Analysis of the Fan Performance in the Turbofan Engine Test

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Abstract. The fan was tested in the whole turbofan engine test condition, and the post-processing of the test data was based on confidence intervals. Through the analysis of distribution characteristics of data, the indirect measurement parameters such as mass flow rate and pressure ratio, which are affected by multiple factors, all obey the normal distribution. Based on the distribution characteristics, a statistic can be constructed to calculate the confidence intervals for these parameters. It is known that the more data, the smaller the confidence interval of the parameters. As a result, it is found that the range of confidence intervals obtained from the final test data is so narrow that point estimates could be used instead of interval estimates. Comparing the test results with the numerical calculation results, the test results are in good agreement with the calculated performance curves. The processed test results show that as the area of bypass(core) throat area decreases, the fan working line will move to the the direction of reduced flow rate. However, that is not absolute. If the area is beyond a certain range of the area, the working line may move in the opposite direction. The effect of throat area variation on the performance of the fan may be related to flow state of the core and bypass. Therefore, multiple adjustments are required to match the design point.

1. Introduction
The fan is one of the main core components of the turbofan engine. The performance of the fan under different working conditions has a direct impact on the whole aero-engine [1][2]. Because fans and compressors have unstable working boundaries such as stall, surge, and choke, the working line of the engine is often plotted on the characteristics diagram of fans and compressors. Through the analysis of the working line in the fan characteristic diagram, the corresponding state variation of the engine can be identified.

Test research is an essential part of the fan/compressor research work. Through test, it is not only possible to verify the accuracy of the computational fluid software for compressor simulation, but also to verify the performance and reliability of the designed fan/compressor. And it provides powerful help for adjustment and improvement of design methods. In the development of modern turbofan engines, most of the performance parameters tested are based on full-size compression components. The test is usually carried out on the single-shaft no-bypass compressor test rig and single-shaft bypass compressor test rig [3-6]. And there are few studies on fan performance test under the condition of the whole aero-engine. Under the condition of the whole engine, the fan characteristics can be tested to obtain the
working line of the fan under different working conditions, which has a very good guiding significance for practical application.

Post-processing of test results is important for the test to get useful information. Statistical analysis of test data is an important means of post-processing of experimental data. Point estimation and interval estimation are two methods for estimating the overall population. Generally, point estimation is used to approximate the mean and variance of the population. Sometimes in order to know the deviation between the estimated value and the true value, interval estimation is often used. And at the same time, the reliability of the estimation can be known. That is, using a number that has a significant meaning to indicate the degree of certainty that the unknown population parameter falls within a certain range, which is a direct and meaningful display of the measurement result in engineering.

2. Test Rig
The test was conducted at the ground test bed of the small aircraft engine laboratory of Beihang University.

2.1. Test Object
The test object is a prototype of a single-axis turbofan engine modified from a turbojet engine. The simplified structure diagram of the modified prototype is shown in the figure 1. The engine is mainly composed of a fan, a centrifugal compressor, a combustor, and a turbine. Except for the redesign of the fan, the other components retain the original turbojet design. Centrifugal compressors consist of an inducer, a centrifugal impeller, a radial diffuser, and an axial diffuser, wherein the inducer and the centrifugal impeller are assembled into one assembly using pins. The combustion chamber is a slinger combustor with fuel supply from the fuel slinger. The turbine is a single-stage axial flow turbine.

![Figure 1. Test turbofan engine structure diagram](image)

2.2. Measurement System
The measurement system adopts self-developed software and hardware measurement and control systems, including Beijing Kunlun Coast JQYB atmospheric pressure transmitter, Beijing Kunlun Coast JWSL-2 wall-mounted temperature and humidity transmitter, total pressure comb, Beijing Kunlun Coast JYB-KO -HVG type pressure sensor, T thermocouple, Advantech ADAM-4117 analog input module, Advantech ADAM-4118 thermocouple input module, serial device server, acquisition computer. The acquisition software is based on LabVIEW and can be used to display fan performance in real time.

2.3. Fan and Performance Measurements.
The fan is designed as a forward swept rotor blade, and its three-dimensional blade characteristics with forward swept near tip portion and back swept near root portion. And controlled diffusion airfoils is adopted near-root portion. It means to increase the fan margin by these means. Design rotation speed is 22000r/min, mass flow rate 22kg/sec, pressure ratio 1.63.

The measuring points of the fan performance are divided 4 sections [7], including the atmospheric pressure and temperature of the test room; section 0: the static pressure of the inlet of the engine; section
2: the total temperature, total pressure, and static pressure behind the fan stator; Section 16: total temperature, total pressure, and static pressure in the bypass.

Figure 2. Test section position

3. Data Processing

3.1. Performance Parameter Calculation
The mass flow rate of the fan are based on the formula as follow.

\[ G = K \frac{p^*}{\sqrt{T^*}} q(\lambda) A \]  

(1)

The parameters in the formula can be calculated by the parameters measured and the flow coefficient of the flow tube considering the boundary layer effect is introduced. The calculation relationship between the flow rate and the measurement parameters will be obtained (the subscript means the section number.):

\[ G_0 = K_c \times K \times A_b \times \frac{P_0^*}{\sqrt{P_0^*}} \times \left( \frac{k + 1}{2} \right)^{\frac{1}{2}} \times \left( \frac{k + 1}{k - 1} \right)^{\frac{1}{2}} \times \left[ \left( \frac{P_0^*}{P_0^*} \right)^{\frac{2}{2}} \right] \]  

(2)

The pressure ratio adopts the total-to-total pressure ratio:

\[ \pi^* = \frac{P^*_2}{P^*_0} \]  

(3)

In order to facilitate the practical application, the measurement parameters are often converted to the standard atmospheric environment. And the calculation method of the corrected parameters is introduced in the Aero-engine Principles, which are not listed here in detail.

3.2. Data Selection
According to GJB 241A-2010, "General Specification for Aviation Turbojet and Turbofan Engines" [8], the measurement error of the rotating speed is required to be no more than 0.2% of the maximum speed. Therefore, if the speed deviation is within 0.2%, it can be considered that the data is in the same rotation speed state. If the data exceeds the range, the data will be deleted. Similarly, GJB 241A-2010 stipulates that the test error of the mass flow rate is no more than 0.5%, and the same selection process is performed on the flow rate and the rotation speed. The selection is based on the mean value, and the data exceeding the positive and negative deviation ranges are deleted. Therefore, the data selection process has less influence on the sample mean value.

3.3. Confidence Interval Analysis
During the processing of the test data, the difference of test results and design results were analyzed by calculating the confidence intervals of the mean values. Interval estimation generally needs to know the distribution of a certain statistics related to the estimated parameter.
Normal distribution is one of the most common distributions. Therefore, comparing between the distribution of the test data and normal distribution is performed. For the case that the sample obeys the normal distribution, if the population variance is unknown, the statistics as follow can be constructed to estimate population mean:

\[ T = \frac{\bar{x} - \mu}{s / \sqrt{n}} \]  

(4)

It follows the t-distribution with a n-1 degree of freedom, so the confidence interval of \( \mu \) can be calculated as follows:

\[ \left[ \bar{x} - t_{1-\alpha/2} (n-1) \frac{s}{\sqrt{n}}, \bar{x} - t_{1-\alpha/2} (n-1) + \frac{s}{\sqrt{n}} \right] \]  

(5)

The degree of confidence is 1-\( \alpha \). And \( t_{1-\alpha/2} \) can be found by searching for the t-distribution table.

4. Results and Analysis

4.1. Test Results and Distribution Characteristics

During the test, the control of the rotation speed is controlled by the physical rotation speed at low rotation speed, and the corrected rotation speed control is adopted at medium and high rotation speed (above 80% rotation speed). The figure 3 shows the scatter plots of the original test data for different test condition. Each data distribution is concentrated. The performance in the test are close to the calculation value at medium and high speeds. The reason that the data point does not fit the calculation curve at low speed is the deviation caused by the difference between the physical speed and the corrected speed.

Figure 3. Flow-pressure ratio characteristic scatter distribution of the test results

Before calculating the confidence interval, the distribution of the calculation parameters (flow and pressure ratio) needs to be determined. After that, the data needs to be selected. Therefore, the distribution of the raw data and the data after the speed and flow selection are analyzed.

Before data selection, the distribution of the parameters is shown in the figure 4-6.
From the above figures, it can be seen that the mass flow rate and pressure ratio at different rotation speeds obtained in the test are in good agreement with the normal distribution to some extent, and the deviation is not significant. The reason for the deviation may be that the amount of data is less, which cause the insufficient randomness. Normally the data obeying normal distribution is from a system influenced by a number of mutually independent factors. The aeroengine test is affected by a variety of factors, and their relationship is generally independent of each other, such as the clearance and test environment, and the geometric outlet area. And the engine itself can be classified as a modular product, so it can explain the normality of its test results.

Because the engine itself is in a relatively strong vibration state, the parameter change is likely to exceed the allowable range of the corresponding error. At the same time, the accuracy of the test is not
high enough, and it may cause an ultra-bad influence. Therefore, in order to further process the data, it is necessary to analyze the distribution of the data after the speed and mass flow rate selection.

**Figure 7.** Flow and pressure ratio distribution characteristics in low speed of processed data

**Figure 8.** Flow and pressure ratio distribution characteristics in medium speed of processed data

**Figure 9.** Flow and pressure ratio distribution characteristics in high speed of processed data

From the results after the selection, it can be seen that the distribution characteristics of the test results are not destroyed after the data that exceeds the deviation from the mean values are filtered out. This can be explained by the fact that due to the random distribution of the parameters (flow, pressure ratio), the amount of data that exceeds the positive and negative deviations of the speed and flow is equal. Therefore, deleting the data means that the range of the data is reduced, and it does not affect the overall distribution and the statistical parameters such as mean and variance.
4.2. Test Data Confidence Interval

After the data was selected, confidence intervals were calculated for the new data. The confidence level was chosen to be 98%, and the difference between the confidence interval and the mean value was taken as the deviation value. The flow rate and pressure ratio deviation at different rotational speeds were given in Table 1 and Table 2.

It can be seen from Table 1 and Table 2 that the relative value of the deviation is small. And the relative deviation of flow rate and pressure ratio is less than 0.1%. The following figure 10-11 shows the distribution of confidence intervals at 95%, 90%, 85%, and 80% rotation speeds. It can also be seen in the figure that the relative deviation is small and can only be discerned in the partial enlargement diagram of the characteristic line. Therefore, replacing interval estimates with point estimates is reasonable. On the other hand, it can be seen from Figure 10 and Figure 11 that the confidence interval is included in the calculation performance curve (Dashed line represents upper and lower limits). The upper and lower limit is calculated by the calculation performance and its deviation, mass flow rate by 0.5% and pressure ratio by 0.5% (based on deviation of the pressure). Though there are still points out of range marked in the figure, it can be concluded that the test and calculated values are well-conformed. The points out of range may caused by different tip clearance or larger rotation speed deviation.

Table 1. Mean and Confidence Deviations of Flow at Different Speeds
(N-rotation speed; MV-mean value; DAV-deviation absolute value; DEV-deviation relative value)

| N% | 48  | 60  | 70  | 80  | 85  | 90  | 95  |
|----|-----|-----|-----|-----|-----|-----|-----|
| MV(kg/s) | 9.57 | 11.82 | 14.10 | 16.74 | 18.30 | 19.78 | 21.21 |
| DAV(kg/s) | 0.00303 | 0.00891 | 0.01863 | 0.00601 | 0.00825 | 0.01088 | 0.01174 |
| DEV% | 0.03162 | 0.07537 | 0.13212 | 0.03591 | 0.04509 | 0.05500 | 0.05534 |

Table 2. Mean and Confidence Deviations of Pressure ratio at Different Speeds

| N% | 48  | 60  | 70  | 80  | 85  | 90  | 95  |
|----|-----|-----|-----|-----|-----|-----|-----|
| MV | 1.13 | 1.20 | 1.29 | 1.37 | 1.43 | 1.49 | 1.54 |
| DAV | 0.00021 | 0.00059 | 0.00099 | 0.00048 | 0.00052 | 0.00072 | 0.00096 |
| DEV% | 0.01876 | 0.04932 | 0.07701 | 0.03494 | 0.03642 | 0.04853 | 0.06247 |

Figure 10. 80% and 85% speed flow-pressure ratio confidence interval distribution
4.3. Fan Working Line by Processed Data

After the data selection and replacing interval estimates with point estimates, and the working line in different core and bypass throat area can be given as figure 12. The legend shows the diameter of the core nozzle (mm)/the diameter of the bypass nozzle (mm).

From the above figure, we can see that when determining the core throat area and reducing the bypass nozzle equivalent diameter from the 600.7mm to 598.4mm and to 596mm, the working line move to the left, where the flow rate decreases. And then reduced the diameter to 595.8mm, the working line move to the opposite direction. Similarly, when determining the bypass throat area and reducing the core nozzle equivalent diameter, similar things will happen. The working line will move to left first and turn to right then. But it can be seen that although the change exists, the effect is not obvious. Changing the area of core area has less impact on the working line, whereas the bypass area has a greater impact on the characteristic line. It is expected that as the area of bypass (core) throat area decreases, the fan working line will move to the direction of reduced flow rate. But the actual situation seems far from that. This may depend on whether the flow state of core and bypass is blockage and choked, or it is in a better flow state. If the blockage and choked happens, the situation will occur that the working move to unexpected direction. In general, the reason is that the core and bypass do not match. For the fan of turbofan engine, the core and bypass always interact with each other. The above figure shows that adjusting the nozzle area requires repeated adjustments before it can finally match the design operating point.
5. Conclusion
This article analyzes the performance parameters such as flow and pressure ratio obtained by the fan test in the environment of the whole aero-engine. The conclusion can be summarized as follows.
1. For the fan test performance, the indirect measurement parameters such as flow rate and pressure ratio obey the normal distribution.
2. Due to the large amount of data, the range of confidence intervals will be so narrow that point estimates can be used instead of interval estimates.
3. The test data and the calculation performance are basically consistent.
4. When adjusting the area of the core and bypass throat, the working line dose not always move in one direction, which depends on the match of the core and bypass. So it is necessary to make repeated adjustments to match the design state.

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