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DIAGNOSTICS MODELS IN EXPERT SYSTEMS OF MEASURING THE STATUS CONDITION OF THE AICRAFT POWER PLANTS

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In the given paper there are considered some types of diagnostics systems: mathematical, stochastic and logical, which could be used in developing expert systems for evaluating the aircraft power plants' technical state as demonstrated by the engines TB-3-117 и PS-90A

Key words: *air gas-turbine engine, technical maintenance, control of parameters, automated diagnostics system, expert system, decision-making system, diagnostics matrix*

1. Introduction

The specific features of modern air gas-turbine engines (GTE) are the complexity of their construction, wide application of automated electric systems, of developed mechanization and of sophisticated laws of control for achieving the required characteristics. Also these modern engines are expected to demonstrate high results in resource, reliability, flights safety and economic efficiency at minimum maintenance expense and labour consumption.

In the process of its exploitation, an engine may appear in one of the multitude of its technical states but the only acceptable state in which it should stay during the flight is that of a good working order. Failures of the aviation technical means depend on many reasons, which cannot be interpreted as major or minor ones in advance. It makes us to treat failures and the time of their occurrence as random factors and values, which depending on the case, may be different and we cannot know this difference beforehand. The process of failures' development, occurrences of defects and faults present some random function and the character of the failure manifestation may be continuous, sudden, and the most dangerous case is when continuous manifestation immediately changes into sudden. The nature of the failures' occurrence is complicated enough because, as a rule, it is the result of coincidence of several unfavourable factors – overloads, deviation from the programmed modes of performance, outside conditions and the like, all of which are characterized by different casual relationships of different degree and nature resulting in sudden overloads, which greatly exceed the programmed values [1]. Such character of the failures' manifestation complicates their forecasting.

High sophistication of the aviation technical means suggested a great variety of the methods of controlling and diagnosing GTE, both instrumental and mathematical methods included.

For measuring the engine technical status condition, there are also used automated onboard and ground systems of controlling and diagnosing the engine parameters. Diagnosing by the thermo-gas-dynamic parameters (temperature, air consumption, pressure, etc.) is one of the most widely used and efficient methods of measuring the engine status condition since the relationship of the measured thermo-gas-dynamic parameters with the engine modules' characteristics is determined and can be described in terms of either physical or statistical models of different sophistication level. In the systems of automated diagnosing GTE [2] there are traditionally applied the algorithms of mathematical models' identification for detecting faults in the get flowing part of the engine and the algorithms of trend-analysis for defining the tendencies of the measured parameters time changes. Identification of a mathematical model is determining the discrepancy between the parameters' measured and programmed values. Application of the trend-analysis procedure to the parameters deviation from the programmed ones allows determining the regularities of their change with the account of random measurement errors.

In modern practice of analyzing and processing information, the majority of diagnosis tasks is sorted out by a human operator, who takes decision about the status condition of the aircraft system and its system management in the course of exploitation judging by the results of comparing the received measurements based on either flight or ground data with the set values of the controlled parameters change. All this requires from the specialist deep knowledge of the engine and its control systems. Actually, the experience of a highly qualified specialist allows to take the decision about the engine status condition. Knowledge of highly qualified specialists, experts in their sphere, may be set in the expert systems (ES). But we cannot solve the task diagnostics completely using only the experts' knowledge of ES.

One of the promising trends of the GTE effective control and diagnostics is application of complex intellectual computer technologies, namely, the systems based on different knowledge of hybrid ES [3]. Hybrid ES present different types of knowledge, such as conceptual, expert and fact-graphic, and the corresponding methods of their processing.

The main task in developing hybrid systems is to find the best combination of different forms and methods of knowledge processing in the process of taking decisions of the diagnostics ES, that is the actual task of the present paper is research of an optimal combination of different mechanisms for processing knowledge with the aim of increasing quality, mobility and efficiency of ES in solving the tasks of the GTE diagnostics and control under the condition of uncertainty.

Integration of the ES in the onboard system of the engine control and diagnostics and in the ground automated control systems allows efficient evaluation of the GTE status condition in the current moment and revealing the correspondence of its parameters to the tactical-technical requirements, and working out recommendations for its further exploitation if necessary.

Development of information technologies of monitoring and managing the GTE exploitation is the process suggesting some particular methodology of using the a priori and a posteriori information about the object, measuring, computing and corporate means making up the resources of the monitoring information technologies and different mathematical methods of solving the tasks of processing and analyzing the information about the engine status condition as well as of taking decisions to achieve the aims of monitoring and its exploitation management [4].

2. Requirements to the expert system of the air engine diagnostics and control

One of the promising means of providing the GTE effective control and diagnostics is application of complex intellectual computer technologies, namely, the systems based on different knowledge of hybrid ES, including such knowledge as: conceptual knowledge saved in conceptual knowledge base (CKB); experts' knowledge saved in expert knowledge base (EKB) and precedents (scenarios of behavior) saved in precedents knowledge base (PKB).

A hybrid ES should include the following functional parts:

- A database storing pattern and actual data about the process, the results of their comparison, GTE conceptual, info-logic an physical models;
- Knowledge base (KB): statistic (knowledge is stored in the form of expert knowledge (product) and formulas, facts, dependencies, tables of notions of a particular subject sphere), dynamic (knowledge is stored as combined models in the form of pattern dynamic processes with the account of partial or complete uncertainty of the diagnostics parameters);
- A mechanism (machine) of logical deduction based on algorithm of generating causal relationship events in the functional-structural model;
- An adaptation mechanism coordinating the performance of the data bases (DB and KB) in the process of logical deduction depending on the situation;
- A mechanism of explanation which is actually the interpretation of the logical deduction process;
- A planner coordinating the process of solving tasks;
- A decider which allows finding effective decisions in the direct, reverse and mixed order of tasks.

Content, forms and algorithms of presenting information in a hybrid ES may vary according to the complexity of the modeled situation, specifics and individual characteristics of the user. Fig.1 presents the structure of the ES interaction with the object of diagnostics: air engine and expert (a person making final decision).

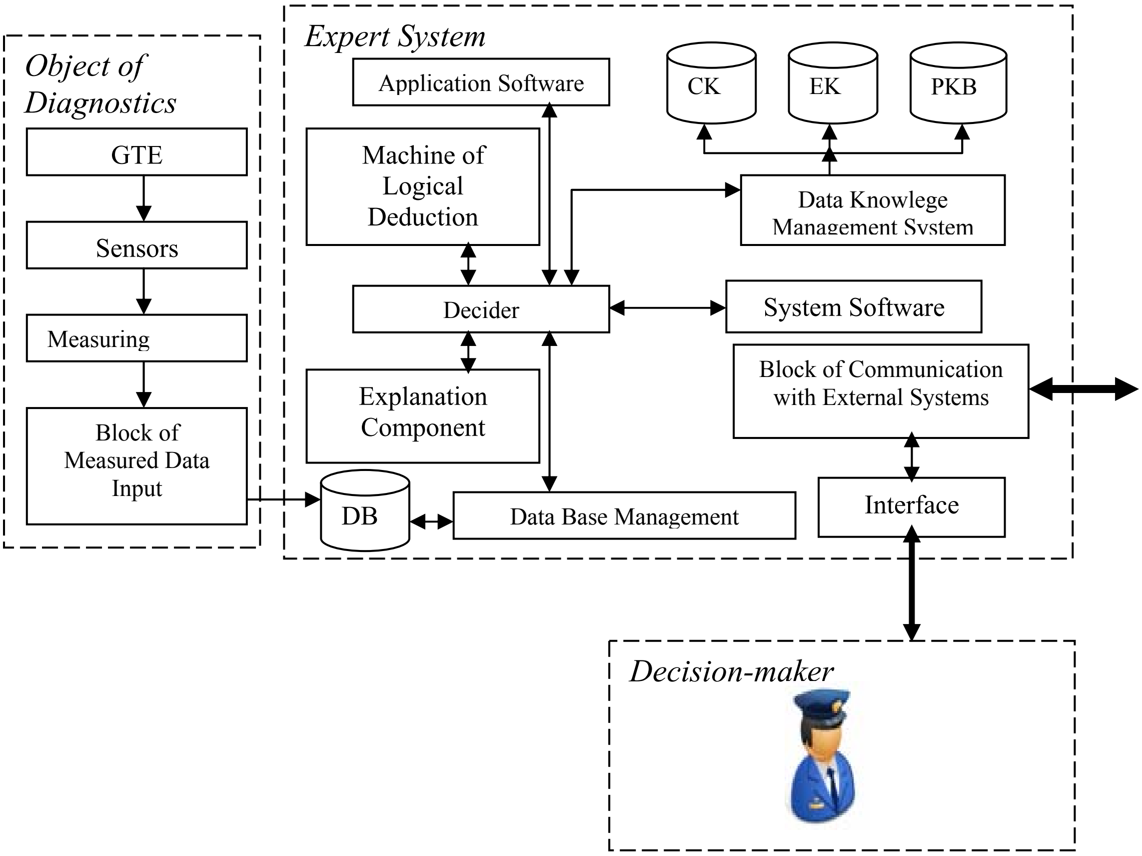

Fig.1. Structure of the expert system of monitoring the GTE status condition

A diagnostic task, in its general case, is the task of revealing the degree of correspondence of the technical object to the necessary requirements and we can differ between two main tasks: a direct diagnostic task or the task of controlling the technical condition and a reverse diagnostic task or the task of detecting the fault.

A diagnostic model is any knowledge used in the process of solving a diagnostic task and presented in a particular form. Each diagnostic model used to reveal the defect is required for:

- building the algorithms of diagnosing;
- building a pattern model of the diagnostics object.

In solving a reverse task, which is search and detection of the defect, the knowledge base should normally include three types of knowledge [3] considered above.

Knowledge of possible defects, of their causes and of their direct and indirect indicators. A separate defect is not an isolated phenomenon; therefore, in a multitude of possible defects there exist different relations which are of a casual relationship and time character.

Knowledge of the structural organization of the diagnostics object. This is knowledge of the functional processes occurring in the object of diagnostics. Functional processes describe the dynamics between the elements of the diagnostics object.

Knowledge of the possible diagnostics experiments. A diagnostic experiment is the process of evaluating the diagnostic indicators (DI*)* under the preset conditions with the aim of localizing defects. The main ways of measuring DI: measurement, control, replacement of the suspected elements in the diagnostics object for the a priori reliable ones, check of the suspected elements on the a priori reliable object, monitoring the object of diagnostics reaction in exerting a managing impact, etc.

Unfortunately, it is actually impossible to formalize all the three types of knowledge in one diagnostic model, that’s why we use some particular models. These are models in which the volume of one of the types of diagnostic knowledge is incomplete. Thus, in ES, there are used some particular models to present all the three types of knowledge.

3. Diagnostic models in an expert system

Let us consider some particular diagnostic models, which are used in ES. If there are given the identifiers of possible defects, there is admitted the existence of the method of measuring the DI vector and there are specified the required a priori probabilities, then for searching we can use the Bayes’ scheme according to which the decision about the current single defect is taken on the biggest value of the a posterior probability.

The Bayes’ formula for a set of attributes looks as follows [4]:

$$P(D_i / K^*) = \frac{P(D_i)P(K^* / D_i)}{P(K^*)}, \tag{1}$$

where *P(Di / K*)* – the probability of diagnosis D_i after the results of examination by the set of attributes *K* have become learnt; $P(D_i)$ – a preliminary probability of diagnosis *Di* (by the prior statistics). Formula (1) refers any of the n possible conditions (diagnoses) of the system.

To determine the probability of diagnoses by the Bayes’ method, it is necessary to build a diagnostic matrix (see table 1, which is formed on the basis of the prior statistics. This table contains the probabilities of the attributes’ grades under different diagnoses.

Table 1. Diagnostic matrix by Bayes’ method

D_i	Attribute k_j									$P(D_i)$
	k_1			K_2				K_3		
	$P(k_{11}/D_i)$	$P(k_{11}/D_i)$	$P(k_{21}/D_i)$	$P(k_{21}/D_i)$	$P(k_{22}/D_i)$	$P(k_{23}/D_i)$	$P(k_{24}/D_i)$	$P(k_{31}/D_i)$	$P(k_{32}/D_i)$	
D_1	0.8	0.2	0	0.1	0.1	0.6	0.2	0.2	0.8	0.3
D_2	0.1	0.7	0.2	0	0	0.3	0.7	0.1	0.9	0.1
...	...	...	...	...	...	...		...	...	...

The diagnostic matrix (DM) includes the diagnoses’ a priori probabilities. The process of learning by Bayes’ method is the DM formation. It is important to envisage the possibility of précising the table in the process of diagnosing. For this, the computer memory should store not only the values $P\,(k_{js} / D_i)$ but the following values as well:

- N – total number of objects used for building the DM;
- N_i — number of objects with diagnosis D_i;
- N_{ij} – number of objects with diagnosis D_i examined by attribute k_j.

When a new object with diagnosis D_μ, enters we perform correction of the previous diagnoses’ a priori probabilities like follows:

$$P(D_i) = \begin{cases} \dfrac{N_i}{N+1} = P(D_i)\dfrac{N}{N+1}, i = 1, 2 \dots n, \quad i \neq \mu \\ \dfrac{N_\mu + 1}{N+1} = P(D_\mu)\dfrac{N}{N+1} + \dfrac{1}{N+1}, \ i = \mu \end{cases}$$

Further corrections are made for the attributes’ probabilities. Let a new object with diagnosis D_μ reveal the *r* grade of attribute k_j. Then for further diagnostics, we admit new values of the probability of intervals for attribute k_j under diagnosis D_μ:

$$P(k_{js} / D_\mu) = \begin{cases} P(k_{js} / D_\mu)\dfrac{N_{\mu j}}{N_{\mu j} + 1}, s \neq r \\ \\ P(k_{jr} / D_\mu)\dfrac{N_{\mu j}}{N_{\mu j}} + \dfrac{1}{N_{\mu j} + 1}, s = r \end{cases}$$

Conditional probabilities of attributes under other diagnoses do not need correction.

Another scheme of the defects’ search and localization uses diagnostic methods. DM are built on the basis of the engine mathematical model, which is received by the method of small deviations [5]. The paper [5] shows the possibility of diagnosing the TB7-117C engine free turbine by the thermo-gas-dynamic parameters with the help of diagnostic matrixes. A diagnostic model includes the list of possible defects and the decision on defect presence is made by comparing the pattern vector of diagnostic parameters (engine in good order) with the current vector of the engine diagnostic parameters.

These models describe the first and the third type’s knowledge suggesting that the second type knowledge is known. The main efforts in developing these models are connected with solving the tasks of the role of the diagnostic parameters’ vector elements. The vector must be such that it could provide the level of the defects’ differentiating. This causes the necessity of examining the engine performance peculiarities in good and faulty orders.

To analyse and determine the engine status condition, there are built **logical models** of diagnosing the air engine built on the principle — “combination of elementary failures”→ “change of the system condition characteristic value” and “elementary failure”→ “change of values of the system condition characteristics’ set”.

Let us take as an object diagnosing the air engine PS-90A. For the characteristics of its condition, it would be reasonable to choose the following diagnostic attributes: z_1 is efficiency (E) of the ventilator; z_2 — efficiency of the low pressure compressor; z_3 — efficiency of the low pressure turbine; z_4 — efficiency of the high pressure turbine; z_5 — efficiency of the low pressure turbine; z_6 — efficiency of burning; z_7 — area of the first contour nose device; z_8 — area of the second contour nose device; z_9 — area of the jet nose; z_{10} — loss factor of full pressure; z_{11} — air collection; z_{12} — factor of providing full pressure in the combustion chamber; z_{13} — degree of the compressor compression; z_{14} — capacity of the high pressure turbine; z_{15} — temperature of the high pressure turbine; z_{16} — temperature of the low pressure turbine; z_{17} — capacity of the low pressure turbine; z_{18} — working pressure; z_{19} — thrust; z_{20} — factor of the jet nose losses; z_{21} — factor of the burning completeness.

Experience shows that the most frequent failures which occur in the engine PS-90A are the following: obstructions *(X_1);* change of geometric characteristics *(X_2),* change of the surface condition (X_3); chop offs (X_4); tear offs (X_5); burn down (X_6); destructions (X_7); soiling (X_8); change of the surface roughness *(X_9);* damages *(X_{10});* change of the letting in section area *(X_{11});* extra coking *(X_{12}).*

The subsystems of the air engine PS-90A as of the diagnostics object are the following places of failures occurrence (breaks, faults): The ventilator blades (c_1); blades’ profile of the ventilator working wheel (c_2); blades’ profile of the ventilator guide apparatus (c_3); ventilator rotor (c_4); ventilator stator (c_5); blades profile of the low pressure compressor (c_6); blades profile of the high pressure compressor (c_7); blades of the low pressure compressor (c_8); blades of the high pressure compressor (c_9); blades profile of the high pressure turbine nose apparatus (c_{10}); working blades profile of the high pressure turbine (c_{11}); blades profile of the low pressure turbine nose apparatus (c_{12}); working blades profile of the low pressure turbine (c_{13}); working blades of the high pressure turbine (c_{14}); blades of the high pressure turbine nose apparatus (c_{15}); working blades of the low pressure turbine (c_{16}); blades of the low pressure turbine nose apparatus (c_{17}); walls of the combustion chamber (c_{18}); sprayers (fuel burners) *(c_{19});* combustion chamber (c_{20}); labyrinth condensations and communications of the cooling air collection and supply (c_{21}); jet nose (c_{22}); letting in section of the outside contour (c_{23}).

To give simplicity and objectivity to the logic models of diagnosing, we are going to introduce the following conditional designations of the air engine condition characteristics’ changes: ↓ — decrease; ↑ — increase; ↓↑ — deviation from the pattern level in this or that direction.

With the account of the fact that one and the same combination of elementary failures may result in simultaneous change of values of several diagnostic attributes of the air engine, a logic model built on “combination of elementary failures” → “change of values of the system condition characteristics”, can be presented as follows:

$X_1(c_1) \vee X_2(c_2) \vee X_2(c_3) \vee X_3(c_4) \vee X_3(c_5) \to D(z_1, \downarrow);$
$X_2(c_6) \vee X_4(c_8) \to D(z_2, \downarrow);$
$X_2(c_7) \vee X_4(c_9) \to D(z_3, \downarrow) \wedge D(z_{13}\ \downarrow\uparrow);$
$X_2(c_{10}) \vee X_2(c_{11}) \vee X_5(c_{14}) \vee X_5(c_{15}) \vee X_8(c_{19}) \to D(z_4, \downarrow) \wedge D(z_{14}, \downarrow) \wedge D(z_{15}, \uparrow);$
$X_2(c_{12}) \vee X_2(c_{13}) \vee X_5(c_{15}) \vee X_5(c_{16}) \vee X_5(c_{17}) \to D(z_5, \downarrow) \wedge D(z_{16}, \uparrow) \wedge D(z_{17}, \downarrow);$
$X_8(c_{19}) \vee X_{12}(c_{19}) \to D(z_6, \downarrow) \wedge D(z_{18}, \downarrow);$
$X_2(c_{10}) \vee X_8(c_{19}) \vee X_9(c_{20}) \vee X_{12}(c_{19}) \to D(z_7, \downarrow);$
$X_2(c_{11}) \vee X_2(c_{13}) \vee X_8(c_{19}) \vee X_9(c_{20}) \to D(z_8, \downarrow);$
$X_2(c_{13}) \vee X_5(c_{14}) \vee X_5(c_{15}) \vee X_5(c_{17}) \to D(z_8, \uparrow);$
$X_{10}(c_{22}) \to D(z_9, \downarrow) \wedge D(z_{19}, \downarrow) \wedge D(z_{20}, \downarrow\uparrow);$
$X_9(c_{23}) \vee X_{11}(c_{23}) \to D(z_{10}, \downarrow) \wedge D(z_{19}, \downarrow);$
$X_7(c_{21}) \to D(z_{11}, \uparrow) \wedge D(z_{15}, \uparrow);$
$X_6(c_{18}) \vee X_7(c_{18}) \vee X_8(c_{19}) \vee X_9(c_{20}) \vee X_{12}(c_{19}) \to D(z_{12}, \downarrow) \wedge D(z_{21}, \downarrow\uparrow).$

A logic model of diagnosing the air engine PS-90A, based on the scheme “elementary failure” → “change of values of the system condition’s set of characteristics”, looks as follows:

$X_1(c_1) \to D(z_1, \downarrow)$
$X_2(c_2) \to D(z_1, \downarrow)$
$X_2(c_{21}) \to D(z_1, \downarrow)$
$X_3(c_4) \to D(z_1, \downarrow)$
$X_3(c_5) \to D(z_1, \downarrow)$
$X_2(c_6) \to D(z_2, \downarrow)$
$X_2(c_7) \to D(z_3, \downarrow) \wedge D(z_{13}. \downarrow\uparrow);$
$X_4(c_8) \to D(z_2, \downarrow)$
$X_4(c_9) \to D(z_3, \downarrow) \wedge D(z_{13}, \downarrow\uparrow);$
$X_2(c_{10}) \to D(z_4, \downarrow) \wedge D(z_{15}, \uparrow) \wedge D(z_{14}, \downarrow) \wedge D(z_7, \downarrow\uparrow);$
$X_2(c_{11}) \to D(z_4, \downarrow) \wedge D(z_{15}, \uparrow) \wedge D(z_{14}, \downarrow) \wedge D(z_8, \downarrow);$
$X_2(c_{12}) \to D(z_5, \downarrow) \wedge D(z_{16}, \uparrow) \wedge D(z_{17}, \downarrow);$
$X_2(c_{13}) \to D(z_5, \downarrow) \wedge D(z_{16}, \uparrow) \wedge D(z_{17}, \downarrow) \wedge D(z_8, \downarrow\uparrow);$
$X_5(c_{14}) \to D(z_4, \downarrow) \wedge D(z_{15}, \uparrow) \wedge D(z_{14}, \downarrow) \wedge D(z_7, \uparrow) \wedge D(z_8, \uparrow);$
$X_5(c_{15}) \to D(z_4, \downarrow) \wedge D(z_{15}, \uparrow) \wedge D(z_{14}, \downarrow) \wedge D(z_5, \downarrow) \wedge D(z_{16}, \uparrow) \wedge D(z_{17}, \downarrow) \wedge D(z_7, \uparrow) \wedge D(z_8, \uparrow);$
$X_5(c_{17}) \to D(z_5, \downarrow) \wedge D(z_{16}, \uparrow) \wedge D(z_{17}, \downarrow) \wedge D(z_8, \uparrow);$
$X_6(c_{18}) \to D(z_{12}, \downarrow) \wedge D(z_{21}, \uparrow\downarrow);$
$X_7(c_{18}) \to D(z_{12}, \downarrow) \wedge D(z_{21}, \uparrow\downarrow);$
$X_8(c_{19}) \to D(z_4, \downarrow) \wedge D(z_{15}, \uparrow) \wedge D(z_{14}, \downarrow) \wedge D(z_6, \downarrow) \wedge D(z_{18}, \downarrow) \wedge D(z_7, \downarrow\uparrow) \wedge D(z_8, \downarrow) \wedge D(z_{12}, \downarrow) \wedge D(z_{21}, \downarrow\uparrow);$
$X_9(c_{20}) \to D(z_7, \downarrow) \wedge D(z_8, \downarrow) \wedge D(z_{12}, \downarrow) \wedge D(z_{21}, \uparrow\downarrow);$
$X_7(c_{21}) \to D(z_{11}, \uparrow) \wedge D(z_{15}, \uparrow);$
$X_{10}(c_{22}) \to D(z_9, \uparrow) \wedge D(z_{20}, \downarrow\uparrow) \wedge D(z_{19}, \downarrow);$
$X_9(c_{23}) \to D(z_{10}, \downarrow) \wedge D(z_{19}, \downarrow);$
$X_{11}(c_{23}) \to D(z_{10}, \downarrow) \wedge D(z_{19}, \downarrow);$
$X_{12}(c_{19}) \to D(z_6, \downarrow) \wedge D(z_{18}, \downarrow) \wedge D(z_7, \downarrow) \wedge D(z_{12}, \downarrow) \wedge D(z_{21}, \uparrow\downarrow);$

A logical diagnostic model reflects, by its essence, a particular diagnostic structure of the object of diagnosing but it may also include such data as: list of points of exerting work and test impacts; list of points of checking the diagnostics parameters, list of acceptable values of the diagnostics parameters; description of possibilities of the diagnostic elements' (DE) test replacements and possible manifestations of different defects of one and the same DE.

Thus, it describes sufficiently enough the knowledge of the second and third types. The logic DM participation in the diagnostic experiment is indirect: it is a means of developing an optimal algorithm for searching defects. Therefore, we should specify for it a notion of a "defect model". "Defect model" is a formalized presentation of the fact of a physical defect manifestation in the form of wrong signals' values at either entrances or exits of the logic diagnostic model DE.

4. Conclusion

The above considered diagnostics models give us three kinds of knowledge, which allow qualitative diagnosis of the air engine. The first diagnostics model (Bayes' scheme) is based the probability-statistical methods, its disadvantage is that we need quite a lot of statistical material but after that material has been accumulated, it is conductive to the correction of the other two models. The diagnostics model based on diagnostics matrixes may also in its turn bring about correction of the logical diagnostics model. Such mutual models' complementation allows full realisation of the defect search and detection and measurement of the engine technical status condition.

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