An extension evaluation model of the operation state of aero engine

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Abstract

Traditional fault diagnosis with single parameter fails to evaluate the operation state of aero engine. This paper analyzes the extension evaluation based on supervision information of engine's performance and works out an evaluation system as well as an extension evaluation model and algorithm based on incidence function in extension theory. Through the model, parameters under the operation state of aero engine are studied. The incidence function in extension theory between classic domain and section domain of all attributes and parameters is established in the corresponding evaluation system. This makes it possible to acquire the state level of aero engine according to incidence in extension theory.

Keywords: aero engine, operation state, incidence function, evaluation, model

1 Introduction

Monitoring the operation state of aero engine is important to prolong its lifespan and ensure a safety flight. With the development of science and technology, modern engine is more and more complicated and can be affected by many factors, some of which are even unknown. Parameters in current monitoring method also fail to reveal the overall performance of the engine. Many remain untestable as is limited to conditions. Without enough data, it becomes a technical difficulty to evaluate the performance of the engine [1-4].

When the engine breaks down, it is significant to obtain relevant information on the operation state of aero engine for fault diagnosis that serves to the maintenance and prediction of the engine. Currently, there are three ways of analytical methods: (1) System operation state analysis based on signal treatment [5, 6]; (2) System operation state analysis based on analytic model [7, 8]; (3) System operation state analysis based on knowledge diagnosis [9, 10].

However, these methods are fuzzy and uncertain that cannot provide accurate diagnosis for the operation state when there are only small samples and little information.

Therefore, this paper constructs an extension evaluation model following the incidence function in extension theory as well as the algorithm. It hopes to advance the fault diagnosis and prediction by finding out possible fault information and learning about the state level to increase the efficiency and accuracy of the diagnosis. This is significant in terms of theory and engineering.

2 Establishment of the evaluation system for the operation state of aero engine

The aero engine controlling system is becoming complicated and bigger in size with the advancement of automation. The fault of the system will bring huge losses, which makes it necessary to improve its reliability and safety as well as the diagnosis technique. However, there are many factors that count. It is hard to monitor the reliability with only one source of information. Thus, various kinds of monitoring methods and flexible and sensitive parameters are needed to realize the judgment on the overall performance of aero engine. The operation state analysis relies on sensor technique, testing technique, computer technology, display technique and artificial intelligence analysis. It also requires the support of large amount of maintenance tests. Fault diagnosis, determination of the state level and the prediction of reliability and accuracy are the key. Therefore, based on previous researches and after technical communication with experts, this paper categories parameters of operation state into low/high pressure rotor speed performance, low/high pressure turbine guide vane angle adjustment performance, turbine exhaust control performance, vibration performance of nozzle, oil performance pressure, slip property and cycle life performance as a part of the evaluation system, as is shown in Figure 1.

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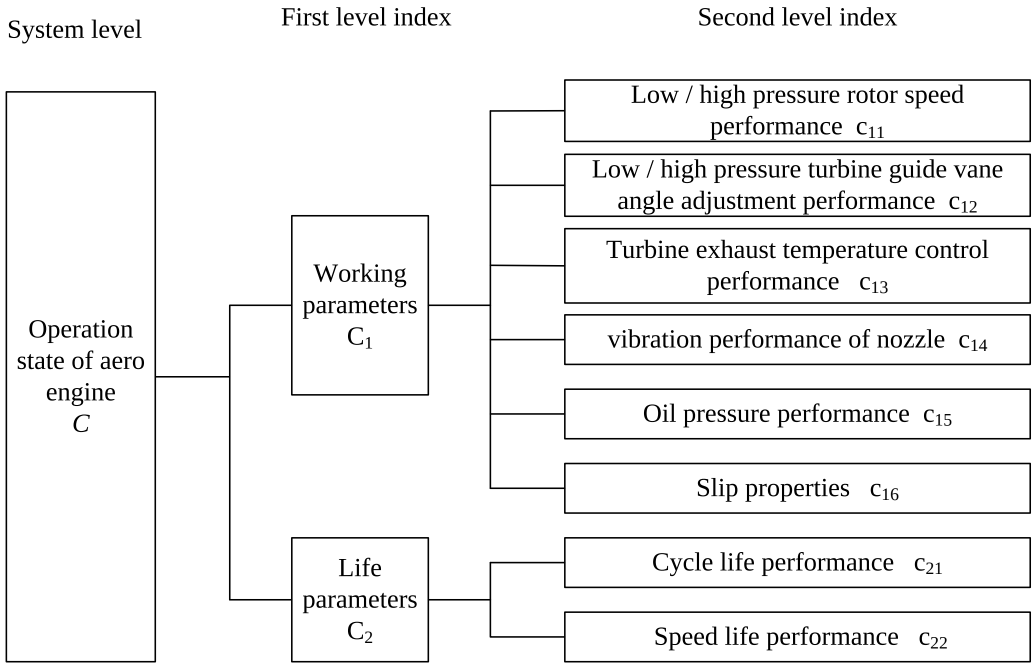

FIGURE 1 The evaluation system for the operation state of aero engine

The extension analysis of the operation state takes the advantage of all state information and existing knowledge to get a whole process of operation state and fault state evaluation.

3 Extension evaluation model and algorithm of the operation state of aero engine

3.1 DETERMINATION OF PERFORMANCE FACTOR SET OF THE OPERATION STATE

According to Figure1, the performance factor set has several levels of indexes. The system level shows the overall performance of the engine and is expressed by $C=\{C_1,C_2\}$ and fits $C_1\cap C_2=O$, which means that parameters of a subordinate level do not mix. The first level indexes are C_1 and C_2, with $C_1=\{c_{11},c_{12},c_{13},c_{14},c_{15},c_{16}\}$ and $C_2=\{c_{21},c_{22}\}$. The second level shows the specific performance of the engine.

3.2 STANDARDIZATION OF INDEXES OF THE OPERATION STATE

Some of the parameters can be measured up accurately while others cannot. Some have a positive effect on the operation state while others may have a negative effect. Therefore, parameters of different types should be normalized and standardized for better analysis.

For those fuzzy or uncertain parameters, fuzzy evaluation is given to the degree of membership. Specific standards are shown in Table 1.

If parameters are measurable, when parameter $v^i(c)$ is the positive index, the standardized index will be:

$$\tilde{v}^i(c)=\left[\tilde{v}_1^i(c),\tilde{v}_2^i(c)\right]=\left(\frac{v_1^i(c)}{v_2^{ik}\mid\max\limits_{1\le j\le m}\left(v_2^{ij}\right)},\frac{v_2^i(c)}{v_2^{ik}\mid\max\limits_{1\le j\le m}\left(v_2^{ij}\right)}\right),\quad(1)$$

TABLE 1 The degree of membership of fuzzy evaluation of parameters

The degree of membership	Performance level
0.9	Best state
0.7	Good state
0.5	Medium state
0.3	Poor state
0.1	Worst state
0.8,0.6,0.4,0.2	State in between

When $v^i(c)$ is the negative index, the standardized index will be:

$$\tilde{v}^i(c)=\left[\tilde{v}_1^i(c),\tilde{v}_2^i(c)\right]=\left(\frac{v_1^{ik}\mid\min\limits_{1\le j\le m}\left(v_1^{ij}\right)}{v_2^i(c)},\frac{v_1^{ik}\mid\min\limits_{1\le j\le m}\left(v_1^{ij}\right)}{v_1^i(c)}\right),(2)$$

$v_2^{ik}\mid\max\limits_{1\le j\le m}\left(v_2^{ij}\right)$ refers to the maximum value of $v^i(c)$ in the intervals of classic domain. $v_1^{ik}\mid\min\limits_{1\le j\le m}\left(v_1^{ij}\right)$ refers to the minimum value of $v^i(c)$ in the intervals of classic domain. After standardization, the index fits $0\le\tilde{v}_1^i(c)\le 1$ and $0\le\tilde{v}_2^i(c)\le 1$. And indexes of classic domain and section domain fit [0,1]. Therefore, the state value, classic domain and section domain of all indexes are standardized and the difference is eliminated.

3.3 WEIGHT OF INDEXES OF THE OPERATIOON STATE

Weight refers to the priority of parameters. It is important to the analysis of the operation state. The more accurate, scientific and objective the weights are the closer to the reality and more convincible the result will be. Gray related analysis makes up the weakness of traditional mathematical calculation. It can address the system which has small samples, little information and regularities. It is close to qualitative analysis. Gray related analysis depends on similarity to judge how closely parameters are related. A closer curve means highly related.

Apply those parameters to the analysis. Suppose there is a pair parameter sequence:

$X_i=(x_i(1), x_i(2), x_i(3), \ldots, x_i(k)), k=1,2,3\ldots,n$.

Select the ideal parameter sequence: $X_0=(x_0(1), x_0(2), x_0(3),\ldots, x_0(k)), k=1,2,3\ldots,n$. And it shall fit:

$$x_0(k)=\max_{1\le i\le n} x_i(k),\ k=1,2,3\ldots,n.$$

Compare the tested result with the standard result. And calculate the incidence coefficient $\varphi_i(k)$ at an index k, and the expression is:

$$\varphi_i(k)=\frac{\min_i\min_k|x_0(k)-X_i(k)|+\beta\max_i\max_k|x_0(k)-X_i(k)|}{|x_0(k)-X_i(k)|+\beta\max_i\max_k|x_0(k)-X_i(k)|}. \quad (3)$$

$$\beta\in(0,1),\quad k=1,2,\ldots,n$$

Calculate all incidence coefficients, normalize them and get the weight of each index.

3.4 CALCULATION BASED ON INCIDENCE FUCTION IN EXTENSION THEORY

Incidence in extension theory is constructed [13-15]. Suppose the classic domain of index i is $V^i_{cla}(c)=\left[v^i_{cla-lef}(c),v^i_{cla-rig}(c)\right]$, $v^i_{cla-lef}(c)\le v^i_{cla-rig}(c)$ and its section domain is $V^i_{\sec}(c)=\left[v^i_{\sec-lef}(c),v^i_{\sec-rig}(c)\right]$, $v^i_{\sec-lef}(c)\le v^i_{\sec-rig}(c)$. When the characteristic value $v^i(c)$ of index i is accurate, the extension distance ρ_i^{cla} between index i and classic domain $V^i_{cla}(c)$ is:

$$\rho_i^{cla}=\left|v^i(c)-\frac{v^i_{cla-lef}(c)+v^i_{cla-rig}(c)}{2}\right|-\frac{v^i_{cla-rig}(c)-v^i_{cla-lef}(c)}{2}. \quad (4)$$

When the characteristic value $v^i(c)$ of index i is accurate, the extension distance $\rho_i^{\sec}$ between index i and section domain $V^i_{\sec}(c)$ is:

$$\rho_i^{\sec}=\left|v^i(c)-\frac{v^i_{\sec-lef}(c)+v^i_{\sec-rig}(c)}{2}\right|-\frac{v^i_{\sec-rig}(c)-v^i_{\sec-lef}(c)}{2}. \quad (5)$$

When the characteristic value $v^i(c)$ of index i is fuzzy, that is when $v^i(c)=\left[v^i_{lef}(c),v^i_{rig}(c)\right]$, the extension distance ρ_i^{cla} between index i and section domain $V^i_{cla}(c)$ is:

$$\rho_i^{cla}=\left(\frac{1}{2}\left|v^i_{lef}(c)-\frac{v^i_{cla-lef}(c)+v^i_{cla-rig}(c)}{2}\right|\right)-v^i_{cla-rig}(c)+v^i_{cla-lef}(c)+\left|v^i_{rig}(c)-\frac{v^i_{cla-lef}(c)+v^i_{cla-rig}(c)}{2}\right|\Bigg). \quad (6)$$

When the characteristic value $v^i(c)$ of index i is fuzzy, that is when $v^i(c)=\left[v^i_{lef}(c),v^i_{rig}(c)\right]$, the extension distance $\rho_i^{\sec}$ between index i and section domain $V^i_{\sec}(c)$ is:

$$\rho_i^{\sec}=\frac{1}{2}\left(\left|v^i_{lef}(c)-\frac{v^i_{\sec-lef}(c)+v^i_{\sec-rig}(c)}{2}\right|-v^i_{\sec-rig}(c)+v^i_{\sec-lef}(c)+\left|v^i_{rig}(c)-\frac{v^i_{\sec-lef}(c)+v^i_{\sec-rig}(c)}{2}\right|\right). \quad (7)$$

When the extension distances are acquired, then there comes the incidence function between classic domain $V^i_{cla}(c)$ and index i is:

$$K_i=\begin{cases}-\rho_i^{cla}/\left|v^i_{cla-lef}(c)-v^i_{cla-rig}(c)\right| & v^i(c)\in\left[v^i_{cla-lef}(c),v^i_{cla-rig}(c)\right]\\ \rho_i^{cla}/\left(\rho_i^{\sec}-\rho_i^{cla}\right) & v^i(c)\notin\left[v^i_{cla-lef}(c),v^i_{cla-rig}(c)\right]\end{cases}. \quad (8)$$

Suppose the weight of index i is w_i and it fits $\sum_{i=1}^{n} w_i = 1$, then the incidence in extension theory Φ_i between index i and classic domain $V_{cla}^{i}(c)$ is:

$$\Phi_i = \sum_{i=1}^{n} (w_i K_i). \quad (9)$$

According to close principle, if there is:

$$\Phi_0 = \max_{1 \le i \le m} (\Phi_i) = \max(\Phi_1, \Phi_2, \cdots, \Phi_m) = \Phi_t, 1 \le t \le m. \quad (10)$$

Then the state attribute belongs to the classic $V_{cla}^{t}(c)$, which means the fault state of the operation state is in the state t. Further maintenance and repair of aero engine can base on the predicted state.

3.5 EXTENSION EVALUATION MODEL AND ALGORITHM OF THE OPERATION STATE

The algorithm can be described as the follows:

Step 1: Monitor the aero engine that needs the extension evaluation analysis based on data extraction and produce standard state samples of data monitoring;

Step 2: Consult relevant experts and engineers, acquire parameters of the operation state and construct an evaluation system based on the operation state analysis;

Step 3: Under the evaluation system, acquire the classic domain and the section domain of indexes based on design knowledge and experience;

Step 4: Acquire the standardized monitoring data, classic domain and the section domain based on Equations (1) and (2) and get the after-standardization data;

Step 5: Acquire weights of indexes under the evaluation system based on Equation (3);

Step 6: Calculate the extension distance between index and its corresponding classic domain based on Equations (4) and (6);

Step 7: Calculate the extension distance between index and its corresponding section domain based on Equations (5) and (7);

Step 8: Acquire the incidence function in extensive theory between index and classic domain based on Equation (8);

Step 9: Acquire the incidence in extensive theory between index and classic domain based on Equation (9);

Step 10: Based on the incidence in extensive theory and the close principle, acquire the classic domain of the operation state of aero engine and determine the state level of the aero engine to be monitored and prepare for further maintenance.

4 Empirical tests

This paper analyses and explains the extension evaluation model with the example of an aero engine in normal state. It leaves the interval to collect parameter information and consult with maintenance staff or experts to get the fuzzy judgment on relevance parameters under the evaluation system (Refer to Figure 1). This paper uses “Best, Good, Normal and Poor” to evaluate. The monitoring data after standardization is shown in Table 2 while the classic domain and the section domain is shown in Table 3.

TABLE 2 Monitoring data after standardization

Parameters	Weight	Indexes	Weight	Standard value
Working parameters	0.585	Low/high pressure rotor speed performance	0.35	0.80-0.90
		Low/high pressure turbine guide vane angle adjustment performance	0.12	0.70-0.80
		Turbine exhaust control performance	0.16	0.50-0.60
		Vibration performance of nozzle	0.23	0.60-0.70
		Oil performance pressure	0.06	0.80-0.90
		Slip property	0.08	0.70-0.80
Life parameters	0.415	Cycle life performance	0.45	0.60-0.70
		Speed life performance	0.55	0.40-0.50

TABLE 3 Classic domain and section domain of indexes after standardization

Indexes	Classic domain				Section domain
	Best	*Good*	*Normal*	*Poor*	
Low/high pressure rotor speed performance	0.80-0.90	0.70-0.80	0.50-0.70	0.10-0.50	0.1-0.9
Low/high pressure turbine guide vane angle adjustment performance	0.70-0.90	0.60-0.70	0.40-0.60	0.10-0.40	0.1-0.9
Turbine exhaust control performance	0.80-0.90	0.70-0.80	0.50-0.70	0.10-0.50	0.1-0.9
Vibration performance of nozzle	0.80-0.90	0.60-0.80	0.50-0.60	0.10-0.50	0.1-0.9
Oil performance pressure	0.80-0.90	0.70-0.80	0.50-0.70	0.10-0.50	0.1-0.9
Slip property	0.80-0.90	0.60-0.80	0.40-0.60	0.10-0.40	0.1-0.9
Cycle life performance	0.70-0.90	0.60-0.70	0.50-0.60	0.10-0.50	0.1-0.9
Speed life performance	0.80-0.90	0.70-0.80	0.50-0.70	0.10-0.50	0.1-0.9

The extension space between index, classic domain and section domain and incidence coefficient are acquired based on the extension evaluation model and algorithm in Section 3.5. The specific values are shown in Tables 4 and 5.

TABLE 4 The extension space between index, classic domain and section domain

Indexes	The extension space between index and classic domain				The extension space between index and section domain
	Best	*Good*	*Normal*	*Poor*	
Low/high pressure rotor speed performance	0.00	0.05	0.1 5	0.35	-0.05
Low/high pressure turbine guide vane angle adjustment performance	-0.05	0.05	0.15	0.35	-0.15
Turbine exhaust control performance	0.25	0.15	-0.05	0.05	-0.35
Vibration performance of nozzle	0.15	-0.05	0.05	0.15	-0.25
Oil performance pressure	0.00	0.05	0.15	0.35	-0.05
Slip property	0.05	-0.05	0.15	0.35	-0.15
Cycle life performance	0.05	0.00	0.05	0.15	-0.15
Speed life performance	0.35	0.25	0.05	-0.05	-0.35

TABLE 5 Coefficient parameter between index and classic domain

Indexes	Coefficient parameter between index and classic domain			
	Best	*Good*	*Normal*	*Poor*
Low/high pressure rotor speed performance	0.000	-0.500	-0.750	-0.875
Low/high pressure turbine guide vane angle adjustment performance	0.250	-0.250	-0.500	-0.700
Turbine exhaust control performance	-0.417	-0.300	0.250	-0.250
Vibration performance of nozzle	-0.375	0.250	-0.167	-0.375
Oil performance pressure	0.000	-0.500	-0.750	-0.875
Slip property	-0.250	0.250	-0.500	-0.700
Cycle life performance	-0.250	0.000	-0.250	-0.500
Speed life performance	-0.500	-0.417	-0.125	0.125

The Incidence in extension theory of index can be acquired with the weight taken into consideration, that is, $\Phi_0 = \max\left(-0.035, -0.221, -0.313, -0.452\right) = \Phi_1$. It is clear that this engine works in a good state and asks no maintenance at present.

5 Conclusions

This paper analyses the extension evaluation based on supervision information of engine's performance and works out an evaluation system as well as an extension evaluation model and algorithm based on incidence function in extension theory. Through the model, parameters under the operation state of aero engine are studies. And the incidence function in extension theory between the classic domain and the section domain of all attributes and parameters is established in the corresponding evaluation system. This makes it possible to acquire the state level of aero engine according to incidence in extension theory and support the computed-based monitoring and prediction of the operation state.

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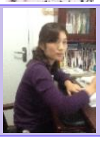	**Shan Xu, born in 1981** **Current position, grades:** lecturer. **University studies:** Master degree at Hebei University, majoring in technology of power system and its automation. **Experience:** Teaching in Department of Electrical Engineering of Tianjin Bohai Vocatioanl and Technical College for 9 years.