it is relevant to support automatic generation of technical proposals. Regarding structures and parameters of HAS to compare these proposals taking into account the proposed energy intensity indicator of HAS $K_{Sys_{H-A}}$ [18, 19], [20].

In order to analyze the state of HAP when designing energy-saving HAS on the basis of the developed SPM of the network and generating parts to solve the problem of automated generation of technical proposals. Models of representation of HAS parameters in the form of graphs are used.

When developing the oriented graph. we took into account that the values of weight coefficients set the degree of mutual influence of the parameters linked by the arc and their signs and the direction of the arc model the cause-effect relationship of the two types: “if $P \uparrow +0.5$ and $Q \uparrow +0.25$ then $P \xrightarrow{+0.2} Q$" and “if $Q \uparrow +0.8$ and $K \downarrow -0.4$ then $K \xrightarrow{-0.5} Q$".

In addition, the orgraph contains amplifying “+” and stabilizing “-“feedback loops (closed paths).

The sign of the cycle is determined by multiplication of the signs of the arc weight coefficients included in it.

Let us define a signed weighted oriented graph G or orgraph as $G =< X . U >$,
where X – set of vertices of an orgraph G, which correspond to the parameters of SPM of network (9) and generating (13) parts $\{K_{SysH-A}. N_{Emajor}. Q_{SysH-A}. P_{SysH-A}. \eta_{Emajor}. R_{Net}. n_{rotor}\}$, taking into account the following conditions:

$Q_{SysH-A} = Q_{Emajor} = Q_{Net}$ – flow rate of the working fluid in the system which is a common parameter in the network and generating parts;

$P_{SysH-A} = P_{Emajor} = P_{Net}$ – pressure in the system which is a common parameter in the network and generating parts;

U – a set of values of weighting coefficients of orgraph arcs G arc is formed by ordered pairs of a set X.

Let us represent the set of vertices of graph X in the form of a vector: $X = \{x_i\}. i = \overline{1.7}$.

In this case the elements of the vector have the following values: $x_1 = K_{SysH-A}$ indicator of energy intensity of the hydro-aerodynamic process;
$x_2 = N_{Emajor}$ – energy intensity of the main element $Emajor$;
$x_3 = Q_{SysH-A}$ – flow rate of the working fluid in the system;
$x_4 = P_{SysH-A}$ – pressure in the system which is a common parameter in the network and generating parts;
$x_5 = \eta_{Emajor}$ – efficiency of the main element $Emajor$;
$x_6 = R_{Net}$ – total hydro-aerodynamic resistance of the network part;
$x_7 = n_{rotor}$ – number of electric motor rotations.

The set U of values of weight coefficients of graph arcs G is represented as a square matrix:

$$U = \{(x_i^* - y_{ji})/x_i^*\}. i = \overline{1.7}. j = \overline{1.7}, \qquad (16)$$

where $X^* = \{x_i^*\}$ – a vector of parameters values of the initial technical proposal for the synthesis of HAS formed as shown earlier; $Y = \{y_{ji}\}$ – matrix of parameters values of technical proposals (Fig. 3) automatically generated considering the fixed values of the vector parameters $X^{**} = \{x_i^{**t}\}$, which is also a generated technical proposal. The values of the vector X^{**} parameters are placed on the main diagonal of the matrix Y.

Fig. 3 shows examples of vectors X^* and X^{**} as well as matrix Y for constructing the orgraph G to evaluate the state of the HAP in the structural-parametric synthesis of technical proposals for the design of the aerodynamic system based on the main element VDN-25.

Fig. 4a shows the values of weight coefficients of orgraph arcs G which are calculated in accordance with (16) considering the values of vectors X^* and X^{**} and matrix Y (Fig. 3). The matrix of weight coefficients U is the adjacency matrix of the orgraph G the general view of which is shown in Fig. 4b.

On the basis of the developed adjacency matrix U (Fig. 4a) of the orgraph (Fig. 4b) an iterative modeling of two technical proposals *to increase the HAS performance* by 44% was performed.

According to the first technical proposal the HAS performance is increased by the pressure increase in the main element P_{Emajor} via increasing the number of rotations of the electric motor n_{Rotor} by 51%. Fig. 5a shows graphs of relative changes of SPM weight coefficients of the parameters of network (9) and generating (13) parts of HAS and in Fig. 5b – absolute values of SPM parameters at each iteration in relation to the modeling of the *first technical proposal*.

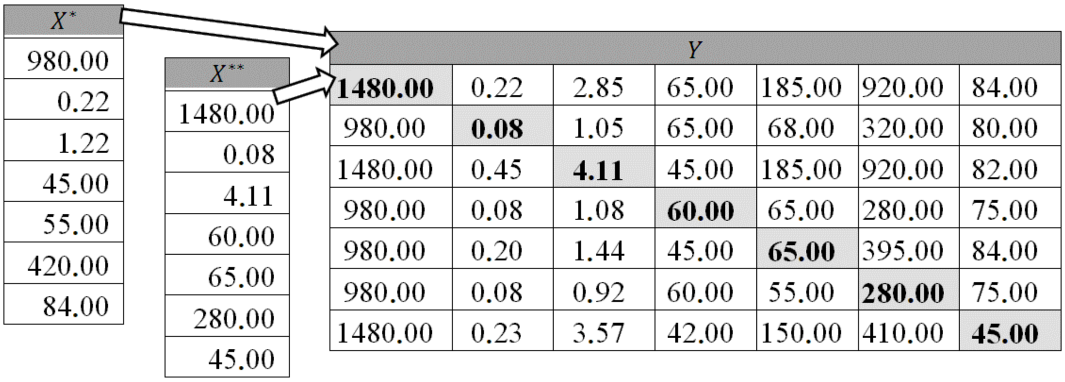
Analysis of the modeling results shows that the choice of the first proposal as a design solution leads to an increase in pressure P_{Emajor} and energy consumption N_{Emajor} by 2.2 and 3.4 times respectively. At the same time the efficiency of the basic element η_{Emajor} remains unchanged but the energy intensity of the hydro-aerodynamic process $K_{Sys_{H-A}}$ increases significantly (by 2.3 times).

Thus the above modeling results regarding the first proposal indicate that such an increase in HAS performance is not energy-saving because it is performed at the expense of a significant increase in energy intensity.

According to the second technical proposal the increase in HAS performance is performed by reducing the pressure loss P_{Net} in the network part by reducing the resistance R by 65.5%.

Fig. 6a shows graphs of relative changes in the weight coefficients of SPM parameters of the network (9) and generating (13) parts of the HAS.

Fig. 6b shows absolute values of SPM parameters at each iteration relative to the modeling of the *second technical proposal.*



X^*
980.00
0.22
1.22
45.00
55.00
420.00
84.00

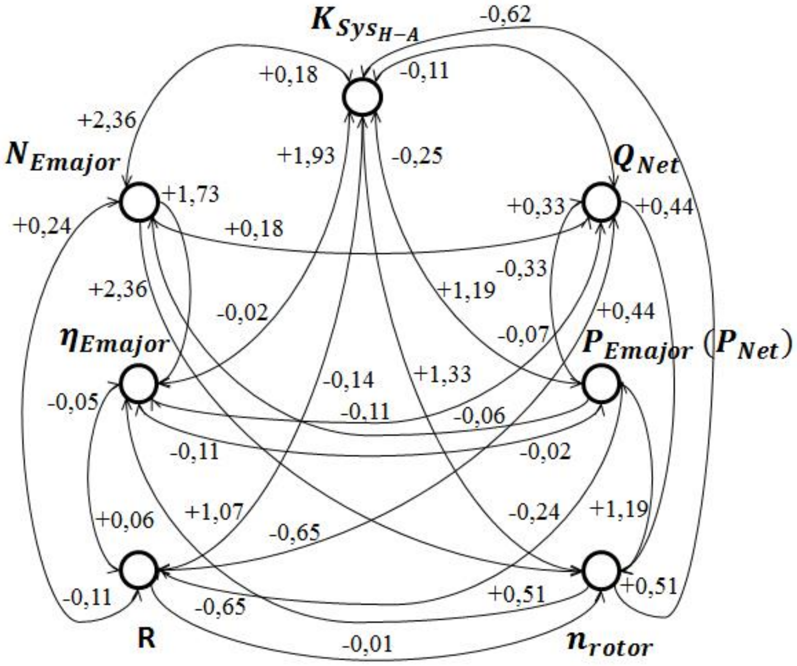
X^{**}
1480.00
0.08
4.11
60.00
65.00
280.00
45.00

Y						
1480.00	0.22	2.85	65.00	185.00	920.00	84.00
980.00	**0.08**	1.05	65.00	68.00	320.00	80.00
1480.00	0.45	**4.11**	45.00	185.00	920.00	82.00
980.00	0.08	1.08	**60.00**	65.00	280.00	75.00
980.00	0.20	1.44	45.00	**65.00**	395.00	84.00
980.00	0.08	0.92	60.00	55.00	**280.00**	75.00
1480.00	0.23	3.57	42.00	150.00	410.00	**45.00**

Fig. 3. **Example of input data for calculating the weighting matrix of the graph G**
Source: **compiled by the authors**

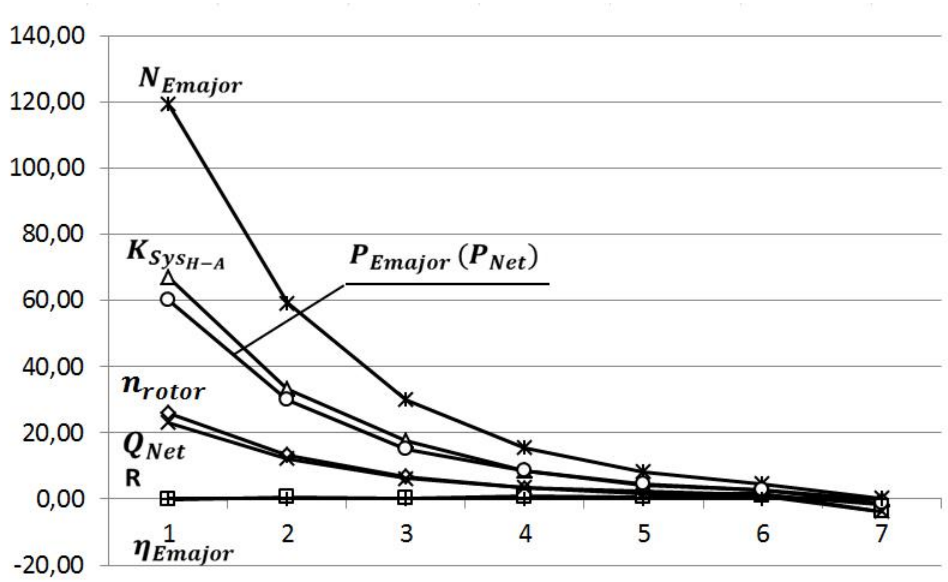
	$K_{Sys_{H-A}}$	N_{Emajor}	Q_{Net}	P_{Emajor} (P_{Net})	η_{Emajor}	R	n_{rotor}
$K_{Sys_{H-A}}$	0.51	-0.01	1.33	0.44	2.36	1.19	0.00
N_{Emajor}	0.00	-0.66	-0.14	0.44	0.24	-0.24	-0.05
Q_{Net}	0.51	1.07	2.37	0.00	2.36	1.19	-0.02
P_{Emajor} (P_{Net})	0.00	-0.65	-0.11	0.33	0.18	-0.33	-0.11
η_{Emajor}	0.00	-0.11	0.18	0.00	0.18	-0.06	0.00
R	0.00	-0.65	-0.25	0.33	0.00	-0.33	-0.11
n_{rotor}	0.51	0.06	1.93	-0.07	1.73	-0.02	-0.46

a



b

Fig. 4. **General view of the:**
a – weighting matrix; b – corresponding sign weighted graph G
Source: **compiled by the authors**



a

	Input data		Modeling by iterations					
			1	2	3	4	5	6
$K_{Sys_{H-A}}$	**1.22**	**0**	2.04	2.44	2.66	2.76	2.81	2.85
N_{Emajor}	**55**	**0**	120.54	153.06	169.46	177.91	182.33	184.89
Q_{Net}	**45**	**0**	55.43	60.86	63.65	65.26	66.03	66.77
$P_{Emajor}(P_{Net}$	**420**	**0**	672.08	797.60	860.73	896.14	914.87	925.82
η_{Emajor}	**84**	**0**	84	84	84	84	84	84
R	**0.22**	**0**	0.22	0.22	0.22	0.22	0.22	0.23
n_{rotor}	**980**	**51**	1234.3	1363.9	1430.5	1462.2	1486.6	1498.1

b

Fig. 5. **Results of modeling of the first technical proposal for iterations 1-7:**
a – relative values of changes in the model weighting coefficients;
b – absolute values of model weighting coefficients
Source: **compiled by the authors**

Analysis of the modeling results shows that the adoption of the second technical proposal as a design solution leads to an insignificant increase in energy consumption N_{Emajor} by 23.6% but provides a reduction of pressure P_{Emajor} and energy intensity of the hydro-aerodynamic process $K_{Sys_{H-A}}$ by 23.8% and 14% respectively. At the same time the efficiency of the main element η_{Emajor} also decreases insignificantly (4.8%).

Thus the choice of the second technical proposal as a design solution will provide energy savings in the designed HAS in accordance with the proposed indicator of energy intensity of the hydro-aerodynamic process.

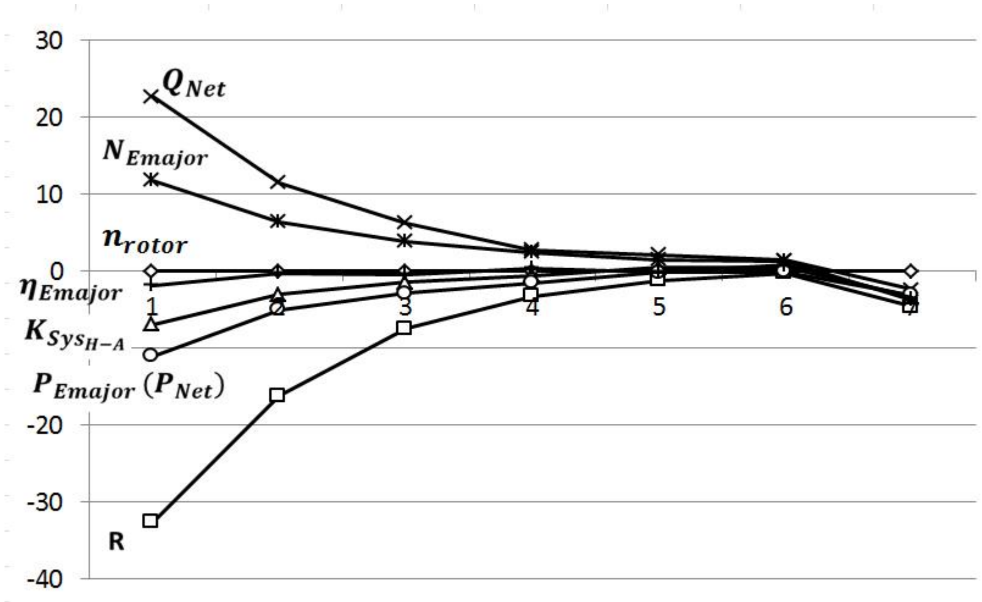
It is seen that the developed logical and numerical model of generation of technical proposals in the form of sign weighted orgraph allows taking into account the mutual influence of SPM parameters of the generating and network parts of HAS and substantiate the feasibility of using the proposed indicator of energy intensity of hydro-aerodynamic process as indicators of energy saving.

Determination of SPM target parameters of energy-efficient HAS

Taking into account the developed SPM of the network $Network$ (1) and generating $Generation$ (3) parts of the HAS as well as the logical and numerical model of their parameters to select an energy-saving technical solution.

It is proposed to estimate the energy intensity of the hydro-aerodynamic process in the following way:

$$K_{Sys_{H-A}} = \frac{N_{Emajor}(Q_{Emajor} \cdot n_{Rotor})}{Q_{Sys_{H-A}}} \xrightarrow[R]{} min, \qquad (17)$$



a

	Input data		Modeling by iterations					
			1	2	3	4	5	6
$K_{Sys_{H-A}}$	**1.22**	**0**	1.14	1.10	1.08	1.08	1.08	1.09
N_{Emajor}	**55**	**0**	61.52	65.06	67.18	68.54	69.35	70.08
Q_{Net}	**45**	**0**	55.21	60.38	63.22	64.48	65.44	66.07
$P_{Emajor}(P_{Net})$	**420**	**0**	373.56	352.49	340.40	334.16	333.45	333.19
η_{Emajor}	**84**	**0**	82.50	82.28	81.96	82.33	82.29	82.94
R	**0.22**	**0**	0.15	0.11	0.10	0.09	0.09	0.09
n_{rotor}	**980**	**51**	980	980	980	980	980	980

b

Fig. 6. **Results of modeling of the second technical proposal for iterations 1-7**
a – relative values of changes in the model weighting coefficients;
b – absolute values of model weighting coefficients
***Source:* compiled by the authors**

under these conditions:

$$\begin{cases} P_{Emajor}\left(Q_{Emajor}.n_{Rotor}\right) = \\ = P_{Net}\left(\sum_{i}^{n}\left(R_{Eminor_i} + R_{Etechnolog_i} + R_{Eminor_{i+1}}\right).Q_{Net}\right). \\ Q_{Emajor} = Q_{Net} = 1.1Q^{*}_{Sys_{H-A}}. \end{cases} \quad (18)$$

Method and information technology for structural-parametric synthesis of energy-saving HAS

On the basis of the SPM of HAS and its components of the network and generating parts of HAS as well as the target energy intensity indicator (17) and conditions (18) to select energy-saving technical solutions. The method of structural-parametric synthesis (MSPS) of technical solutions allowing to formalize the task of automated energy-efficient design of HAS is proposed.

The method of structural-parametric synthesis consists of several steps (Fig.7): structural-parametric synthesis of technical proposals with the design of the network part of the HAS and the HAS in general; modeling of the HAS state in the designed HAS; evaluation of the HAS SPM in order to synthesize an energy-saving design solution.

On the basis of the proposed method the information technology integrated in the engineering CAD is developed.

The use of the developed software allows automating of the following tasks:

– structural-parametric synthesis of energy-efficient physical prototypes of HAS auxiliary elements.

Taking into account the results of modeling the state of real HAS in these prototypes to eliminate the causes of high hydraulic resistance;

– creating design solutions (templates) for energy-efficient auxiliary elements based on the synthesized prototypes;

– storing modified templates of auxiliary elements with reduced hydraulic resistance in the base of auxiliary elements;

– using modified templates of auxiliary elements for structural-parametric synthesis of the design solution of the network part of the HAS with reduced pressure losses;

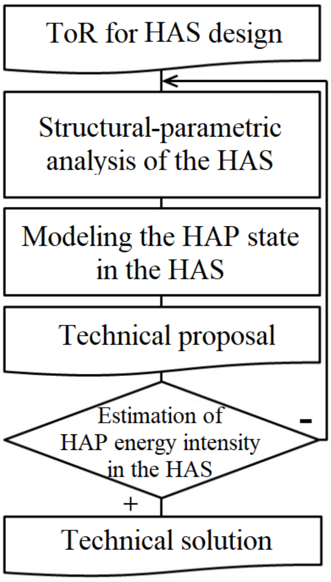


Fig. 7. **Method of structural-parametric synthesis of energy efficient hydro-aerodynamic system**
Source: **compiled by the authors**

– substantiated selection of a generating element from the basic element database taking into account the energy intensity of the HAP in the HAS for the structural-parametric synthesis of the energy-saving design solution.

The system software architecture was based on the principles of structural programming: modularity and decentralization of control [20]. According to that, separate parts of the software were allocated in the form of separate subsystems. This increases the reliability of the system in general and simplifies its further modernization.

CONCLUSION

The paper compares the possibilities of structural parametric, and structural-parametric synthesis of energy-efficient HAS using information technologies integrated in machine building and engineering CAD. The advantages of using graph models in constructing a logical-numerical model. which allows taking into account the mutual influence of SPM parameters of generating and network parts of HAS and offer the indicator of energy intensity of HAS as energy efficiency are also analyzed.

Iterative modeling of the relative changes in the parameters of the structural-parametric models of the network and generating parts of the hydro-aerodynamic system in relation to the technical proposal for increasing the productivity of the system by 44% through the reduction of hydraulic drag by 65.5% generated by the logic-numerical model showed that the value of energy intensity of hydro-aerodynamic process is reduced by 14% at the same time the value of the efficiency coefficient of the main element is also reduced by 4.8%.

On the basis of the developed SPM of energy-efficient HAS and its components as well as the indicator of energy intensity of HAS the MSPS of technical solutions which allows formalizing the tasks of automated design of energy-efficient HAS was developed. The developed models and method are the basis for the creation of information technology and allow formalizing the creation of technical proposals and the choice of energy-saving technical solutions in the design of energy-efficient HAS in engineering CAD.

Experimental studies of the developed information technology integrated in CAD showed that the reduction of hydro-aerodynamic resistances in the network part of the HAS allowed increasing the energy efficiency of the synthesized HAS by reducing the energy consumed to provide the specified working fluid consumption created by the main elements such as feed pumps blower fans and smoke exhausters by 24%, 43% and 45% respectively.

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Структурно-параметричні моделі гідро аеродинамічних систем для підвищення ефективності об'єктів енергетичної інфраструктури

Арсірій Василь Анатолійович ¹⁾
ORCID: https://orcid.org/0000-0003-3617-8487; vasily.arsiry@gmail.com. Scopus Author ID 54419479400
Арсірій Олена Олександрівна²⁾
ORCID: https://orcid.org/0000-0001-8130-9613. e.arsiriy@gmail.com Scopus Author ID 54419480900
Кравченко Олег Володимірович³⁾
ORCID: https://orcid.org/0000-0001-9765-2344; sir.Kravchenko777@gmail.com. Scopus Author ID 57204660061
Рябоконь Петр Мусійович¹⁾
ORCID: https://orcid.org/0000-0002-3006-8757; Petr070567@gmail.com
Крошка Олександр Вікторович¹⁾
ORCID: https://orcid.org/0000-0003-0975-3079; Kolvi@epg-kolvi.com
¹⁾ Одеської державної академії будівництва і архітектури, вул. Дідріхсона, 4. Одеса, 65029, Україна
²⁾ Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна
³⁾ Національний університет "Одеська морська академія", вул. Дідріхсона, 8. Одеса, 65029, Україна

АНОТАЦІЯ

Аналіз структури енергоспоживання в Україні показує. що необхідно враховувати сучасні світові тенденції щодо енергоефективності підчас післявоєнного відновлення таких основних об'єктів енергетичної інфраструктури як теплової та електричної генерації. тепло- газо- і водопостачання, вентиляції, кондиціонування, тощо. Однак аналіз існуючих інформаційних технологій автоматизованого проектування енергетичних об'єктів, основою яких є гідро аеродинамічні системи, показав, що моделі і методи структурного і параметричного синтезу складових гідро аеродинамічних систем – генеруючих енергетично активних основних елементів і мережевих енергетично пасивних допоміжних елементів не повною мірою враховують вплив стану реальних гідро аеродинамічних процесів при формуванні бази типових проектних рішень елементів. Це призводить до зниження до сорока відсотків енергоефективності спроектованих інфраструктурних об'єктів. Тому розробка структурно-параметричних моделей енергоефективних гідро аеродинамічних систем та створення на їх основі відповідної інформаційної технології інтегрованої в інженерну САПР, є особливо актуальною в період післявоєнного відновлення об'єктів енергетичної інфраструктури України. При розробці структурно-параметричних моделей енергоефективних гідро аеродинамічних систем вирішувались такі задачі: на основі порівняльного аналізу можливостей структурного, параметричного та структурно-параметричного синтезу енергоефективних гідро аеродинамічних систем. Для створення інформаційних технологій інтегрованих в машинобудівні та інженерні САПР обгрутовано обрано структурно-параметричний підхід; розроблено структурно-параметричні моделі енергоефективної гідро аеродинамічної системи та її складових – мережевої та генеруючої частин; з врахуванням переваг використання топологічних властивостей графових моделей в просторово-часової області, розроблено логіко-чисельную модель генерації технічних пропозицій щодо структурно-параметричного синтеза енергозберігаючих, гідро аеродинамічних систем; запропоновано визначення додаткових цільових параметрів структурно-параметричної моделі, гідро аеродинамічної системи. Розроблені моделі було використано при створенні інформаційної технології структурно-параметричного синтезу енергозберігаючих гідро аеродинамічних систем, яку інтегровану в САПР. Апробація запропанованої інформаційної технології показала, що зниження гідроаеродинамічних опорів у мережевій частини гідро аеродинамічних систем дозволило, підвищити енергоефективність синтезованих гідро аеродинамічних систем за рахунок зменшення потужності, яка витрачається на забезпечення заданих витрат робочого тіла, що створюються основними елементами такими як поживні насоси, вентилятори дуттьові та димососи від двадцяти п'яти до сорока п'яти відсотків.

Ключові слова: Інформаційні технології інтегровані в САПР; структурно-параметричний синтез; графові моделі; гідро-аеро-динамічні процеси; енергоефективність; енергетична інфраструктура

ABOUT THE AUTHORS

Vasyl A. Arsirii - Dr.Sci. (Eng), Professor, Professor of Department of Head Supply and Ventilation, Odessa State Academy of Civil Engineering and Architecture, 4, Didrikson Str. Odessa, 65029, Ukraine
ORCID: https://orcid.org/0000-0003-3617-8487; vasyly.arsiriy@gmail.com. Scopus Author ID: 54419479400
***Research field*:** Energy technology; energy efficiency; hydro and gas dynamics; hydraulic and aerodynamic machines; applied ecology; sustainable development

Арсірій Василь Анатолійович - доктор технічних наук, професор кафедри Теплогазопостачання і вентиляції, Одеська державна академія будівництва і архітектури, вул. Дідріхсона, 4. Одеса. 65029. Україна

Olena O. Arsirii - Dr.Sci. (Eng), Professor, Head of the Department of Information Systems, Odessa National Polytechnic University, 1, Shevchenko Ave. Odessa, 65044, Ukraine
ORCID:https://orcid.org/0000-0001-8130-9613; e.arsiriy@gmail.com
Research field: Information technology; artificial intelligence; decision support systems; machine learning; neural networks

Арсірій Олена Олександрівна - доктор технічних наук. професор. завідувач кафедри Інформаційних систем. Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна

Oleg V. Kravchenko - PhD in Engineering Sciences. Associate Professor of Department of Technology of Materials and Ship Repair, National University "Odessa Maritime Academy", 8, Didrikhson Str. Odessa, 65029, Ukraine
ORCID: http://orcid.org/0000-0001-9765-2344; sir.kravchenko777@gmail.com
***Research field*:** Energy technology; energy efficiency; hydro and gas dynamics; hydraulic and aerodynamic machines; applied ecology; sustainable development

Кравченко Олег Володимірович – доктор философії, доцент кафедри Технології матеріалів і судноремонту. Національний університет "Одеська морська академія", вул. Дідріхсона, 8. Одеса, 65029, Україна

Petro M. Ryabokon - Aspirant of Department of Head Supply and Ventilation, Odessa State Academy of Civil Engineering and Architecture, 4, Didrikson Str. Odessa, 65029, Ukraine
ORCID: https://orcid.org/0000-0002-3006-8757; Petr070567@gmail.com
***Research field*:** Energy technology; energy efficiency; hydro and gas dynamics; hydraulic and aerodynamic machines; applied ecology; sustainable development

Рябоконь Петр Мусійович – аспірант кафедри Теплогазопостачання і вентиляції Одеської державної академії будівництва і архітектури, вул. Дідріхсона, 4. Одеса, 65029, Україна

Oleksandr V. Kroshka - Aspirant of Department of Head Supply and Ventilation of Odessa State Academy of Civil Engineering and Architecture, 4, Didrikson Str. Odessa, 65029, Ukraine
ORCID: https://orcid.org/0000-0003-0975-3079; Kolvi@epg-kolvi.com
***Research field*:** Energy technology; energy efficiency; hydro and gas dynamics; hydraulic and aerodynamic machines; applied ecology; sustainable development

Крошка Олександр Вікторович - аспірант кафедри Теплогазопостачання і вентиляції Одеської державної академії будівництва і архітектури, вул. Дідріхсона, 4. Одеса, 65029, Україна