

Determination method for aero-engine optimal operation performance interval

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Abstract. Considering total cost with the aim to minimize operation cost and maintenance cost in unit time, an aero-engine optimal operation performance interval determination model is proposed in this paper. Compared with previous researches, this model is more reasonable, because the model takes into consideration both operation cost and maintenance cost. The lower limit of the optimal operation performance interval corresponds to maintenance occasion, and the upper limit corresponds to performance restoration degree. Taking an aero-engine as an example, the performance degradation, the operation cost and the maintenance cost are studied and the optimal operation performance interval is solved based on the proposed model. The results show that the proposed model can be applied to solving the aero-engine optimal operation performance interval and determining aero-engine maintenance occasion and maintenance scope.

1. Introduction

Aero-engine is a typical complex equipment, which has the characteristic of long running cycle and high maintenance cost. One of the most complicated problems in aero-engine operation is to determine the maintenance occasion and the maintenance scope. The problem can be decomposed into multiple sub problems such as maintenance occasion determination problem, maintenance objective determination problem, and maintenance scope determination problem based on single factor or multiple factors. These factors include performance degradation, life limited parts, hardware damage, and lubrication consumption. In these problems, one of the key problems is to determine the aero-engine maintenance occasion and the performance restoration degree based on performance degradation.

The performance is declining with the operation of equipment. To ensure the availability of equipment, a performance threshold will be set generally. When performance drops to the threshold, the equipment must be maintained to restore its performance. The present study mainly focuses on forecasting the time when equipment degrades to its performance threshold, that is, to determine maintenance occasion by performance degradation. The methods used to forecast performance threshold include regression analysis [7-8], neural network [9-11], support vector machine [12-14], pattern recognition [15], combination forecasting [16], etc. Because aero-engine performance degradation has significant influence on the maintenance cost, the maintenance occasion solved by above method is generally not the optimal one. The performance restoration degree is generally determined by the engineer's experience.

Obviously, the method for determining maintenance occasion and performance restoration degree considering both operation cost and maintenance cost was not proposed up to now. Equipment performance has significant influence on the equipment operation cost. In general, the better the



performance is, the lower the equipment operation cost is, and vice versa. The equipment maintenance cost is affected deeply by performance restoration degree. The higher the restoration degree is, the higher the maintenance cost is. When the performance degradation pattern is known, determining the equipment maintenance occasion and performance restoration degree is equivalent to determine an operation performance interval. The lower bound of the optimal operation performance interval corresponds to maintenance occasion, and the upper bound corresponds to optimal performance restoration degree. How to solve the optimal operation performance interval considering the total cost is the main problem to be solved in this paper.

The optimal operation performance interval of aero-engine is connected with the performance degradation pattern, the effect of performance status on operation cost and the effect of performance restoration degree on maintenance cost. In this paper, an aero-engine optimal operation performance interval determination model considering the total cost is presented to minimize the operation cost and maintenance cost in unit time.

The paper is organized as follows. In section II, we describe the processing of the model establishment. In section III, we selected a case for validation analysis and got the results. In section IV, we summarized the conclusion.

2. Model Establishment

The aero-engine performance degradation is showed by the performance parameters degradation which can be expressed by a monotonic continuous function. The function is expressed by $p = f_p(t)$, where p means performance parameter value and t means operation time.

The aero-engine operation performance interval can be expressed as $[p_2, p_1]$, corresponding to the operation time interval $[t_1, t_2]$. In this interval, initial value of the aero-engine performance parameter is p_1 . With the increase of t , the performance degrades gradually. When the performance parameter falls to p_2 , the aero-engine must be repaired to restore its performance parameter to p_1 .

The constitution of aero-engine operation cost and maintenance cost is complicated, so this paper just study the operation cost and maintenance cost influenced by performance. Unit operation cost generally increases with the performance degradation. Denoting $f_o(p)$ as unit operation cost, then the operation cost c_o in the interval $[t_1, t_2]$ can be defined as follows:

$$c_o = \int_{t_1}^{t_2} f_o(p) dt \quad (1)$$

The aero-engine maintenance cost is related with both the performance before maintenance and the performance after maintenance. For $[p_2, p_1]$, the performance before maintenance is p_2 , and the performance after maintenance is p_1 ; then the maintenance cost is represented as $c_m = f_m(p_1, p_2)$.

To minimize the operation cost and maintenance cost in unit time from t_1 to t_2 , and take t_1 and t_2 as decision variables, the aero-engine optimal operation performance interval determination model considering total cost can be expressed as equation (2).

$$\min c_u = \frac{f_m[f_p(t_1), f_p(t_2)] + \int_{t_1}^{t_2} f_o[f_p(t)] dt}{t_2 - t_1} \quad (2)$$

$$s.t. \begin{cases} p_{r,\min} \leq f_p(t_1) \leq p_{r,\max} \\ p_{\min} \leq f_p(t_2) < f_p(t_1) \end{cases}$$

where $p_{r,\min}$ is the minimum of performance restoration, $p_{r,\max}$ is the maximum of performance restoration, and p_{\min} is the performance parameter threshold.

In general, equation (2) is a nonlinear programming model which can be solved by intelligent optimization algorithm such as particle swarm optimization, genetic algorithm and so on [17]. Equation (2) can be solved by interior point method when this equation can be proved that it is a convex optimization problem and that both the objective function and the constraint function are

differentiable two times [18]. Besides, when the solution space scale is not big, the traversal search method can be used to solve this problem.

3. Case Description

In this section, the proposed model is applied to solving the optimal operation performance interval of an aero-engine. The unit of operation time is indicated as flight cycle considering that aero-engine performance degradation has higher correlation with flight cycle.

3.1. Performance Degradation

The parameter which is used to represent aero-engine performance in engineering application is exhaust gas temperature margin (EGTM). The higher the EGTM is, the better the aero-engine performance is, and vice versa. When the EGTM is lower than 0, the aero-engine core components would be damaged due to the high temperature, such as, turbine blades. Therefore, the aero-engine must carry out maintenance in this occasion. In order to ensure flight safety, EGTM threshold is generally set to a value greater than 0. In this paper, $p_{\min} = 0^{\circ}\text{C}$.

A lot of EGTM data of multiple aero-engines in the same type is collected to obtain the EGTM recession tendency. Short term fluctuation of EGTM data is very large, but there is a clear downward trend for a long time. Linear regression model is adopted to match the EGTM data, and the result is shown in equation (3).

$$p = -4 \times 10^{-3}t + 95 \quad (3)$$

From equation (3), the EGTM initial value of this type of aero-engine is 95, namely $p(0) = 95$.

According to the historical data, when this type of aero-engine is maintained, the minimum of performance restoration is 60, and the maximum of performance restoration is 95. Namely, $p_{r,\min} = 60^{\circ}\text{C}$ and $p_{r,\max} = 95^{\circ}\text{C}$.

3.2. Operation Cost

The aero-engine operation cost influenced by performance is mainly fuel cost. The main performance parameters related to fuel consumption are fuel flow (FF) and delta fuel flow (DFF). The actual measured value of FF which fluctuates larger is closely related to the flight environment and flight state. DFF is the percentage that FF standardized value deviates from the FF baseline value. Namely, DFF is the FF deviation percentage that the aero-engine in the standard flight environment compares to the healthy aero-engine in the same flight state. Compared with the actual measured value of FF, DFF can essentially reflect the aero-engine fuel consumption. Therefore, this paper presents a method to calculate the fuel consumption in the time interval $[t_1, t_2]$ based on DFF. Firstly, the DFF calculation equation is given as equation (4).

$$f_d = \frac{f_s - f_b}{f_b} \times 100 \quad (4)$$

where f_d is DFF; f_s is FF standardized value (kg/h); and f_b is FF baseline value (kg/h).

According to equation (4), the calculation equation of f_s can be obtained, which can be showed as equation (5).

$$f_s = f_b + f_d f_b / 100 \quad (5)$$

The FF average value of aero-engine in health condition is about 1600kg/h, then $f_b = 1600\text{kg/h}$. The flight hour cycle ratio of the aero-engine is 2.2, and let unit fuel price be u . The fuel cost per unit time in standard flight environment is shown as equation (6).

$$f_o(p) = 2.2u \cdot (1600f_d / 100 + 1600) \quad (6)$$

To build the relationship between fuel cost and EGTM, the data of EGTM and DFF from multiple aero-engine in the same type is collected, as shown in figure 1. As can be seen from figure 1, although there is a big fluctuation between EGTM and DFF, but a clear trend can be found.

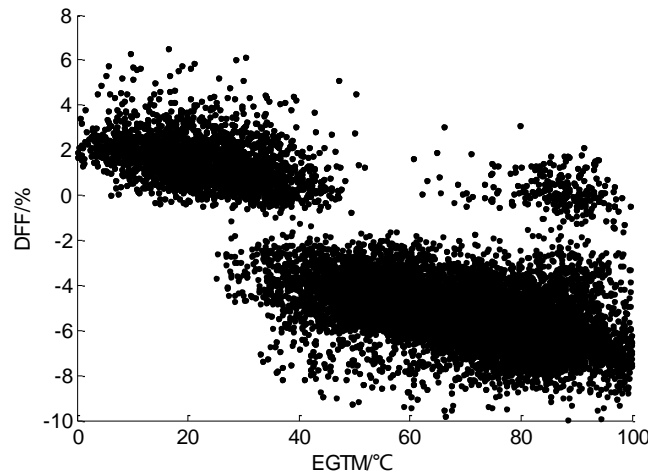


Figure 1. Data of EGTM and DFF

The relationship between EGTM and DFF can be fitted by two degree polynomial regression model, and the result is shown in equation (7).

$$f_d = 1.5 \times 10^{-3} p^2 - 0.2646p + 5.8924 \quad (7)$$

Bring equation (6) and equation (7) to equation (1), then the total fuel cost in interval $[t_1, t_2]$ can be calculated.

3.3. Maintenance Cost

The aero-engine maintenance cost influenced by performance is mainly the maintenance cost except the cost of life limited parts replacement. This part maintenance cost can be divided into the basic decomposition cost c_b that dividing whole engine into module and the cost c_p caused by module performance restoration. The maintenance cost can be expressed by equation (8).

$$C_M = C_b + C_p \quad (8)$$

According to the historical maintenance data, the basic decomposition cost c_b is about 160 thousand dollars. When the maintenance level of each module is performance restoration, EGTM can generally be restored to about 60 degree, and the corresponding maintenance cost c_p is about \$1350000. When the maintenance level of each module is overhaul, EGTM can generally be restored to about 95 degree, and the corresponding maintenance cost c_p is about \$2250000. Since the quantity limitation of the collected historical repair sample, the establishment of precise maintenance cost model is difficult. In order to simplify the maintenance cost model, assuming that c_p is independent of the EGTM before maintenance p_2 , the EGTM after maintenance $p_1 \in [60, 95]$, and the relationship of c_p and p_1 is linear, then the calculation equation of c_p can be presented by equation (9).

$$c_p = 25714.29p_1 - 192857.4 \quad (9)$$

3.4. Model Solution

Equation (3), Equation (6-9) is plugged into (2). The optimal operation performance interval determination model of this type of aero-engine is built and shown as (10).

$$\min c_u = v \cdot \frac{-102.86t_1 + 2.41 \times 10^6}{t_2 - t_1} + u \cdot \left[2.8 \times 10^{-7} \cdot (t_1^2 + t_1 t_2 + t_2^2) - 1.4 \times 10^{-3} \cdot (t_1 + t_2) + 3319.11 \right] \quad (10)$$

$$s.t. \begin{cases} 0 \leq t_1 \leq 8750 \\ t_1 < t_2 \leq 23750 \end{cases}$$

When $v=1$, is a fluctuate coefficient considering the maintenance cost affected by market, the maintenance cost does not change; and when $v>1$, the maintenance cost increases by $(v-1) \times 100\%$. As $(v, u) \in \{1, 1.05, 1.1, 1.15, 1.2\} \times \{0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.2, 2.4\}$, and the unit of u is dollars/kg. The standard particle swarm optimization algorithm (PSO) is used to solve equation (10). Some results are shown in Table 1 and figure 2.

Table 1. Partial optimization results

v	u /(dollars /kg)	t_1 /cycles	p_1 /°C	t_2 /cycles	p_2 /°C	c_u /(dollars /cycles)
1	0.6	0	95	20155.66	14.38	2162.35
1	0.8	0	95	18396.06	21.42	2841.50
1	1.0	0	95	17143.32	26.43	3517.98
1	1.2	0	95	16187.08	30.25	4192.66
1	1.4	0	95	15423.00	33.31	4866.03
1	1.6	0	95	14792.35	35.83	5538.39
1	1.8	0	95	14259.08	37.96	6209.95
1	2.0	0	95	13799.63	39.80	6880.86
1	2.2	0	95	13397.81	41.41	7551.23
1	2.4	0	95	13042.06	42.83	8221.13
1.2	0.6	0	95	21361.8	9.55	2185.57
1.2	0.8	0	95	19491.47	17.03	2866.93
1.2	1.0	0	95	18159.83	22.36	3545.27
1.2	1.2	0	95	17143.32	26.43	4221.57
1.2	1.4	0	95	16331.04	29.68	4896.38
1.2	1.6	0	95	15660.58	32.36	5570.04
1.2	1.8	0	95	15093.62	34.63	6242.79
1.2	2.0	0	95	14605.13	36.58	6914.79
1.2	2.2	0	95	14177.89	38.29	7586.18
1.2	2.4	0	95	13799.63	39.80	8257.04

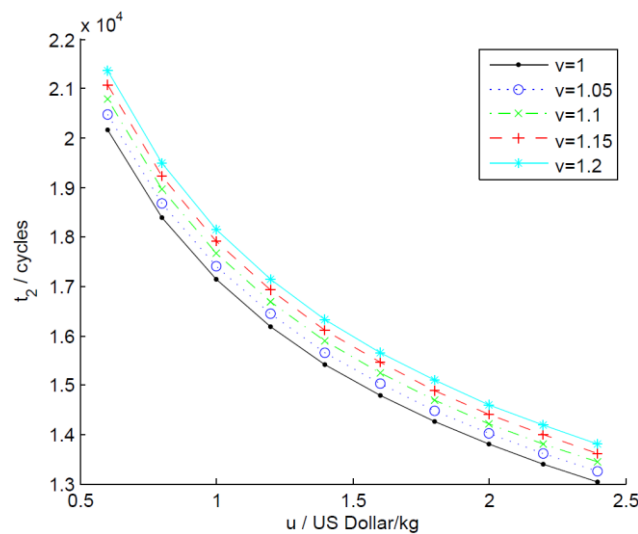


Figure 2. Relation for u , v , t_2

According to the Table I, when $v=1$ and $u=0.6$, the optimal operation performance interval of this type of aero-engine is $[14.38^{\circ}\text{C}, 95^{\circ}\text{C}]$, the corresponding maintenance interval is 20155.66 flight cycles, and the operation cost and maintenance cost in unit time is \$2162.35 per flight cycle.

Combined with Fig 2, when the maintenance cost (v) is constant and the fuel price (u) increases, the optimal operation performance interval gradually shorten, the corresponding maintenance interval also gradually shorten, but the operation cost and maintenance cost in unit time gradually rises. When $v=1$ and $u=2.4$, the optimal operation performance interval of this type of aero-engine is $[42.83^{\circ}\text{C}, 95^{\circ}\text{C}]$, and the corresponding maintenance interval is 13042.06 flight cycles.

When the maintenance cost (v) increases and the fuel price (u) is constant, the optimal operation performance interval gradually enlarges, the corresponding maintenance interval also gradually enlarges, and the operation cost and maintenance cost in unit time gradually rises. When $v=1.2$ and $u=2.4$, the optimal operation performance interval is $[39.80^{\circ}\text{C}, 95^{\circ}\text{C}]$, and the corresponding maintenance interval is 13799.63 flight cycles.

In conclusion, if the maintenance cost is higher and the fuel price is lower, the optimal operation performance interval is larger; vice versa. The result is consistent with the engineering practice.

The model optimization result is closely related to the performance degradation function, the operation cost function and the maintenance cost function. With the accumulation of the performance data samples and the historical maintenance samples, the optimization result will be more reasonable.

The fact that the maintenance occasion decided by the optimal operation performance interval only takes into account the performance factor deserves to be noticed. The factors which influence maintenance occasion include the replacement of multiple life limited parts, the mechanical failure and the execution of airworthiness directive. Therefore, the determination of aero-engine maintenance occasion needs to combine with the above factors. The determination method based on the optimal operation performance interval presented in this paper can be an important reference to determine the maintenance occasion.

4. Conclusion

To solve the problem of the maintenance occasion and the performance restoration degree based on the performance degradation, an aero-engine optimal operation performance interval determination model considering total cost that influenced by aero-engine performance is presented to minimize the operation cost and maintenance cost in unit time.

The optimal operation performance interval is solved based on the above model. This paper analyzes the aero-engine performance degradation, the operation cost and the maintenance cost. The results show that the established model is suited to solve the optimal operation performance interval,

and the maintenance cost and fuel price have a great impact on the interval. When the maintenance cost increases and the fuel price decreases, the optimal operation performance interval of the aero-engine will become larger, which indicates the aero-engine maintenance interval become larger, vice versa.

In determining the aero-engine maintenance occasion and the maintenance workscope, in addition to considering the performance degradation, it is also necessary to consider other factors such as life limited parts, hardware damage, etc. Integrating the various factors to determine the optimal maintenance occasion and the maintenance workscope is a research direction.

5. Acknowledgments

Thanks to the National Natural Science Foundation of China (No. 51305096). The project was also funded by the Civil Aviation Administration of China (No. MHRD20150104), Shandong Independent Innovation and Achievements Transformation Fund (No. 2014CGZH1101) and the Fundamental Research Funds for the Central Universities (No. HIT.NSRIF.201704).

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