Fuzzy Situational Control of Complex Technical Systems based on Composite Hybrid Models

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Abstract

The paper considers the proposed method of fuzzy situational control for complex technical systems (CTS) based on composite hybrid models. The method consists in using a pre-designed Fuzzy Situational Control Network (FSCN) to identify current situations of the CTS, defining the target situation, setting a strategy, searching for routes to achieve the target situation, depending on the strategy and the adaptation of the FSCN to changes in the compositional hybrid model of the CTS. The method provides an increase in the efficiency of complex technical systems control, taking into account the specifics of compositional modeling and various strategies of fuzzy situational control of these systems, depending on the prevailing conditions and requirements, and also provides an organic combination of the processes of compositional modeling and fuzzy situational control. The effectiveness of the proposed method is demonstrated by the example of compressor unit control.

Keywords

Composite hybrid model, fuzzy situational network, fuzzy situational control

1. Introduction

There is a whole class of complex technical systems (CTS), characterized by: the complexity of the structure, multicomponent, a large number of quantitatively and qualitatively specified parameters, nonlinearity of interdependencies between them; incompleteness of the initial information, the complexity of experimental research, the risks of hazardous situations and the catastrophic nature of their consequences; the uniqueness of the modes and conditions of the CTS functioning; a variety of impacts of internal and external factors on the CTS; changes in the structure, parameters and modes of operation during the life cycle of the CTS; the inclusion of such CTS in larger systems. CTS with the listed properties include, for example, centrifugal compressors, pumps, turbines.

The peculiarities of such CTS determine the specifics of their analysis and modeling: the impossibility of creating and using general analytical models of CTS and the processes of their functioning; the complexity of ensuring the reliability of modeling due to the uniqueness, insufficient data on hazardous and emergency modes of CTS functioning; impossibility of modeling in certain situations due to the risks of dangerous operating modes; confidentiality and complexity of obtaining information from different developers.

The properties of the CTS of the class under consideration, the peculiarities of their modeling, make it possible to substantiate the expediency of combining various approaches and methods for constructing and composing into a single CTS model from the models of its individual components. There are various approaches to the analysis and modeling of CTS [1], [3], [5], [9], [10]. However, in these studies, as a rule, the composition of the same type of component models is carried out, methods of substantiation and hybridization of models of different types are not proposed, as well as the creation of composite hybrid CTS models as a whole, taking into account both the specifics of the development, training and interaction of different types of component models, and "transfer" of the unique

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information about dangerous and emergency situations for their adaptive structural and parametric adjustment.

The control features of such CTS are as follows: it is carried out according to parameters, as a rule, taking into account safety restrictions, without optimization of efficiency; it is assumed the development and implementation of various sequences of control decisions for the transition from the current to the target situation, depending on the selected control strategy; incompleteness and uncertainty of data on the CTS, the complexity of formalizing the criteria for the effectiveness of CTS control complicates the selection and implementation of appropriate control strategies, as well as obtaining the required control results; it is important not only to achieve the target situation, but also to ensure the requirements when passing through intermediate situations, primarily from the point of view of ensuring safety; control errors can lead to failure of the CTS, as well as to emergency (including man-made) situations and negative consequences; the need to adapt control processes to changes in the structure and parameters of the CTS, wear and tear and modernization of equipment, climate and change of seasons and other factors; the inertial nature of the CTS functioning significantly reduces the requirements for the promptness of the development and implementation of control actions in the control process; tasks and processes of modeling and control of the CTS, as a rule, are isolated from each other, and their fragmentation limits the possibilities of both modeling and control of the CTS.

The described features make it possible to substantiate the feasibility of using a fuzzy situational approach to control the CTS, which makes it possible to take into account the specifics of compositional modeling and various strategies of situational control, depending on the prevailing conditions and requirements. The theoretical foundations of situational representation and control are described in [7], [8], [11], [12]. Fuzzy situational networks, which can significantly reduce the number of controlled situations, are described in the works [2], [4], [6], [15]. At the same time, these works did not investigate the issues of fuzzy situational control of CTS based on their composite hybrid models, as well as the possibility of organically combining the processes of compositional modeling and fuzzy situational control. The article discusses the proposed method of fuzzy situational control of CTS based on composite hybrid models, which consists in using a pre-built fuzzy situational control network to identify current situations, search and select sequences of control decisions when transferring CTS to target situations, providing an increase in control efficiency depending on control strategies and constraints, as well as allowing to organically combine the processes of compositional modeling and fuzzy situational control.

2. Analysis and compositional hybrid modeling of CTS

Let us consider the stages of the proposed method of analysis and compositional hybrid modeling of CTS, focused on the features of these systems and their processes under conditions of incomplete information, different quality data on the state and functioning of CTS, which is characterized by a combination of the capabilities of analytical, neural network and fuzzy approaches to the construction of composite hybrid CTS models, which makes it possible to carry out adaptation to changes in systemic and external factors, to improve the accuracy of modeling, as well as to typify the presentation of fuzzy situational indicators for effective control of the CTS.

Stage 1. Collecting and summarizing the information about the CTS.

Stage 2. Identification of CTS components and their significant indicators.

2.1. Identification and grouping of indicators of CTS components.

2.2. Assessment of the significance of the CTS components indicators.

Stage 3. Creation of a logical model of the CTS.

3.1. Construction of the CTS parametric flow graph.

3.2. Construction of the CTS incidence matrix.

3.3. Building a matrix of link types for the CTS.

3.4. Construction of the CTS adjacency matrix.

Stage 4. Justification and selection of component models for building a composite hybrid CTS model.

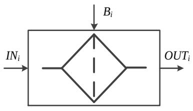
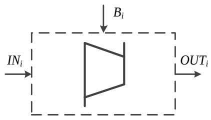
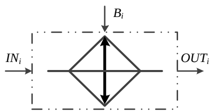
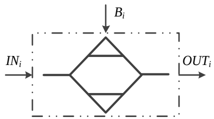
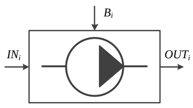
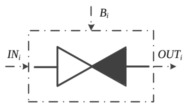
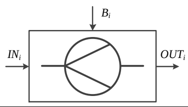
4.1. Justification of types and assessment of the component models capabilities for the analysis and modeling of CTS components.

4.2. Determination of the component models requirements for analysis and modeling of CTS components.

4.3. Selection of a set of component models (analytical models with certain and fuzzy parameters, artificial neural networks of direct propagation, fuzzy-logical models; neuro-fuzzy networks; fuzzy-neural network models) to build a compositional hybrid CTS model. Table 1 shows the component models selected to build a composite hybrid model of a turbocompressor air unit.

Table 1

Component models for building compositional hybrid model of turbocompressor air unit

CTS component	Designation	Component model type
Air blower (filter)		analytical model with crisp parameters
Compressor		artificial neural networks
Heat exchanger (cooler)		fuzzy-logical model
Water separator (air dryer)		fuzzy-logical model
Pump		analytical model with crisp parameters
Anti-surge control valve		fuzzy-logical model
Air flowmeter		analytical model with crisp parameters

Stage 5. The component models designing of various types for describing all CTS components and assessing the reliability of modeling CTS components using the constructed component models.

Stage 6. Formation of the compositional hybrid model structure based on the combination of the component models and the structural-parametric adjustment of the relationships between the component models in the compositional hybrid model of the CTS.

Figure 1 shows an example of the structure of a compositional hybrid model of a turbocompressor unit with one compressor.

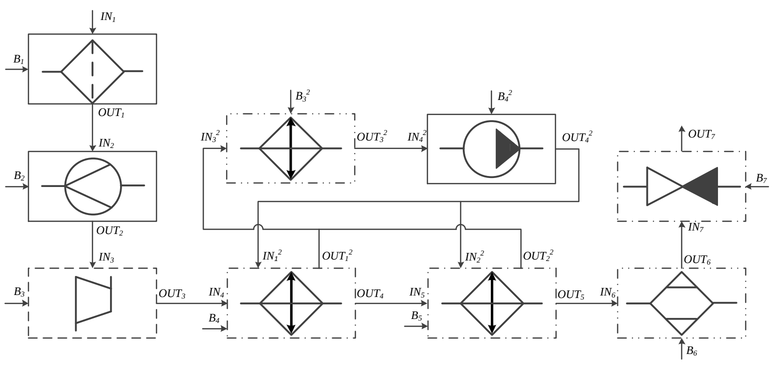


Figure 1: Structure of the compositional hybrid model for the turbocompressor unit with one compressor

Stage 7. Monitoring the state of the CTS components, structural-parametric adjustment and changing the types of component models.

3. CTS fuzzy situational control method

The proposed method of fuzzy situational control of CTS allows to take into account the compositional modeling specifics and various strategies for situational control of these systems, depending on the prevailing conditions and requirements, and also provides an organic combination of the processes of compositional modeling and fuzzy situational control. The method consists of the steps described in subsections 2.1–2.4.

3.1. The Fuzzy Situational Control Network

Let's represent the Fuzzy Situational Control Network (FSCN) for the CTS as follows:

$$FSCN = \langle P, S, R, U, D \rangle, \tag{1}$$

where $P = \{p_i \mid i = 1, ..., I\}$ – is the set of fuzzy situational indicators that describes the state of the CTS; $S = \{s_j \mid j = 1, ..., J\}$ – the set of fuzzy situations; $R = \{r_{k_i}^{(p_i)} \mid k_i = 1, ..., K_i, i = 1, ..., I\}$ – the set of fuzzy control decisions; $U = \{u_{j_k, j_l} \mid s_{j_k}, s_{j_l} \in S\}$ – the set of control transitions between fuzzy situations; $D = \{D_{s_{cur}, s_{tar}}\}$ – the set of all FSCN routes, including $D_{s_{cur}, s_{tar}} = \left\{ d_b^{(s_{cur}, s_{tar})} \mid b = 1, ..., B_{s_{cur}, s_{tar}} \right\}$, $s_{cur}, s_{tar} \in S$ subsets of routes between various current (identified) s_{cur} and target s_{tar} FSCN fuzzy situations.

The method for constructing an FSCN includes the following steps.

Step 1. Setting of fuzzy situational features $p_i, i = 1, ..., I$ (for describing of fuzzy situations), which are described by fuzzy variables $\langle p_i, T_{p_i}, X_{p_i} \rangle$, where $T_{p_i} = \left\{ T_m^{(p_i)} \mid m = 1, ..., M \right\}$ – is a term-set of a variable; X_{p_i} – the base set of the feature p_i. For the task $T_m^{(p_i)}, m = 1, ..., M$, the corresponding fuzzy sets $T_m^{(p_i)} = \left\{ \left(\mu_{T_m^{(p_i)}}(x) / x \right) \right\}, x \in X_{p_i}$ are used.

Step 2. Setting of fuzzy situations.

A fuzzy situation is represented as a level-2 fuzzy set:

$$\forall s_j \in S: \tilde{s}_j = \left\{ \left(\mu_{\tilde{s}_j}(\tilde{p}_i) / P \right) \right\}, \; p_i \in P,$$
$$\tilde{p}_i = \left\{ \left(\mu_{\tilde{p}_i}\left(T_m'^{(p_i)} \right) / T_m^{(p_i)} \right) \mid m = 1, ..., M \right\}, i \in \{1, ..., I\}. \tag{2}$$

Due to this, a limited set of fuzzy situations, presented in this way, makes it possible to describe an almost infinite number of certain states of the CTS.

Step 3. Setting the governing decisions.

Fuzzy control decisions, as a rule, are aimed at changing the values of individual fuzzy situational indicators for transferring the CTS from one fuzzy situation to another and are presented as follows:

$$r_{k_i}^{(p_i)} = \left\langle Tr^{\left(r_{k_i}^{(p_i)}\right)}, Er^{\left(r_{k_i}^{(p_i)}\right)}, Xr^{\left(r_{k_i}^{(p_i)}\right)} \right\rangle, \; r_{k_i}^{(p_i)} \in R, k_i = 1, ..., K_i, i = 1, ..., I, \tag{3}$$

where $Tr^{\left(r_{k_i}^{(p_i)}\right)}$ – is the term-set of "directions" of influence $r_{k_i}^{(p_i)}$ on the attribute p_i; $Er^{\left(r_{k_i}^{(p_i)}\right)}$ – term-set of the degree of influence $r_{k_i}^{(p_i)}$ on the attribute p_i; $Xr^{\left(r_{k_i}^{(p_i)}\right)}$ – scale of the degree of influence $r_{k_i}^{(p_i)}$, for example, [–1, 1].

The control decision $r_{k_i}^{(p_i)}$ used in the situation s_j and acting on the attribute p_i is represented by a fuzzy relation of influence $\tilde{r}_{k_i}^{(p_i)}$. The very influence of the control decision $r_{k_i}^{(p_i)}$ on a feature p_i is realized by a fuzzy *max-min*-composition between a fuzzy set $\tilde{p}_i$ and a fuzzy relation $\tilde{r}_{k_i}^{(p_i)}$. As a result of this influence, the fuzzy value of the attribute changes p_i: $\tilde{p}_i' = \tilde{p}_i \bullet \tilde{r}_{k_i}^{(p_i)}$.

If the control decision changes the values of *k* features at once, it is called *k-local*. For fuzzy situational control of the CTS of the class under consideration, it is expedient to decompose *k*-local control decisions and represent them in the form of a sequence of 1-local control decisions, ordered by the degree of impact on various fuzzy situational indicators. This allows:

- form and rank the sets of 1-local control decisions corresponding to the k-local control decision, taking into account the setting of threshold values of the influence of control decisions on dependent fuzzy situational indicators;
- to simplify the construction and use of the FSCN for the control of the CTS;
- to increase the flexibility of adaptation of the FSCN in the structural-parametric tuning of the compositional hybrid model of the CTS.

For this, it is proposed to assess the indirect impact of control decisions on the change in dependent fuzzy situational indicators in accordance with the following procedure.

Step 3.1. For each pair of features (for all pairwise combinations of the values of their term sets), a fuzzy relation of the influence Ef_{p_i,p_z} of the feature p_i on the feature p_z is built.

Step 3.2. For all constructed fuzzy relations of the influence of features on each other, a transitivity check is carried out:

$$\forall p_i, p_z \in P : Ef_{m_j,m_l}^{(p_i,p_z)} \geq \max_{m_k}\left(\min\left(Ef_{m_j,m_k}^{(p_i,p_z)}, Ef_{m_k,m_l}^{(p_i,p_z)}\right)\right), \forall m_j, m_k, m_l \in \{1,...,M\}. \quad (4)$$

Step 3.3. If for fuzzy relations of the influence of features on each other the property of transitivity is violated, then for them transitive closure is performed, for example:

$$Ef_{p_i,p_z} = Ef_{p_i,p_z} \vee Ef_{p_i,p_z}^{2} \vee ... \vee Ef_{p_i,p_z}^{I} \vee ..., \quad (5)$$

where $Ef_{p_i,p_z}^{k} = Ef_{p_i,p_z}^{k-1} \bullet Ef_{p_i,p_z}$.

If it is not possible to provide a transitive closure for any fuzzy relations, then an expert may need to clarify them.

Step 3.4. A generalized matrix of coordinated fuzzy relations of the influence of all situational indicators on each other is formed Ef.

Step 3.5. Let us assume that as a result of applying the control decision $r_{k_i}^{(p_i)}$, the value of the feature p_i represented by the fuzzy set $\tilde{p}_i = \left\{\left(\mu_{\tilde{p}_i}\left(T_m^{(p_i)}\right)/T_m^{(p_i)}\right) | \, m = 1, ..., M\right\}$, has changed as follows: $\tilde{p}_i' = \left\{\left(\mu_{\tilde{p}_i}\left(T_m'^{(p_i)}\right)/T_m^{(p_i)}\right) | \, m = 1, ..., M\right\}$.

Step 3.6. The resulting change in the attribute p_i is presented in the form of two fuzzy sets for separate accounting of positive and negative influences:

- $\delta p_i^{+} = \left\{\left(\mu_{\delta p_i^{+}}(T_m^{(p_i)})/T_m^{(p_i)}\right) | \, m = 1, ..., M\right\}, i \in \{1, ..., I\}$ – to take into account the positive changes in the values of the attribute p_i;
- $\delta p_i^{-} = \left\{\left(\mu_{\delta p_i^{-}}(T_m^{(p_i)})/T_m^{(p_i)}\right) | \, m = 1, ..., M\right\}, i \in \{1, ..., I\}$ – to take into account negative changes in the values of the attribute p_i.

Step 3.7. Fuzzy sets δp_z^{+} and δp_z^{-} are determined, specifying positive and negative changes in the attribute p_z, taking into account its interdependence with the attribute p_i:

$$\begin{aligned} \delta p_z^{+} &= \delta p_i^{+} \bullet Ef_{p_i,p_z} = \left\{\left(\mu_{\delta p_z^{+}}\left(T_m^{(p_z)}\right)/T_m^{(p_z)}\right) | \, m = 1, ..., M\right\}, i \in \{1, ..., I\}, \\ \delta p_z^{-} &= \delta p_i^{-} \bullet Ef_{p_i,p_z} = \left\{\left(\mu_{\delta p_z^{-}}\left(T_m^{(p_z)}\right)/T_m^{(p_z)}\right) | \, m = 1, ..., M\right\}, i \in \{1, ..., I\}. \end{aligned} \quad (6)$$

Step 3.8. The indirect influence on the attribute p_z of the control decision $r_{k_i}^{(p_i)}$ is determined, which directly affects the attribute $r_{k_i}^{(p_i)}$:

$$\forall p_z \in P:\ \tilde{p}'_z = \left\{ \left(\min\left(1, \max\left(0, \left(\mu_{\tilde{p}_z}\left(T_m^{(p_z)}\right) + \mu_{\delta p_z^+}\left(T_m^{(p_z)}\right) - \mu_{\delta p_z^-}\left(T_m^{(p_z)}\right)\right)\right)\right) / T_m^{(p_z)} \right) \mid m = 1,...,M \right\}. \quad (7)$$

Similarly, the indirect impact of the control decision $r_{k_i}^{(p_i)}$ on all other fuzzy situational indicators from is taken into account P.

Step 3.9. Formation and ranking of a set of 1-local control decisions corresponding to a *k*-local control decision, ordered according to the degree of their influence on dependent fuzzy situational indicators. Moreover, the number of these 1-local control decisions can be limited depending on the established threshold values of the impact of control decisions on dependent features.

The results of assessing the degree of influence of control decisions on fuzzy situational indicators are the basis for specifying control transitions in the implementation of the so-called direct approach to the construction of the FSCN for CTS control.

Step 4. Setting control transitions. The set of control transitions $U = \{u_{j_k, j_l} \mid s_{j_k}, s_{j_l} \in S\}$ characterizes the potential for a direct transition from one fuzzy situation to another under the influence of the corresponding control decisions from $R = \{r_{k_i}^{(p_i)} \mid k_i = 1,...,K_i, i = 1,...,I\}$. The control transition from a fuzzy situation s_{j_k} to a fuzzy situation s_{j_l} is represented as:

$$u_{j_k, j_l} = \left\langle s_{j_k}, s_{j_l}, w_{s_{j_k}, s_{j_l}}, r_{k_i}^{(p_i)} \right\rangle, u_{j_k, j_l} \in U, \quad (8)$$

where s_{j_k} is the initial situation of the transition; s_{j_l} – the final transition situation, into which the CTS can go when the control decision $r_{k_i}^{(p_i)} \in R$ affects the fuzzy situational indicator p_i; $w_{s_{j_k}, s_{j_l}}$ – the weight of the control transition.

So, for each fuzzy situation, a subset of situations is determined, into which the CTS can go under the influence of control decisions. As a result, the structure and the FSCN as a whole are formed.

3.2. Identification of the current fuzzy situation

The identification of the current CTS situation s_{cur} consists in:

- firstly, comparing the values of the current situation features with the values of the features of all reference fuzzy situations of the FSCN;
- secondly, defining the reference fuzzy situation of the FSCN, which is closest in a certain sense to the current situation of the CTS s_{cur} in accordance with the chosen method of comparing them;
- thirdly, identifying the current fuzzy situation with the found closest reference situation of the FSCN.

An important requirement for comparing fuzzy situations is the ability to establish the degree of their proximity (similarity). This requirement is satisfied, for example, by the index of fuzzy equality of situations for comparing level-2 fuzzy sets [6]. As other operations to compare the features of fuzzy situations, the operations of a disjunctive, disconnected sum of fuzzy sets or the operation of calculating pseudo-distances (Euclidean, Hamming, etc.) between fuzzy sets with aggregation of the results of these comparisons to compare fuzzy situations in general [14].

3.3. Determination of the target situation, setting a strategy, finding routes

Strategies for CTS situational control are formed sequences of control decisions affecting fuzzy situational indicators for the CTS transition from the current s_{cur} to the target situation s_{tar}.

As strategies of fuzzy situational control under various conditions of the CTS functioning to achieve the target situation s_{tar}, the following can be chosen, for example:

- minimization of the number of applied control solutions (control strategy "Quality");
- minimization of the cost of applied control solutions (control strategy "Economy");
- maximum reliability of the route, i.e. minimization of the risks of failure of the CTS equipment (control strategy "Security");
- maximum average weight of the route – the ratio of the sum of the weights of the control transitions of the arcs included in the route to the number of these arcs for one selected strategy (the "Balanced" control strategy);
- mixed strategies.

The restrictions imposed on the choice of the route can serve as requirements for intermediate situations on the route, namely, for the composition and values of the features of fuzzy situations.

To ensure the possibility of choosing the appropriate strategy of fuzzy situational control, it is necessary to carry out a preliminary assessment (weighing) of each control decision with respect to the criteria of the corresponding strategy of fuzzy situational control.

Figure 2 shows a fragment of the FSCN for energy efficiency control of the air intercooler of a centrifugal compressor unit.

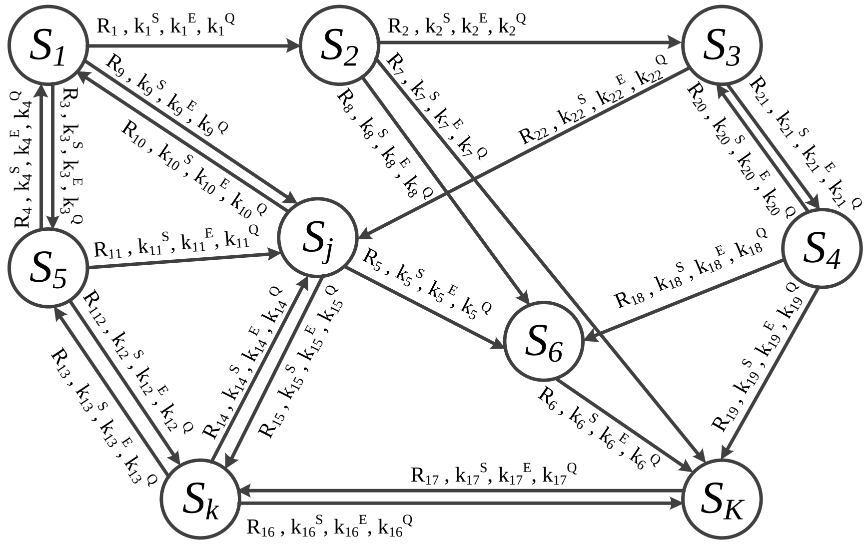


Figure 2**:** Fragment of the FSCN for fuzzy situational energy efficiency control of the intermediate air cooler of a centrifugal compressor unit

Here k_i^S are the weights of control decisions for the control strategy "Safety", k_i^E are the weights of control decisions for the control strategy "Economy", k_i^Q are the weights of control decisions for the control strategy "Quality".

To achieve the target fuzzy situation s_{tar} from the current one s_{cur}, different routes can be involved, the choice of which depends on the specified strategy of fuzzy situational control of the CTS:

$$\forall s_{cur}, s_{tar} \in S,\ s_{cur} \xrightarrow{D_{s_{cur},s_{tar}} \subset D} s_{tar} : D_{s_{cur},s_{tar}} = \left\{ d_b^{(s_{cur},s_{tar})} \mid b = 1, ..., B_{s_{cur},s_{tar}} \right\}, \quad (9)$$

where $B_{s_{cur},s_{tar}}$ is the number of possible routes between situations s_{cur} and s_{tar}.

The choice of this or that route is carried out depending on the given strategy and is implemented in the form of executing the corresponding sequence of control decisions that transfer the CTS through possible control transitions and intermediate situations. So, after identifying the current situation, the impact of a given control decision $r_{k_i}^{(p_i)} \in R$ on s_{cur} is reduced to a fuzzy composition of a fuzzy set $\tilde{s}_{cur}$ and a fuzzy relation $\tilde{r}_{k_i}^{(p_i)}$. Then the resulting fuzzy set $\tilde{s}_{mid}$ (defining some intermediate situation s_{mid}) is compared with the fuzzy set $\tilde{s}_{fin}$ (defining a fuzzy situation s_{fin}). When the specified degree of similarity is exceeded, a conclusion is made about the transition of the CTS from situation s_{cur} to situation s_{fin}:

$$\tilde{s}_{mid} = \tilde{s}_{cur} \bullet r_{k_i}^{(p_i)},\ \tilde{s}_{fin} \approx \tilde{s}_{mid}. \quad (10)$$

After that, the assignment to the indicators of the current situation of the CTS of the reference values of the indicators of the situation s_{fin} can be carried out.

Direct search and selection of routes in the FSCN, taking into account the chosen strategy, can be carried out both by an exhaustive method and based on well-known search algorithms in directed weighted graphs, for example, Ford, Moore, Bellman and Floyd.

3.4. Adaptation of the FSCN to changes in the compositional hybrid model of the CTS

Adaptation of the FSCN is necessary if there are changes in the compositional hybrid model based on the results of monitoring the state of the CTS components and the system as a whole.

The following typical cases of FSCN adaptation are possible:

Case 1. Change in the aggregate of fuzzy situational indicators. At the same time, the task of fuzzy situations, control decisions, control transitions, the structure of the FSCN, routes is carried out anew.

Case 2. Direct change in the composition of fuzzy situations. The task of additional control transitions is performed, the structure of the FSCN is supplemented, the routes are changed.

Case 3. Change in the composition of governing decisions. The task of additional control transitions is carried out, the structure of the FSCN is supplemented, the routes are changed.

4. Evaluation of the effectiveness of fuzzy situational control of the compressor unit

The efficiency of using the proposed method of fuzzy situational control of centrifugal compressors was assessed using the ECC-55 experimental stand (experimental centrifugal compressor, electric drive power 55 kW) with replaceable flow parts (RFP), which made it possible to conduct experiments with various designs of centrifugal compressor stages with the possibility of prompt replacement of trained component models of various designs of replaceable flow paths during monitoring of their condition [13].

As indicators for fuzzy situational control, the following are highlighted: p_1 – pressure of compressed gas after the compressor; p_2 – is the temperature of the compressed gas after the compressor; p_3 – compressed gas consumption; p_4-p_6 – temperature, pressure and humidity of gas after coolers and dryers before delivery to the consumer, respectively.

Table 2 shows examples of the description of fuzzy situations of the FSCN for fuzzy situational control of the compressor unit.

The following fuzzy situational control strategies were taken into account: “Safety” (S), “Quality” (Q), “Economy” (E), “Safety-Quality” (S-Q), “Safety-Economy” (S-E).

Table 3 shows the results of a comparative assessment of the effectiveness of control of a compressor unit by an operator without and with the use of the proposed method of fuzzy situational control for various strategies.

Table 2

Examples of the description of fuzzy situations FSCN for fuzzy situational control of the compressor unit

Situation	Fuzzy situational indicators					
	p_1	p_2	p_3	p_4	p_5	p_6
…	…	…	…	…	…	…
s_6	{0,8; 0,4; 0,2} below	{0,8; 0,2; 0,2} below	{0,8; 0,4; 0,2} below	{1,0; 0,4; 0,2} below	{0,2; 1,0; 0,2} norm	{0,2; 1,0; 0,2} norm
…	…	…	…	…	…	…
s_8	{0,2; 1,0; 0,2} norm	{0,2; 8,0; 0,4} norm	{0,2; 1,0; 0,2} norm	{0,4; 1,0; 0,2} norm	{0,0; 8,0; 0,2} above	{0,2; 1,0; 0,0} norm
s_9	{0,2; 0,4; 0,8} above	{0,0; 0,4; 01} above	{0,0; 0,2; 0,8} above	{0,0; 0,2; 1,0} above	{0,2; 0,4; 0,1} above	{0,2; 0,2; 0,8} norm
s_{10}	{0,2; 1,0; 0,0} norm	{0,4; 1,0; 0,2} norm	{0,2; 1,0; 0,2} norm	{0,2; 1,0; 0,2} norm	{0,2; 1,0; 0,2} norm	{0,2; 1,0; 0,2} norm
s_{11}	{0,2; 1,0; 0,2} norm	{0,0; 1,0; 0,2} norm	{0,2; 1,0; 0,4} norm	{0,8; 0,4; 0,2} below	{0,4; 0,8; 0,2} norm	{0,2; 1,0; 0,4} norm
…	…	…	…	…	….	…

Table 3

Comparative evaluation of the efficiency of control of the compressor unit

Performance indicators	Expert	Fuzzy situational control strategies				
		S	E	Q	S-Q	S-E
Head coefficient	0.46	0.47	0.49	0.51	0.49	0.45
efficiency	0.75	0.74	0.76	0.78	0.76	0.77

The results of a comparative assessment of the effectiveness of control of a compressor unit by an operator without and using the proposed method of fuzzy situational control for various strategies allow us to draw the following conclusions:

- the greatest increase in efficiency when using the proposed method of fuzzy situational control is ensured if the strategy of minimizing the number of applied control decisions is implemented (the "Quality" control strategy);
- also the use of the proposed method of fuzzy situational control makes it possible to increase the efficiency of the compressor plant control: while implementing the strategy of minimizing the cost of the applied control solutions (the "Economy" control strategy); and also for a mixed strategy of maximizing the reliability of the route and minimizing the number of applied control solutions (mixed control strategy "Safety-Quality").

5. Conclusion

A method of fuzzy situational control of CTS based on composite hybrid models is proposed, which includes: firstly, the construction of an FSCN; secondly, identification of the current fuzzy situation of the CTS; third, defining the target situation, setting a strategy, searching for routes to achieve the target situation, depending on the given strategy; fourth, the adaptation of the FSCN to changes in the compositional hybrid model of the CTS.

The proposed method provides an increase in the efficiency of CTS control, taking into account the specifics of compositional modeling and various strategies of fuzzy situational control of these systems, depending on the prevailing conditions and requirements, and also provides an organic combination of the processes of compositional modeling and fuzzy situational control.

The effectiveness of the proposed method is demonstrated by the example of compressor unit control.

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