Sensitivity Analysis of Safety Factors Based on Model of Aviation Reciprocating Engine Turbocharging System

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Abstract

Aviation reciprocating engines dominant the low-power general aviation power, but air intake method of most engines is natural aspiration that engine performance will decrease significantly in high-altitude environments. Assembling the turbocharging system, the high-altitude performance of engines can be effectively restored and the working ceilings of general aircraft can be significantly improved. While improving engine performance, safety of turbocharging system should be paid enough attention. The Response Surface Methodology explores the influence of factors on the response value by fitting the function relationship of multiple quadratic regression equations, and avoids the limitation of ignoring the interaction between factors.Sobol factor analysis is a global sensitivity analysis method that calculates the response index of the response value by matrix calculation to quantify the influence of parameters on the response value. In this paper, model-based system safety analysis method is combined with the "V" type safety analysis process, the response surface methodology and the Sobol factor sensitivity analysis method to compare turbocharging system performances of the sensitivity of different safety influencing factors by constructing the engine model and fitting the equation for global sensitivity analysis, in order to improve the level of safety analyzing. A methodical case of sensitivity analysis of safety influencing factor of the engine quasi-dimensional model built by Rotax914 as a prototype is given using the proposed method in this paper. Results show that the sensitivity index of altitude is much higher than other factors. The sensitivity index of the diameter of the intake valve is higher than that of the diameter of the exhaust valve, but in the same quantity. The effective length of the air filter in a normal operating environment has almost no impact on the turbocharging system. Therefore, the scope of the safety influencing factors can be adjusted based on the analysis during the actual running, reducing the uncertainty of critical factors, allowing an efficient and intuitive safety analysis.

Keywords: turbocharging system；response surface methodology；Sobol factor；Sensitivity analys

1. General Introduction

Aviation reciprocating engines have unique advantages within 300kW due to their economy, reliability, flexibility in use, and ease of maintenance, and will occupy an important position in current and future aviation power systems for a long time. However, most of them adopt a naturally aspirated intake method, and when in high-altitude environments, the engine output power decreases, making it difficult to meet the aircraft's high-altitude power requirements, which restricts the working ceiling of reciprocating engines. After adopting a turbocharging system, the power of aviation reciprocating engines can be effectively restored, but if the turbocharging system fails, it can cause various negative effects [1], and even damage engine components and systems, leading to engine failure. The investigation report of the National Transportation Safety Board (NTSB) in the United States shows that from 1988 to 1993, there were 88 aircraft accidents caused by engine failure due to turbocharging system failures, resulting in a total of 6 deaths and 35 injuries [2]; From 1986 to 1993, the Federal Aviation Administration (FAA) received 580 reports of service difficulties related to turbocharging systems [3], of which 44 were received in just one year in 1993 [4]. Therefore, while improving engine performance, the safety issues of turbocharging systems must be given equal attention.

The model-based system security analysis method can overcome the limitations of traditional methods that cannot consider coupling problems when facing complex coupling problems [5]. By establishing a turbocharging system model for aviation piston engines, multiple safety factors affecting aviation piston engines can be numerically transformed into input variables for sensitivity analysis of the turbocharging system model. This can effectively obtain the sensitivity level of aviation piston engine performance under different safety factors, and classify safety factors to achieve safety analysis in the face of complex coupled problems. The response surface analysis method uses multiple quadratic regression equations to fit functional relationships and explore the degree of influence of influencing factors on response values, avoiding the limitation of ignoring the mutual influence between factors. Sobol factor analysis is a global sensitivity analysis method that quantifies the degree of influence of parameters on response values by calculating the response index of response values through matrix calculations.

This paper uses a safety assessment process and an efficient analysis method for the turbocharging system by combining model-based system safety analysis with the "V" type safety analysis process, response surface analysis method and Sobol factor sensitivity analysis method. By constructing the engine model and fitting equations for global sensitivity analysis, the sensitivity of the aviation piston engine turbocharging system performance to different safety influencing factors is analyzed and compared. During actual running, the range of safety influencing factors can be adjusted based on the analysis results, reducing the uncertainty of key factors, and conducting efficient and intuitive safety analysis to improve the safety level of the turbocharging system.

2. Safety Assessment Process and Analysis Method for Turbocharging System

2.1 Safety Assessment Process for Turbocharging System

The model-based system safety analysis method can overcome the limitations of traditional methods when dealing with complex coupling problems. When analyzing the safety of turbocharging systems, a complete engine model should be established for analysis. The typical V-shaped process of model-based system security assessment is shown in Figure 1, which mainly involves three stages: FHA, PSSA, and SSA. For the safety analysis of the engine turbocharging system, a model can be used in the PSSA stage to analyze the possible influencing factors of the failure modes that occur in the FHA stage, and targeted operation can be conducted to explore the specific degree of impact.

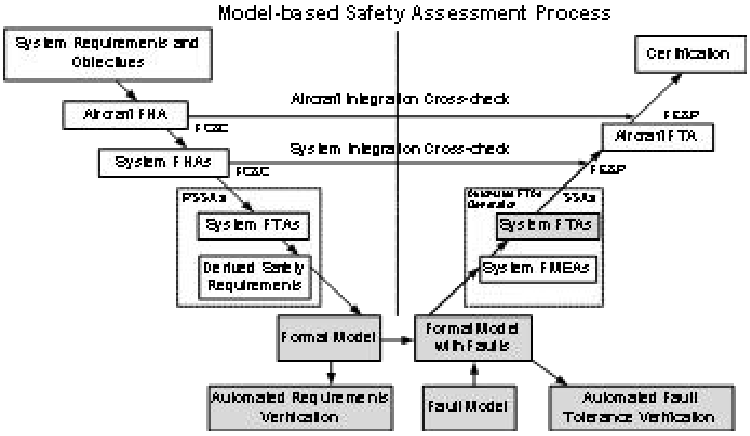

Figure 1 - Model -based aircraft safety assessment process[6]

2.2 Analysis Method for Turbocharging System

2.2.1 Boundary of Safety Influencing Factors

The safety boundary is a constraint condition on various systems or components to avoid failure forms, forming the maximum allowable range of variation for the research object. The safety boundaries of each subsystem or component of the engine turbocharging system are not consistent with the optimal operating state or safety boundary of the entire system when analyzed independently. Therefore, the maximum allowable range of each parameter under each operating state can be analyzed based on the operating safety boundary of the engine, and the safety boundary of the turbocharging system can be determined based on this. Referring to the operating manual of the Rotax914 engine [7], the safe zone boundary for engine speed can be determined as 2500r/min-5500r/min, the warning zone is the area between engine speed 5500r/min-5800r/min, and the boundary line area between engine speed 5800r/min is the limit operating boundary. Therefore, in the process of selecting safety influencing factors and conducting operation and analysis in this article, it is necessary to ensure that the engine operating speed is stable within the safe zone boundary.

2.2.2 Interaction of Safety Influencing Factors

The safety boundary is to use Response Surface Methodology (RSM) to fit the functional relationship between safety influencing factors $(X_1, X_2, X_3, \cdots, X_n)$ and the performance index Y of the engine turbocharging system through multiple quadratic regression equations, in order to explore the degree of influence of influencing factors on response values, avoiding the limitation of ignoring the mutual influence between factors.

$$Y = f(X_1, X_2, X_3 \cdots X_n) \tag{1}$$

Simulate the real limit state surface through a series of multivariate and deterministic experiments. First, write down the basic equation of the quadratic term:

$$\mathrm{y} = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \sum_{i=1}^{m} \beta_{ii} x_i x_i + \sum \sum\nolimits_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

Among them, y is the response value, β is the coefficient of each item, x is the safety influencing factor, and ε is the error. After multiple experiments, the equation can be written in matrix form:

$$y = X\beta + \varepsilon \tag{3}$$

The minimum variance is:

$$L = \sum_{i=1}^{n} \varepsilon_i^2 = \varepsilon^{'} \varepsilon = (\mathrm{y} - X\beta)^{'} (\mathrm{y} - X\beta) \tag{4}$$

When the minimum variance is taken as the minimum value, it is obvious that the fitted surface is closest to the actual value, and the fitted response surface can be obtained.

2.2.3 Sensitivity of Turbocharging System to Safety Influencing Factors

Sobol factor analysis is a global sensitivity analysis method that quantifies the degree of influence of parameters on response values by calculating the response index of response values through matrix calculation under given independent variable types and ranges. By constructing a correlation matrix between the number of influencing factors and their respective ranges of variation, solving the impact index and analyzing sampling points, the response values of safety influencing factors are obtained based on statistical formulas, intuitively reflecting the sensitivity of the aviation piston engine turbocharging system to safety influencing factors, in order to analyze and compare the impact of each safety influencing factor on the engine turbocharging system.

3. Establishment of Complete Aviation Reciprocating Engine Model

3.1 Establishment of System Model Architecture

Aviation reciprocating engines have strong coupling, transient, integrity, and nonlinearity. Therefore, when selecting the system model, there are roughly two constraints: on the one hand, specific requirements, maneuverability, and time cost need to be considered; On the other hand, it is necessary to consider whether the model interface is convenient for analysis and iteration. Therefore, a quasi-dimension model is selected to model the aviation reciprocating turbocharging engine system as shown in Figure 2.

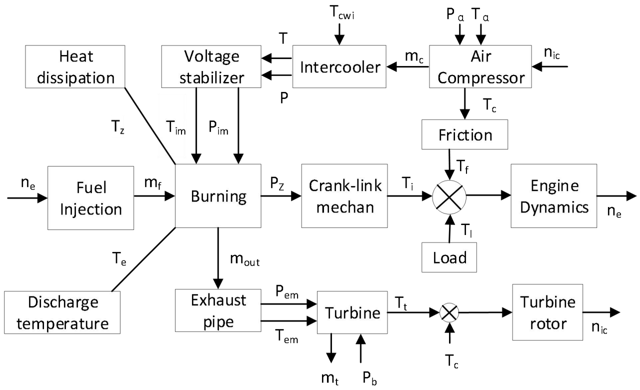

Figure 2 - Model architecture of two-stage turbocharging aviation reciprocating engine

It is specifically divided into multiple parts, including the cylinder working process model, intake and exhaust system model, turbocharging system model, and control system model. The turbocharging system also includes the inter-cooler model, compressor model, and turbine model.

3.2 System Model of Complete Aviation Reciprocating Engine

Decompose the actual complex system into several subsystems and establish corresponding physical models before converting them into mathematical models. Without considering the filters of the intake system and the mufflers of the exhaust system, the overall model of the engine is divided into three main subsystems: the cylinder working process system, the intake and exhaust system, and the turbocharging system.

3.2.1 Cylinder Working Process System

The differential equation of temperature on crankshaft angle φ is:

$$\frac{dT}{d\varphi}=\frac{1}{mC_v}\left(\frac{dQ_B}{d\varphi}+\frac{dQ_w}{d\varphi}-p\frac{dV}{d\varphi}+h_s\frac{dm_s}{d\varphi}+h_c\frac{dm_e}{d\varphi}-u\frac{dm}{d\varphi}\right) \tag{5}$$

Q_B is the heat released from combustion, m_s is the mass of inflow, h_s is the specific enthalpy of the gas in front of the intake valve, Q_w is the boundary flow heat, m_e is the mass of outflow, and h_c is the specific enthalpy of the gas in the cylinder.

The combustion process inside the cylinder adopts the Weibe function:

$$x_b(\theta) = \frac{m_b}{m} = 1 - \exp[-\alpha(\frac{\theta - \theta_0}{\Delta\theta_b})^{s+1}] \tag{6}$$

$x_b(\theta)$ is the mass fraction of burned gas, θ is the instantaneous crankshaft angle, α is an adjustable empirical parameter, and s is the combustion quality index.

The heat transfer process inside the cylinder adopts the semi-empirical formula Woschni function:

$$\alpha_g = 820 p^{0.8} T^{-0.53} D^{-0.2} [C_1 C_m + C_2 \frac{T_a V_s}{P_a V_a}(p - p_0)]^{0.8} \tag{7}$$

D is the diameter of cylinder, C_m is the speed of piston, V_s is the working volume of the cylinder, and p_0 is the pressure of cylinder when the engine is pulled backwards.

3.2.2 Intake and Exhaust System

Considering the intake and exhaust valve throats as the flow area changing over time, assume the flow process as one-dimensional isentropic adiabatic flow, and represent the rate of change in the intake volume flowing into the cylinder through the intake valve as (s subscript to the intake pipe state):

$$\frac{dm_s}{d\varphi} = \frac{1}{6n}\mu_s A_S \frac{p_s}{\sqrt{R_s T_s}} \sqrt{\frac{2k_s[(\frac{p}{p_s})^{\frac{2}{k_s}} - (\frac{p}{p_s})^{\frac{k_s+1}{k_s}}]}{k_s - 1}} \tag{8}$$

μ_s is the flow coefficient, A_S is the instantaneous flow cross-sectional area, p is the pressure of the working fluid behind the intake valve, R_s k_s is the gas constant and adiabatic index of the working fluid before the intake valve, p_s and T_s is the pressure and temperature of the working fluid before the intake valve.

During the initial stage of exhausting, due to the huge pressure difference of the gas in the cylinder, it may lead to a supercritical flow state of the gas flowing out through the exhaust valve, and then as the pressure difference continues to decrease, it may transition to a subcritical flow state. Therefore, the rate of change in the exhaust volume flowing out of the cylinder through the exhaust valve can be expressed as:

When $\frac{p_r}{p} < (\frac{2}{k+1})^{\frac{k}{k-1}}$, supercritical flow occurred and the rate of change in exhaust volume was:

$$\frac{dm_e}{d\varphi} = \frac{1}{6n}\mu_e F_e \frac{p}{\sqrt{RT}}(\frac{2}{k+1})^{\frac{1}{k+1}}\sqrt{\frac{2k}{k+1}} \tag{9}$$

When $\frac{p_r}{p} \geq (\frac{2}{k+1})^{\frac{k}{k-1}}$, it transitioned to a subcritical state and the rate of change in exhaust volume was:

$$\frac{dm_e}{d\varphi} = \frac{1}{6n}\mu_e F_e \frac{p}{\sqrt{RT}} \sqrt{\frac{2k[(\frac{p_r}{p})^{\frac{2}{k}} - (\frac{p_r}{p})^{\frac{k+1}{k}}]}{k-1}} \tag{10}$$

F_e is the instantaneous flow area of the intake valve, p_r is the pressure of the exhaust pipe after the exhaust valve, μ_e is the flow coefficient of the exhaust valve, p T and k is the pressure, temperature, and adiabatic index of the working fluid in the cylinder.

3.2.3 Turbocharging System

The matching accuracy between the turbocharging system and the whole engine directly affects the performance and safety of the turbocharging engine.

Turbine output power is:

$$W_t = \eta_t m_t \frac{k_t}{k_t - 1} R_t T_t [1 - (\frac{p_{t0}}{p_t})^{\frac{k_t - 1}{k_t}}] \tag{11}$$

The torque balance equation of the booster rotor is:

$$M_t - M_c = J_{tc} \frac{\pi}{30} \frac{dn_{tc}}{dt} \tag{12}$$

M_t is the turbine torque, M_c is the compressor torque, J_{tc} is the rotational inertia of the turbocharger, n_{tc} is the turbocharger speed.

3.3 Establishment of Simulation Model for Two-stage Turbocharging Engine

The process of establishing the model involves parameters such as engine geometry, operating environment, and characteristic experience, which can be obtained through engine technical manuals and relevant literature. To adopt a two-stage turbocharging engine system based on the Rotax914 first-stage turbocharging engine, equipping it with a first-stage compressor and a high-pressure intercooler. According to the engine manual [7], the main parameters are determined.

To meet the characteristics of the engine at an altitude of 10000 meters, the design goal is to achieve an output power of 70.5kw at a load of 100% and a rated speed of 5500rpm. When a resistance coefficient of 0.9 is given, the total boost ratio is determined to be 5.2. To ensure the stable running of the system and ensure that all parameter indicators do not exceed the maximum allowable values, except for the air filter at the inlet end and the muffler at the exhaust end, the component connection form of the prototype has been basically reproduced. The final established two-stage turbocharged aviation piston engine system model is shown in Figure 3.

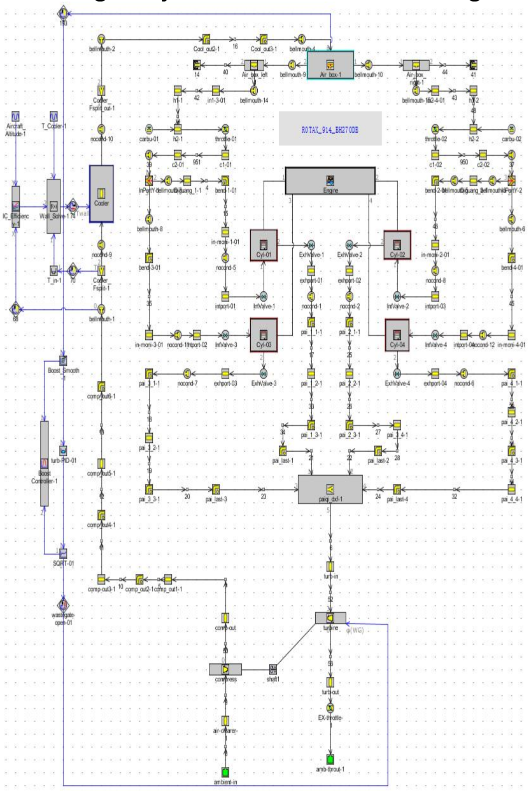

Figure 3 - Two -stage turbocharging engine system model schematic diagram

4. Establishment of Response Surface Methodology Surrogate Model

The impact of various safety influencing factors on the engine turbocharging system has an interactive effect, and analyzing only a single variable is incomplete and inaccurate. Therefore, response surface methodology (RSM) is used to conduct response optimization experiments and establish a safety influencing factor surrogate model, which can effectively improve the efficiency of safety analysis and explore the impact of safety influencing factors and their interactions on the performance of engine turbocharging systems

4.1 Design Response Surface Experiment

The experiment takes the average speed of the compressor during the four processes of cylinder intake, compression, combustion, and exhaust as the response value (Y), selects four safety influencing factors: altitude (X_1), inlet valve diameter (X_2), exhaust valve diameter (X_3), and effective length of air filter (X_4), and designs a four factor and three level response surface experiment based on the principle of response surface analysis. The experimental factors and parameter values are shown in Table 1.

Table 1 - Factors and parameter values of the response surface experiment

No.	X_1/km	X_2/mm	X_3/mm	X_4/mm	Y/RPM	No.	X_1/km	X_2/mm	X_3/mm	X_4/mm	Y/RPM
1	5	30	30	120	3058.14	16	1	30	27	120	3185.81
2	9	27	30	120	2954.85	17	5	33	33	120	3117.39
3	5	30	27	108	3007.23	18	5	30	30	120	3058.14
4	5	30	30	120	3058.14	19	5	30	33	132	3056.31
5	9	30	33	120	2883.94	20	9	30	30	132	2882.95
6	5	33	30	132	3106.35	21	9	30	27	120	2951.80
7	5	27	30	108	2954.88	22	1	33	30	120	3308.29
8	5	27	27	120	2923.78	23	5	30	30	120	3058.14
9	5	30	33	108	3057.48	24	5	30	27	132	3005.90
10	9	33	30	120	2894.31	25	5	33	30	108	3107.39
11	1	30	30	132	3234.36	26	9	30	30	108	2881.74
12	5	27	33	120	2962.41	27	1	30	33	120	3246.47
13	5	33	27	120	3056.87	28	5	30	30	120	3058.14
14	1	27	30	120	3115.63	29	5	27	30	132	2953.71
15	1	30	30	108	3235.68						

29 control experiments were designed using the Box Behnken method, and response surface models were obtained based on simulation results. According to Table 2, the F value of altitude is 421.61, $P<10^{-5}$; The F value of diameter of the intake valve is 62.98, $P<10^{-5}$; The F value of the exhaust valve diameter is 4.44, $P<10^{-5}$; The F value of the effective length of the air filter is 0.0028, $P=0.9587$. $P>0.0500$ Indicates that the model item is not significant, $P<0.0500$ indicates that the model item is significant, and $P<0.0100$ indicates that the model item is extremely significant.

Table 2 - The significance level of safety influencing factors

Source	F-value	P-value	Source	F-value	P-value

A-Altitude	421.61	<0.0001	AC	5.93	0.0288
B-Int-valve	62.98	<0.0001	AD	0.0023	0.9624
C-Exh-valve	4.44	0.0536	BC	119.79	0.6845
D-L-Cleaner	0.0028	0.9587	BD	6.070E-06	0.9981
AB	16027.56	0.0003	CD	9.194E-06	0.9976
A^2	4.79	0.0460	B^2	2.79	0.1168
C^2	2.81	0.1156	D^2	1.78	0.2040

As shown in Figure 4, the changes in altitude and intake valve diameter have a significant impact on the performance of the aviation piston engine turbocharging system. The changes in exhaust valve diameter have no significant impact on the performance of the engine turbocharging system, and the effective length of the air filter has little effect on the performance of the engine turbocharging system. The interaction term AB , AC , A^2 has a significant impact on the performance of the engine turbocharging system, while the other secondary terms have no significant impact on the performance of the engine turbocharging system.

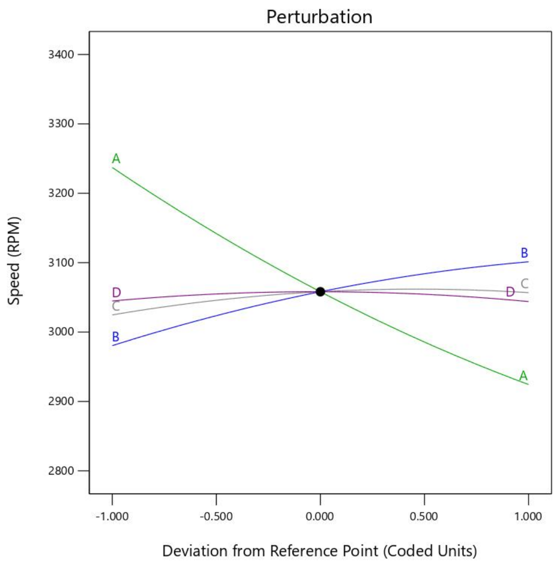

Figure 4 - The effect of experimental factors on the response value

4.2 Establishment and Analysis of Surrogate Model

After the establishment of the safety influencing factor surrogate model, Figures 5 and 6 illustrate the establishment and fitting of the surrogate model.

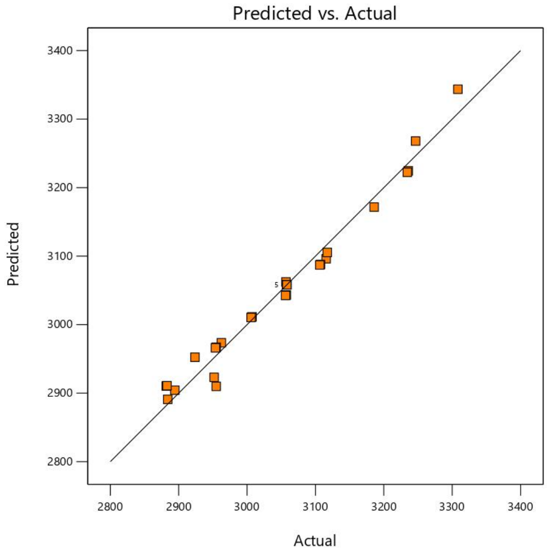

Figure 5 - Diagram of the forecast and actual value distribution

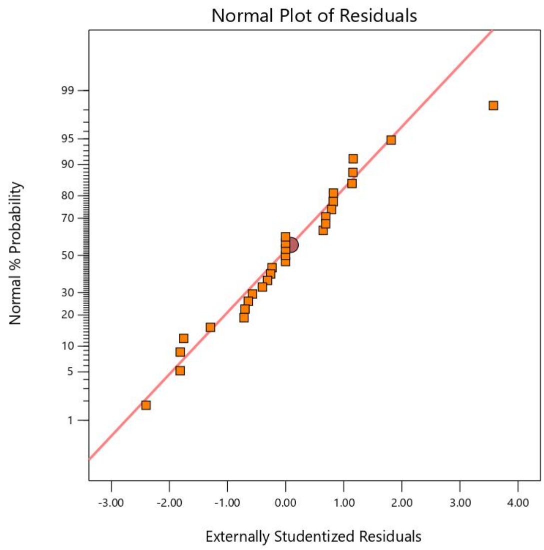

Figure 6 - Diagram of the normal probability distribution of residuals

The distribution map of predicted values and actual values as well as the normal probability distribution map of residuals show a linear relationship, with a multivariate correlation coefficient R^2 is 0.9744. It indicates that the fitting model of the database has good correlation and adaptability. The final proxy model obtained is:

$$Y = 3058.14 - 156.39X_1 + 60.44X_2 + 16.05X_3 - 0.4017X_4 - 63.30X_1X_2 - 32.13X_1X_3 + 0.6325X_1X_4 +$$

$$5.47X_2X_3 + 0.0325X_2X_4 + 0.0400X_3X_4 + 22.68X_1^2 - 17.32X_2^2 - 17.38X_3^2 - 13.80X_4^2 \quad (13)$$

4.3 Response Surface Analysis of Interaction Terms in Surrogate Model

Response surface graph is a three-dimensional spatial surface graph formed by quantifying the response values of various safety influencing factors. The shape of the surface graph can represent the level of interaction between safety influencing factors. The possible effects of their interactions can be analyzed by changing the observed response values of the studied variable on the response surface graph while keeping other parameters constant. Figure 7 shows the response surface of six interaction terms generated by the aviation piston engine turbocharging system on four safety influencing factors.

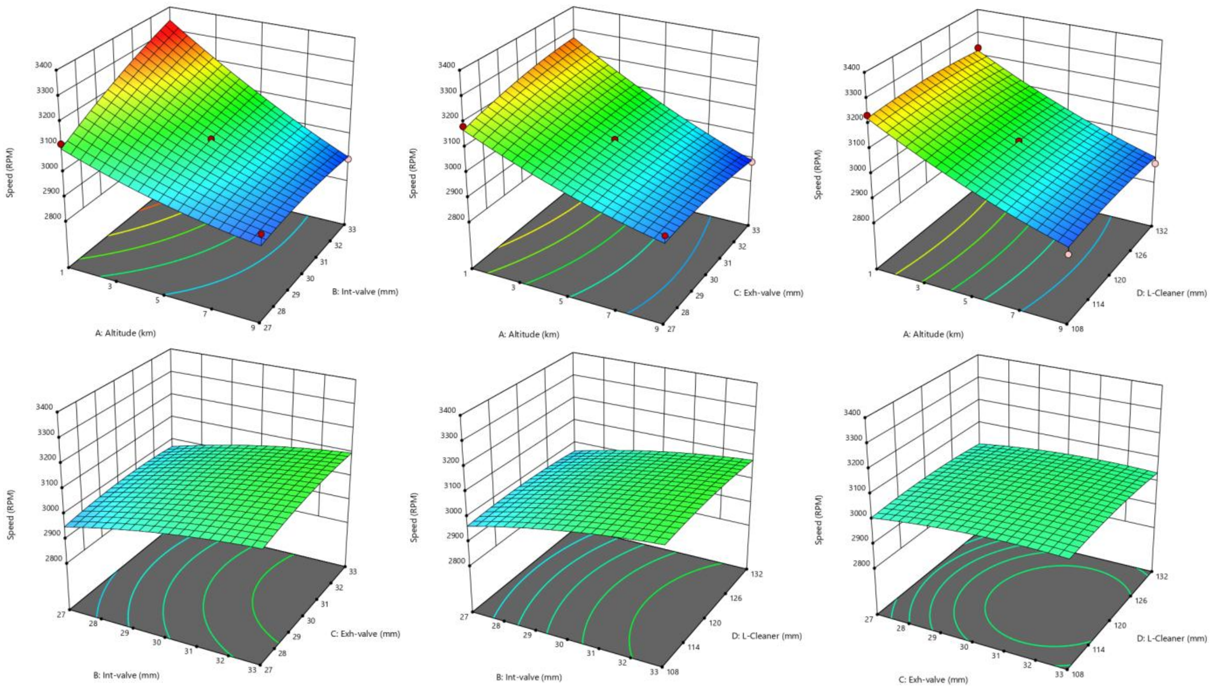

Figure 7 - Diagram of the turbocharging system responds to the interaction

The steeper curve is, the more significant the impact of this factor on the performance of the turbocharging system. When the number of elliptical contours on the contour lines is smaller and the contour shape of the contour lines is closer to a circle, it indicates that the interaction between the two factors is smaller, and vice versa, it is larger. It can be concluded that the interaction between altitude and intake valve diameter is significant, which has a significant impact on the performance of the engine turbocharging system; The interaction between the diameter of the exhaust valve and the effective length of the air filter is relatively small, and the impact on the performance of the engine turbocharging system is relatively small.

5. Sensitivity Analysis of Safety Influencing Factors

According to the response surface analysis method, a safety influencing factor proxy model is obtained, and the working safety boundary of the engine is set to determine the value range and number of sampling sample points for four safety influencing factors. A sample matrix, sample transformation matrix, and response value matrix are generated, and the sensitivity value of the engine turbocharging system to safety influencing factors is solved based on the influence index formula.

5.1 Generation of Sample Point for Sensitivity Analysis

According to the previous text, the safety boundary for selecting the engine for operation is 2500-5500 RPM , with various safety influencing factors floating by $\pm$ 5%, $\pm$ 10%, $\pm$ 15%, and $\pm$ 20%. The more sample points there are, the more accurately the relationship between variables and response values can be reflected, but once a certain value is reached, the accuracy will tend to stabilize. Taking into account the running results and time costs, a total of 900000 sample points were selected. Figures 8-11 show the fluctuation curves of the first-order impact index and total impact index of each safety influencing factor with the number of sample points.

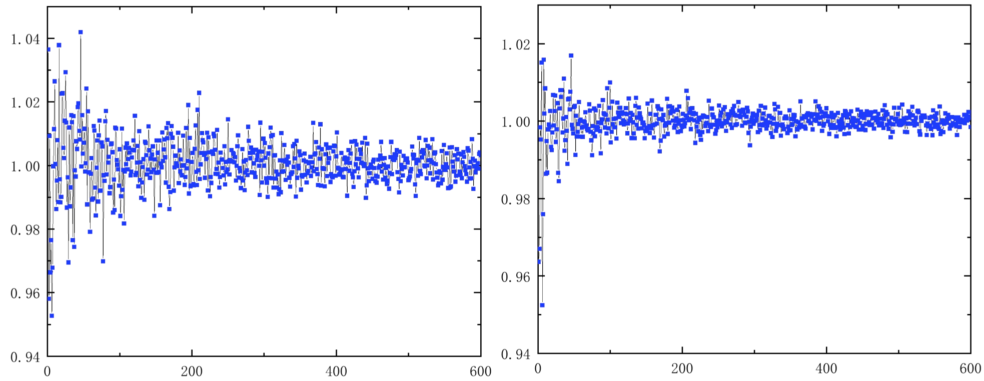

Figure 8 - Diagram of altitude first-order impact index and total impact index

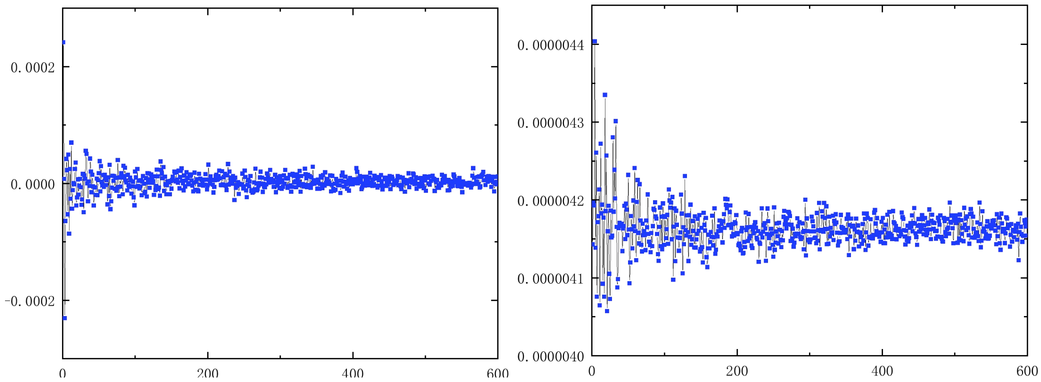

Figure 9 - Diagram of int-valve first-order impact index and total impact index

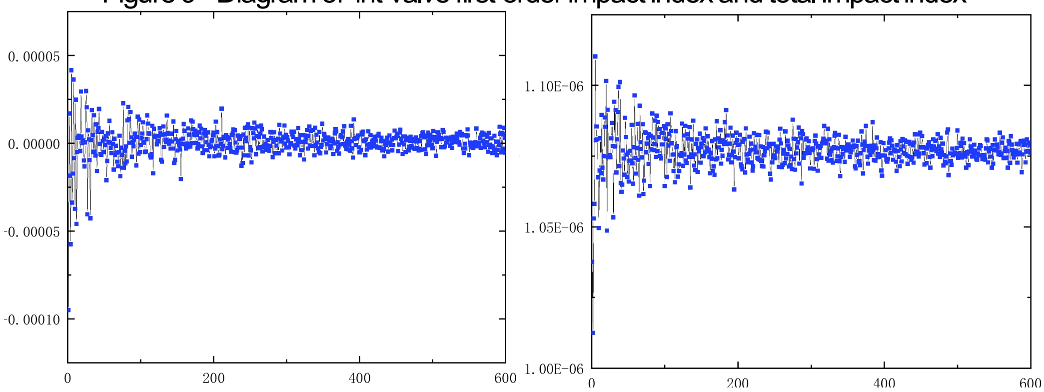

Figure 10 - Diagram of exh-valve first-order impact index and total impact index

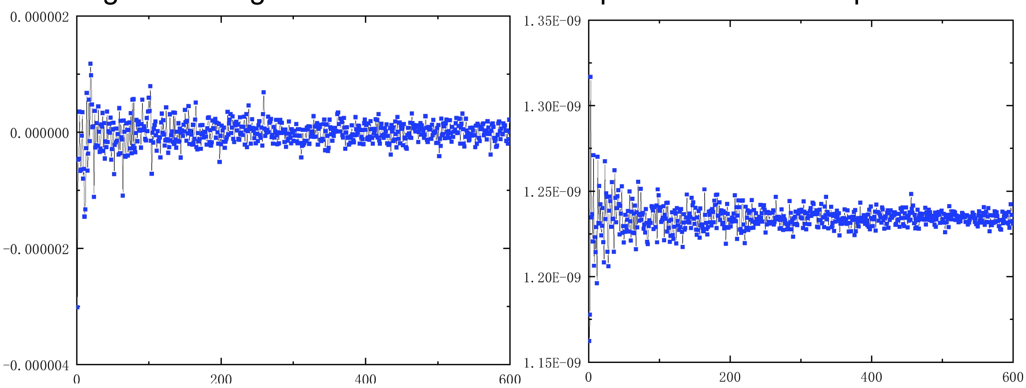

Figure 11 - Diagram of I-cleaner first-order impact index and total impact index

5.2 Generation of Matrix for Sensitivity Analysis

After determining the number of safety influencing factors D , their range of values and the number of sample points N , a $N*2D$ sample matrix M is generated (referred to in this article as $900000*8$). Set the first 4 columns of the matrix M as the matrix A and the last 4 columns as the matrix B , and the resulting matrix A , B is the sample matrix. Then replace the column i of the matrix B with the column i of the matrix A to construct the $N*D$ sample transformation matrix AB^i ($i=1,2,3,\cdots D$). At this point, six matrices A , B , AB^1 , AB^2 , AB^3 and AB^4 were constructed, resulting in $N*(D+2)$ which is 5400000 sets of input data X_1 , X_2 , X_3 , X_4 , corresponding to 5400000 sets of Y value data and six response value matrices Y_A , Y_B , Y_{AB^1} , Y_{AB^2} , Y_{AB^3} , Y_{AB^4} .

5.3 Generation of Index for Sensitivity Analysis

In the previous section, six response value matrices Y_A , Y_B , Y_{AB^1} , Y_{AB^2} , Y_{AB^3} , Y_{AB^4} were obtained. Calculate the first-order impact index and total impact index of each safety influencing factor according to the formula.

The formula for the first-order impact index is:

$$S_i = \frac{Var_{x_i}(E_{x_i}(Y \mid X_i))}{Var(Y)} \tag{14}$$

The formula for the total impact index is:

$$S_{Ti} = \frac{E_{x_i}(Var_{x_i}(Y \mid X_i))}{Var(Y)} \tag{15}$$

Among that:

$$Var_{x_i}(E_{x_i}(Y \mid X_i)) \approx \frac{1}{N}\sum_{j=1}^{N} f(B)_j * (f(AB^i)_j - f(A)_j) \tag{16}$$

$$E_{x_i}(Var_{x_i}(Y \mid X_i)) \approx \frac{1}{2N}\sum_{j=1}^{N} (f(A)_j - f(AB^i)_j^2) \tag{17}$$

Therefore,the first-order impact index and the total impact index are shown in the Table 3.

Table 3 - The significance level of safety influencing factors

	Altitude	Int-valve	Exh-valve	L-Cleaner
First-order impact index	1.0041	2.5749e-05	5.3312e-06	5.4342e-10
Total impact index	1.0012	4.1750e-06	1.0788e-06	1.2311e-09

The first-order impact index and total impact index of altitude are much higher than other factors. During the actual running environment of the engine, it is necessary to select appropriate flight space according to the running objectives to avoid performance fluctuations or even engine failure caused by the high sensitivity of the engine to altitude. The sensitivity level of the engine turbocharging system to the diameter of the intake valve and the diameter of the exhaust valve is similar, both in the range of 10^{-5} to 10^{-6} , but the sensitivity level to the diameter of the intake valve is still significantly higher than that to the diameter of the exhaust valve. Under normal running conditions, the effective length of the air filter has almost no effect on the engine turbocharging system, and the first-order impact index and total impact index are much lower than the other three safety factors.

6. Conclusion

This paper proposes a model-based safety assessment process and an efficient sensitivity analysis method for turbocharging systems, and constructs a quasi-dimensional model of the entire two-stage turbocharging aviation reciprocating engine. By using Response Surface Methodology to establish a safety influencing factor surrogate model and using Sobol factor analysis method to calculate the sensitivity of the engine turbocharging system to safety influencing factors, the following conclusions are drawn.

1.Aircraft engines can apply the "V" type safety analysis process and integrate the model into the analysis process during the PSSA stage to achieve model-based system safety analysis.

2.A system model of a two-stage turbocharging aviation reciprocating engine was established as a quasi-dimensional model, referring to the performance parameters, structural parameters, and matching principles of the actual model.

3.Design response experiments using response surface analysis method, establish a four factor proxy model for safety impact, and use it as an important basis for sensitivity analysis.

4.Sensitivity analysis was conducted using the Sobol factor analysis method, and it was found that the sensitivity index of altitude was much higher than other factors. The sensitivity index of intake valve diameter was higher than that of exhaust valve diameter, but in terms of magnitude, it was similar. Under normal running conditions, the effective length of the air filter had almost no effect on the engine turbocharging system.

During actual flight, the range of changes in safety influencing factors can be adjusted based on the above conclusions to reduce the uncertainty of key factors, thus conducting efficient and intuitive safety analysis.

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9. Copyright Statement

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