

Aircraft Gas Turbine Engines' Technical Condition Identification System

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Abstract—In this paper is shown that the probability-statistic methods application, especially at the early stage of the aviation gas turbine engine (GTE) technical condition diagnosing, when the flight information has property of the fuzzy, limitation and uncertainty is unfounded. Hence is considered the efficiency of application of new technology Soft Computing at these diagnosing stages with the using of the Fuzzy Logic and Neural Networks methods. Training with high accuracy of fuzzy multiple linear and non-linear models (fuzzy regression equations) which received on the statistical fuzzy data basis is made. Thus for GTE technical condition more adequate model making are analysed dynamics of skewness and kurtosis coefficients' changes. Researches of skewness and kurtosis coefficients values' changes show that, distributions of GTE work parameters have fuzzy character. Hence consideration of fuzzy skewness and kurtosis coefficients is expedient. Investigation of the basic characteristics changes' dynamics of GTE work parameters allows to draw conclusion on necessity of the Fuzzy Statistical Analysis at preliminary identification of the engines' technical condition. Researches of correlation coefficients values' changes shows also on their fuzzy character. Therefore for models choice the application of the Fuzzy Correlation Analysis results is offered. For checking of models adequacy is considered the Fuzzy Multiple Correlation Coefficient of Fuzzy Multiple Regression. At the information sufficiency is offered to use recurrent algorithm of aviation GTE technical condition identification (Hard Computing technology is used) on measurements of input and output parameters of the multiple linear and non-linear generalised models at presence of noise measured (the new recursive Least Squares Method (LSM)). The developed GTE condition monitoring system provides stage-by-stage estimation of engine technical conditions. As application of the given technique the estimation of the new operating aviation engine temperature condition was made.

Keywords—Gas turbine engines, neural networks, fuzzy logic, fuzzy statistics.

NOMENCLATURE

H	flight altitude	[m]
M	Mach number	-
T_H^*	atmosphere temperature	[°C]
p_H^*	atmosphere pressure	[Pa]
n_{LP}	low pressure compressor speed (RPM)	[%]
T_4^*	exhaust gas temperature	[°C]
G_T	fuel flow	[kg/h]

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p_T	fuel pressure	[kg/cm ²]
p_M	oil pressure	[kg/cm ²]
T_M	oil temperature	[°C]
V_{BS}	back support vibration	[mm/s]
V_{FS}	forward support vibration	[mm/s]
a_1, a_2, a_3, \dots	regression coefficients in initial linear multiple regression equation of GTE condition model	
a'_1, a'_2, a'_3, \dots	regression coefficients in actual linear multiple regression equation of GTE condition model	
$\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \dots$	fuzzy regression coefficients in linear multiple regression equation of GTE condition model	
\tilde{X}, \tilde{Y}	measured fuzzy input and output parameters of GTE condition model	
$r_{X,Y}$	correlation coefficients between GTE work parameters	
$\tilde{r}_{X,Y}$	fuzzy correlation coefficients between GTE work parameters	
\otimes	fuzzy multiply operation	
ini	initial	
act	actual	

I. INTRODUCTION

ONE of the important maintenance requirements of the modern aviation GTE on condition is the presence of efficient parametric technical diagnostic system. As it is known the GTE diagnostic problem of some aircraft's is mainly in the fact that onboard systems of the objective control do not register all engine work parameters. This circumstance causes additional manual registration of other parameters of GTE work. Consequently there is the necessity to create the diagnostic system providing the possibility of GTE condition monitoring and elaboration of exact recommendation on the further maintenance of GTE by registered data either on manual record and onboard recorders.

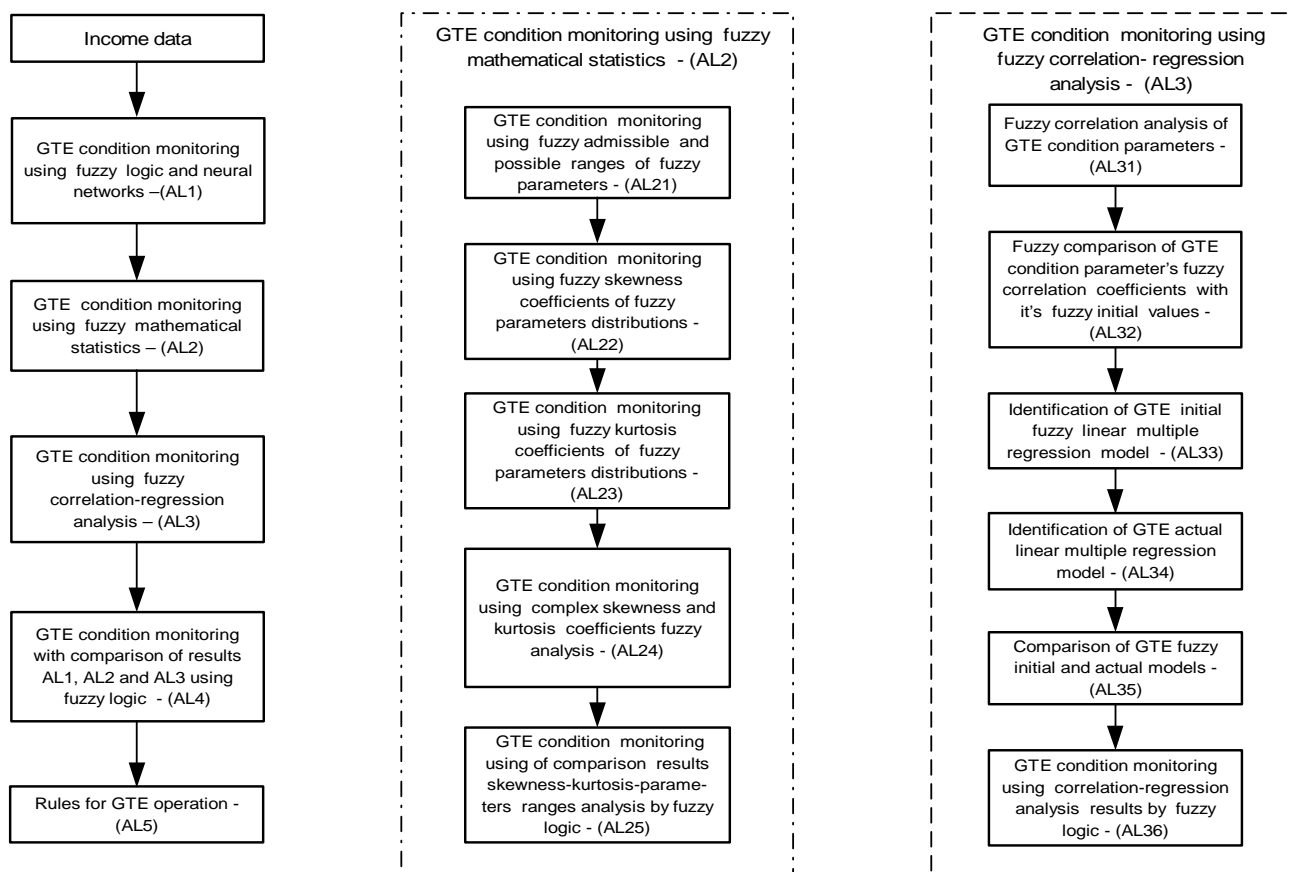


Fig. 1. Flow chart of aircraft gas turbine engine fuzzy-parametric diagnostic algorithm

Currently in the subdivisions of CIS airlines are operated various automatic diagnostic systems (ASD) of GTE technical conditions. The essence of ASD method is mainly to form the flexible ranges for the recorded parameters as the result of engine operating time and comparison of recorded meaning of parameters with their point or interval estimations (values).

However, it should be noted that statistic data processing on the above-mentioned method are conducted by the preliminary allowance of the recorded parameters meaning normal distribution. This allowance affects the GTE technical condition monitoring reliability and causes of the error decision in the GTE diagnostic and operating process¹⁻³. More over some identical combination of the various GTE work parameters' changes can be caused by different malfunctions. Finally it complicates the definition of the defect address.

II. FUZZY-NEURAL IDENTIFICATION SYSTEM OF GTE TEHCHNICAL CONDITION (PRELIMINARY STAGE)

Combined diagnostic method of GTE condition monitoring based on the evaluation of engine parameters by Soft Computing methods, mathematical statistic (high order statistics) and regression analysis is suggested. The method provides stage-by-stage (3 stages) evaluation of GTE technical

conditions (Fig.1). Experimental investigation conducted by manual records shows that at the beginning of monitoring during 40÷60 measurements accumulated values of recorded parameters of good working order GTE aren't normal distribution.

Consequently, on the first stage of diagnostic process (at the preliminary stage of GTE operation) when initial data is insufficient and fuzzy, GTE condition is estimated by the Soft Computing methods - Fuzzy Logic (FL) method and Neural Networks (NN). In spite of the rough parameters estimations of GTE conditions the privilege of this stage is the possible creation of initial image (initial condition) of the engine on the indefinite information.

As is known one of GTE technical condition estimation methods, used in the practice, is the exhaust gas temperature values control and analysis of this values' changes tendency in operation. Application of various mathematical models described by the regression equations for aviation GTE condition estimation is presented in [4,5].

Let's consider mathematical linear and non-linear models of aviation GTE temperature condition, described by fuzzy regression equations:

$$\tilde{Y}_i = \sum_{j=1}^n \tilde{a}_{ij} \otimes \tilde{x}_j; i = \overline{1, m} \quad (1)$$

$$\tilde{Y}_i = \sum_{r,s} \tilde{a}_{rs} \otimes \tilde{x}_1^r \otimes \tilde{x}_2^s; r = \overline{1, l}, s = \overline{1, l}; r+s \leq l \quad (2)$$

where \tilde{Y}_i fuzzy output parameter (e.g. GTE exhaust gas temperature T_4^*), \tilde{x}_j or \tilde{x}_1, \tilde{x}_2 input parameters ($H, M, T_H^*, p_H^*, n_{LP}, G_T, p_T, p_M, T_M, V_{BS}, V_{FS}$), \tilde{a}_{ij} and \tilde{a}_{rs} -required fuzzy parameters (fuzzy regression coefficients).

The general task is definition of fuzzy values \tilde{a}_{ij} and \tilde{a}_{rs} parameters of the equations (1) and (2) on the basis of the fuzzy statistical experimental data - input co-ordinates \tilde{x}_j and \tilde{x}_1, \tilde{x}_2 , output co-ordinates \tilde{Y} of model.

Let's consider the decision of the given tasks by using FL and NN [6-8]. NN consists of interconnected fuzzy neurons sets. At using NN for the decision of equations (1) and (2) input signals of the network are accordingly fuzzy values of variable $\tilde{X} = (\tilde{x}_1, \tilde{x}_2, \dots, \tilde{x}_n)$, $\tilde{X} = (\tilde{x}_1, \tilde{x}_2)$ and output \tilde{Y} .

As parameters of the network are fuzzy values of parameters \tilde{a}_{ij} and \tilde{a}_{rs} . We shall present fuzzy variables in the triangular form which membership functions are calculated under the formula:

$$\mu(x) = \begin{cases} 1 - (\bar{x} - x) / \alpha, & \text{if } \bar{x} - \alpha < x < \bar{x}; \\ 1 - (x - \bar{x}) / \beta, & \text{if } \bar{x} < x < \bar{x} + \beta; \\ 0, & \text{otherwise.} \end{cases}$$

At the identification task decision of parameters \tilde{a}_{ij} and \tilde{a}_{rs} for equations (1) and (2) with using NN, the basic problem is training the parameters \tilde{a}_{ij} and \tilde{a}_{rs} . For training values of parameters we shall take advantage of a α -cut [8].

We suppose, there are statistical fuzzy data received on the basis of experiments. On the basis of these input and output data are made training pairs (\tilde{X}, \tilde{T}) for training a network. For construction of process model on the input of NN gives input signals \tilde{X} and further outputs are compared with reference output signals \tilde{T} [1-3].

After comparison the deviation value is calculated

$$\tilde{E} = \frac{1}{2} \sum_{j=1}^k (\tilde{Y}_j - \tilde{T}_j)^2$$

With application α -cut for the left and right part of deviation value are calculated under formulas

$$E_1 = \frac{1}{2} \sum_{j=1}^k [y_{j1}(\alpha) - t_{j1}(\alpha)]^2,$$

$$E_2 = \frac{1}{2} \sum_{j=1}^k [y_{j2}(\alpha) - t_{j2}(\alpha)]^2, \quad E = E_1 + E_2,$$

where $\tilde{Y}_j(\alpha) = [y_{j1}(\alpha), y_{j2}(\alpha)]$; $\tilde{T}_j(\alpha) = [t_{j1}(\alpha), t_{j2}(\alpha)]$.

If for all training pairs, deviation value E is less than given then training (correction) parameters of the network comes to end [1-3]. In opposite case it continues until value E reach minimum.

Correction of network parameters for left and right part is carried out as follows:

$$a_{rs1}^n = a_{rs1}^o + \gamma \frac{\partial E}{\partial a_{rs}}, \quad a_{rs2}^n = a_{rs2}^o + \gamma \frac{\partial E}{\partial a_{rs}},$$

where $a_{rs1}^o, a_{rs1}^n, a_{rs2}^o, a_{rs2}^n$ -old and new values of left and right parts NN parameters, $\tilde{a}_{rs} = [a_{rs1}, a_{rs2}]$; γ -training speed.

The structure of NN for identification of the equation (1) parameters is given in [1-3].

For the equation (2) we shall consider a concrete special case as the regression equation of the second order

$$\tilde{Y} = \tilde{a}_{00} + \tilde{a}_{10}\tilde{x}_1 + \tilde{a}_{01}\tilde{x}_2 + \tilde{a}_{11}\tilde{x}_1\tilde{x}_2 + \tilde{a}_{20}\tilde{x}_1^2 + \tilde{a}_{02}\tilde{x}_2^2 \quad (3)$$

Let's construct neural structure for decision of the equation (2) where as parameters of the network are coefficients $\tilde{a}_{00}, \tilde{a}_{10}, \tilde{a}_{01}, \tilde{a}_{11}, \tilde{a}_{20}, \tilde{a}_{02}$. Thus the structure of NN will have four inputs and one output [1-3].

Using NN structure we are training network parameters. For value $\alpha = 0$, we obtain the following expressions:

$$\begin{aligned} \frac{\partial E_1}{\partial a_{001}} &= \sum_{j=1}^k (y_{j1} - t_{j1}); \quad \frac{\partial E_2}{\partial a_{002}} = \sum_{j=1}^k (y_{j2} - t_{j2}); \\ \frac{\partial E_1}{\partial a_{101}} &= \sum_{j=1}^k (y_{j1} - t_{j1})x_{11}; \quad \frac{\partial E_2}{\partial a_{102}} = \sum_{j=1}^k (y_{j2} - t_{j2})x_{12}; \\ \frac{\partial E_1}{\partial a_{011}} &= \sum_{j=1}^k (y_{j1} - t_{j1})x_{21}; \quad \frac{\partial E_2}{\partial a_{012}} = \sum_{j=1}^k (y_{j2} - t_{j2})x_{22}; \\ \frac{\partial E_1}{\partial a_{111}} &= \sum_{j=1}^k (y_{j1} - t_{j1})x_{11}x_{21}; \quad \frac{\partial E_2}{\partial a_{112}} = \sum_{j=1}^k (y_{j2} - t_{j2})x_{12}x_{22}; \\ \frac{\partial E_1}{\partial a_{201}} &= \sum_{j=1}^k (y_{j1} - t_{j1})x_{11}^2; \quad \frac{\partial E_2}{\partial a_{202}} = \sum_{j=1}^k (y_{j2} - t_{j2})x_{12}^2; \\ \frac{\partial E_1}{\partial a_{021}} &= \sum_{j=1}^k (y_{j1} - t_{j1})x_{21}^2; \quad \frac{\partial E_2}{\partial a_{022}} = \sum_{j=1}^k (y_{j2} - t_{j2})x_{22}^2 \quad (4) \end{aligned}$$

It is necessary to note, that at negative values of the coefficients \tilde{a}_{rs} ($\tilde{a}_{rs} < 0$), calculation formulas of expressions which include parameters \tilde{a}_{rs} in equation (3) and correction of the given parameter in equation (4) will change the form. For example, we allow $\tilde{a}_{rs} < 0$, then formula calculations of the fourth expression, which includes in equation (3) will have the following kind:

$$y_{41} = a_{111}x_{12}x_{22}; \quad y_{42} = a_{112}x_{12}x_{21},$$

and the correction formulas

$$\frac{\partial E_1}{\partial a_{111}} = \sum_{j=1}^k (y_{j1} - t_{j1}) x_{12} x_{22}; \quad \frac{\partial E_2}{\partial a_{112}} = \sum_{j=1}^k (y_{j2} - t_{j2}) x_{11} x_{21};$$

For value $\alpha = 1$ we shall receive

$$\begin{aligned} \frac{\partial E_3}{\partial a_{003}} &= \sum_{j=1}^k (y_{j3} - t_{j3}); \quad \frac{\partial E_3}{\partial a_{113}} = \sum_{j=1}^k (y_{j3} - t_{j3}) x_{13} x_{23}; \\ \frac{\partial E_3}{\partial a_{103}} &= \sum_{j=1}^k (y_{j3} - t_{j3}) x_{13}; \quad \frac{\partial E_3}{\partial a_{203}} = \sum_{j=1}^k (y_{j3} - t_{j3}) x_{23}^2; \\ \frac{\partial E_3}{\partial a_{013}} &= \sum_{j=1}^k (y_{j3} - t_{j3}) x_{23}; \quad \frac{\partial E_3}{\partial a_{023}} = \sum_{j=1}^k (y_{j3} - t_{j3}) x_{23}^2; \quad (5) \end{aligned}$$

As the result of training (4) and (5) we find parameters of the network satisfying the knowledge base with required training quality.

III. GTE CONDITION MONITORING BY FUZZY STATISTICAL ANALYSIS (FIRST STAGE)

Choice of GTE technical condition model (linear or non-linear) may be made with the help of the complex comparison analysis of fuzzy correlation coefficients \tilde{r}_{xy} and fuzzy correlation ratios $\tilde{\rho}_{y/x}$ values. Thus the following cases are possible:

- if \tilde{y} is no dependent from \tilde{x} , $\tilde{\rho}_{y/x} \cong \tilde{0}$ (fuzzy zero);
- if there is the fuzzy functional linear dependence \tilde{y} from \tilde{x} , $\tilde{r}_{xy} \cong \tilde{\rho}_{y/x} \cong \tilde{1}$ (fuzzy one);
- if there is the fuzzy functional non-linear dependence \tilde{y} from \tilde{x} , $\tilde{r}_{xy} \lesssim \tilde{\rho}_{y/x} \cong \tilde{1}$;
- if there is the fuzzy linear regression \tilde{y} from \tilde{x} , but there is no functional dependence, $\tilde{r}_{xy} \cong \tilde{\rho}_{y/x} \lesssim \tilde{1}$;
- if there is some fuzzy non-linear regression \tilde{y} from \tilde{x} , but there is no functional dependence, $\tilde{r}_{xy} \lesssim \tilde{\rho}_{y/x} \lesssim \tilde{1}$,

where \lesssim, \cong - fuzzy relations which are determined by the appropriate membership functions $\mu(r_{xy})$ and $\mu(\rho_{y/x})$.

Values of \tilde{r}_{xy} and $\tilde{\rho}_{y/x}$ may be estimated as follows

$$\tilde{r}_{xy} = \frac{\tilde{R}}{\tilde{R}_x \otimes \tilde{R}_y}; \quad \tilde{\rho}_{y/x} = \sqrt{1 - \frac{\tilde{\sigma}_{y/x}^2}{\tilde{\sigma}_y^2}}$$

where

$$\tilde{R} = \sum \tilde{x} \otimes \tilde{y} - \frac{1}{n} \sum \tilde{x} \otimes \sum \tilde{y};$$

$$\tilde{R}_x = \sqrt{\sum \tilde{x}^2 - \frac{1}{n} \left(\sum \tilde{x} \right)^2}; \quad \tilde{R}_y = \sqrt{\sum \tilde{y}^2 - \frac{1}{n} \left(\sum \tilde{y} \right)^2};$$

$$\tilde{\sigma}_{y/x}^2 = \frac{\sum (\tilde{y} - \tilde{y}_x)^2}{n} - \text{residual dispersion } \tilde{y}, \text{ which is}$$

formed by \tilde{x} influence; $\tilde{\sigma}_y^2 = \frac{\sum (\tilde{y} - \tilde{y})^2}{n}$ - general variation, which is taking into account all fuzzy factors influences; \tilde{y}_x - partial fuzzy average value of \tilde{y} , which is formed by \tilde{x} influence; \tilde{y} - general fuzzy average value of \tilde{y} .

However, the carried out researches show that of GTE work parameters' distributions have unstable character (fuzzy character). Therefore, it is necessary to note that correct application of fuzzy correlation-regression approach demands the analysis of fuzzy characteristics of GTE work parameters distributions. With this purpose should be carried out fuzzy analysis of distribution character of GTE work parameters on the basis of fuzzy values of skewness and kurtosis coefficients under the following formulas [1-3]

$$\tilde{A}(P) = \frac{\tilde{M}(P)_3}{\tilde{S}_n^3}; \quad \tilde{E}(P) = \frac{\tilde{M}(P)_4}{\tilde{S}_n^4} - 3$$

where $\tilde{A}(P)$ and $\tilde{E}(P)$ - fuzzy skewness and kurtosis coefficients of GTE work parameter P (e.g. for output y or input x parameter); $\tilde{M}(P)_3 = \frac{1}{n} \sum_{i=1}^n (\tilde{P}_i - \tilde{P}_n)^3$ - fuzzy third

central moment of parameter P ; $\tilde{M}(P)_4 = \frac{1}{n} \sum_{i=1}^n (\tilde{P}_i - \tilde{P}_n)^4$ - fuzzy fourth central moment of parameter P ;

$\tilde{S}_n^2 = \frac{1}{n-1} \sum_{i=1}^n (\tilde{P}_i - \tilde{P}_n)^2$ - fuzzy standard deviation of parameter P (e.g. $H, M, T_H^*, p_H^*, n_{LP}, T_4^*, G_T, p_T, p_M, T_M, V_{BS}, V_{FS}$).

IV. GTE CONDITION MONITORING USING STATISTICAL ANALYSIS AND KALMAN TYPE FILTER (SECOND STAGE)

The analysis show, that during following 60-120 measurements occurs the approach of individual parameters values of GTE work to normal distribution. Therefore at the second stage, on accumulation of the certain information, with the help of mathematical statistics are estimated GTE conditions. Here the given and enumerated to the one GTE work mode and standard atmosphere parameters are controlled on conformity to their calculated admissible and possible ranges.

Further by the means of the Least Squares Method (LSM) there are identified the multiple linear regression models of

GTE conditions changes. These models are made for each correct subcontrol engine of the fleet at the initial operation period. In such case on the basis analysis of regression coefficient's values (coefficients of influence) of all engine's multiple regression models with the help of mathematical statistics are formed base and admissible range of coefficients [3,9].

GTE Condition Monitoring using Regression Analysis and Kalman type Filter (Second Stage) is present in [1].

V. GTE CONDITION MONITORING USING COMPLEX ANALYSIS OF FIRST AND SECOND STAGE' RESULTS (THIRD STAGE)

On the third stage (for more than 120 measurements) by the LSM estimation conducts the detail analysis of GTE conditions. Essence of this procedures is in making actual model (multiple linear regression equation) of GTE conditions and in comparison actual coefficients of influence (regression coefficients) with their base admissible ranges. The reliability of diagnostic results on this stage is high and equal to $0.95 \div 0.99$. The influence coefficient's values going out the mentioned ranges allows make conclusion about the meaning changes of physical process influence on the concrete GTE work parameters. The stable going out one or several coefficient's influences beyond the above-mentioned range affirms about additional feature of incorrectness and permits to determine address and possible reason of faults. Thus for receiving stable (robust) estimations by LSM is used ridge-regression analysis.

With the view of forecasting of GTE conditions the regression coefficients are approximated by the polynomials of second and third degree.

As an example on application of the above-mentioned method changes of GTE (aviation engine D-30KU-154) conditions has been investigated. At the preliminary stage, when number of measurements is $N \leq 60$, GTE technical condition is described by the fuzzy linear regression equation (1). Identification of fuzzy linear model of GTE is made with help of NN which structure is given in [1-3]. Thus as the output parameter of GTE model is accepted the GTE exhaust gas temperature

$$(\tilde{T}_4^*)_{ini} = \tilde{a}_1 \tilde{H} + \tilde{a}_2 \tilde{M} + \tilde{a}_3 \tilde{T}_H^* + \tilde{a}_4 \tilde{n}_{LP} + \tilde{a}_5 \tilde{p}_T + \tilde{a}_6 \tilde{p}_M + \tilde{a}_7 \tilde{T}_M + \tilde{a}_8 \tilde{G}_T + \tilde{a}_9 \tilde{V}_{FS} + \tilde{a}_{10} \tilde{V}_{BS} + \tilde{a}_{11} \tilde{p}_H^* \quad (6)$$

On the subsequent stage for each current measurement's $N > 60$, when observes the normal distribution of the engine work parameters, GTE temperature condition describes by linear regression equation (6) which parameters is estimated by recurrent algorithm [1]

$$D = (T_4^*)_{act} = a_1' H + a_2' M + a_3' T_H^* + a_4' n_{LP} + a_5' p_T + a_6' p_M + a_7' T_M + a_8' G_T + a_9' V_{FS} + a_{10}' V_{BS} + a_{11}' p_H^* \quad (7)$$

As the result of the carried out researches for the varied technical condition of the considered engine was revealed certain dynamics of the correlation and regression coefficients values changes which is given in [1-3].

The basic characteristics of correlation coefficients [1-3]

show the necessity of fuzzy NN application at the flight information processing. In that case correct application of this approach on describing up of the GTE technical condition changes is possible by fuzzy linear or non-linear model [1,3].

For the third stage was made the following admission of regression coefficients (influence coefficients of various parameters) of various parameters on GTE exhaust gas temperature in linear multiple regression equation (1): frequency of engine rotation (RPM of low pressure (LP) compressor)- $0.596 \div 0.622$; fuel pressure- $1.16 \div 1.25$; fuel flow- $0.0240 \div 0.0252$; oil pressure- $11.75 \div 12.45$; oil temperature- $1.1 \div 1.2$; vibration of the forward support- $3.0 \div 5.4$; vibration of the back support- $1.2 \div 1.9$; atmosphere pressure- $112 \div 128$; atmosphere temperature- $(-0.84) \div (-0.64)$; flight speed (Mach number)- $57.8 \div 60.6$; flight altitude- $0.00456 \div 0.00496$. Within the limits of the specified admissions of regression coefficients was carried out approximation of the their (regression coefficients) current values by the polynomials of the second and third degree with help LSM and with use cubic splines [1-3].

VI. CONCLUSIONS

1. The GTE technical condition combined diagnosing approach is offered, which is based on engine work fuzzy and non-fuzzy parameters estimation with the help of Soft Computing methods (Fuzzy Logic and Neural Networks) and the confluent analysis.

2. It is shown, that application of Soft Computing methods in recognition GTE technical condition has certain advantages in comparison with traditional probability-statistical approaches. First of all, it is connected by that the offered methods may be used irrespective of the kind of GTE work parameters distributions. As at the early stage of the engine work, because of the limited volume of the information, the kind of distribution of parameters is difficult for establishing.

3. By complex analysis is established, that:

-between fuzzy thermodynamic and mechanical parameters of GTE work there are certain fuzzy relations, which degree in operating process and in dependence of fuzzy diagnostic situation changes' dynamics increases or decreases,

-for various situations of malfunctions development is observed different fuzzy dynamics (changes) of connections (correlation coefficients) between engine work fuzzy parameters in operating, caused by occurrence or disappearance of factors influencing GTE technical condition,

-for improvement of accepted decisions accuracy about GTE technical condition is expedient to apply Fuzzy Statistics in offered Condition Monitoring System.

The suggested methods make it possible not only to diagnose and to predict the safe engine runtime. This methods give the tangible results and can be recommended to practical application both for automatic engine diagnostic system where the handle record are used as initial information and for onboard system of engine work control.

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