Rapid Prediction Method of Fan Broadband Noise Based on A Three-dimensional Sound Source Model

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Abstract. The fan/compressor broadband noise is an important noise source of civil large bypass ratio turbofan engine. The empirical method requires massive amounts of test data for support. Adopting the computational aeroacoustic (CAA) method to predict the fan/compressor broadband noise will cost high amounts of computing resources or time. Thus, this study combines flow field calculation with analytical model to study the prediction method of fan/compressor broadband noise, this method can be used for quick and efficient preliminary evaluation and parameter studies. On the basis of the simulation and modeling of the stator – rotor interference phenomenon of fans, rotor wake flow field and the corresponding parameters are obtained. On this basis, the three-dimensional sound source model is used to calculate the blade surface sound source and its propagation under different working conditions. The distribution of sound energy in the duct is obtained. Then, the broadband noise prediction of fan is further acquired. The broadband noise of a typical single-stage TA36 fan is predicted using this method. Study results suggest that (1) turbulence model and turbulence kinetic energy of inlet boundary condition will have an important effect on the prediction results of broadband noise. (2) When the inlet turbulence kinetic energy is small, different turbulence models slightly influence the prediction results of broadband noise; when the inlet turbulence kinetic energy is large, the sound pressure level of sound field obtained by SST model is approximately 5dB larger than that obtained by model. This method can be used in the early stage of fan/compressor design, and the characteristics of blade broadband noise can be rapidly obtained.

1. Introduction

The noise problem always exists in the development of human society. Acoustic phenomena are also encountered in people’s daily lives. Acoustic technology is widely used in the field of natural science and engineering[1-6]. With the increase in people’s disposable income, traveling by air has become increasingly popular. This situation brings a strong development vitality to the civil aviation transportation industry. Therefore, the noise problem has gradually attracted people’s attention.

Jet noise dominates in early turbojet engines. Jet speed decreases with the increase in bypass ratio. Given that the intensity of jet noise is directly proportional to jet speed to the power of 8, the proportion of jet noise in the total noise level of engine gradually decreases. With the increase in
bypass ratio, the proportion of fan/compressor noise becomes increasingly large and becomes an important noise source[7-8]. This situation makes the generation and propagation of fan/compressor noise become one of the main problems in the study of aeroacoustics[9].

The broadband noise of fan is generated from the interaction between nonperiodic air flow and solid surface. According to different generation mechanisms, it is classified as rotor self noise, secondary flow interference noise, and turbulence wake and stator interference noise[10]. Two prediction methods can be used. The first one is the CAA method. According to different calculation modes, it can be divided into hybrid and direct computational methods. In 2005, by using a hybrid computational method, Jacob[11] first obtained the flow field information of cylinder-wing section interference problem through CFD and then acquired its sound field distribution by using the FW-H equation. This hybrid computational method overcomes too much simplification of the semiempirical formula. However, it cannot solve many blade rows. In 2012, Tam & Ju[12] directly numerically simulated wing section turbulence problems by using high-precision CAA method. This direct computational method is not simplified. It is helpful for understanding the mechanism and propagation law of fan noise. However, its computational amount is too much to be used in engineering research at this moment.

The second is to use analytic model. In 1971, Mani[13] and Amiet[14] studied the noise problem of the interference between turbulence and isolated blade and proposed a general idea of establishing a broadband noise sound source model. The response function of the blade was first established to solve the unsteady force on the surface of blade produced by the upwash speed and then to solve the sound field in the duct caused by the unsteady force. On the basis of this idea, Glegg[15] grafted the response function of blade proposed by the former onto the broadband interference noise of fans and achieved a good result in 1998. On this basis, Hanson[16] considered the effects of the nonuniformity of turbulence and swept-curved blade on broadband noise in 2001. In 2002, Evers and Peake[17] established another fan broadband interference noise model by using the response function of blade row developed by Peake and studied the effects of blade shape and nonuniform mainstream. They proved that the blade thickness and small curvature slightly contribute to the broadband noise in high-frequency range. In 2005, Nallasamy[18] improved the fan broadband noise program developed by Ventres and regarded the turbulence flow obtained by the Reynolds average NS equation as the input, including the effects of background turbulence intensity and rotor wake turbulence. In 2011, Grace[19] studied the effects of turbulence model selection, radial wave number, integral scale, and other parameters on fan broadband interference noise. The prediction program of RSI fan broadband noise developed by NASA based on Nallasamy method has achieved a good result, but most of the current prediction models of fan broadband noise still simplify the blade into a two-dimensional rectangular plate and cannot consider the effects of geometric blade parameters. Atassi[20-21] extended the response function of the three-dimensional annular cascade developed by himself to the prediction of broadband noise and proved that the three-dimensional and swirl effects considerably influence the prediction result. However, solving the blade response function at each frequency and wave number by using numerical method will lead to a huge amount of computation.

In summary, the fan/compressor broadband noise is an important component of aeroengine noise, and the proportion is still increasing. Although the prediction method of two-dimensional rectangular plate has achieved some results in the prediction of fan/compressor broadband noise, the three-dimensional geometric effect greatly influences the noise prediction result. Input conditions for the sound propagation design should be provided by noise prediction. The denoise effect will be reduced if the sound propagation design of the sound source is ignored. Zhang Weiguang [22] proposed 3D sound source model, in the algorithm benchmark test, compared with other broadband noise prediction algorithms[21], [23], error is less than 2 dB. Compared with the experimental results, it is also proved that this is a successful broadband noise prediction model. However, the stream input mainly depends on the test data. This increases the overall prediction cycle. CFD computation can rapidly capture the flow field information and can therefore compensate for the shortcomings of the above-mentioned method. By combining the advantages of both methods, the rapid prediction method
for the three-dimensional fan/compressor broadband noise established by using CFD rotor wake as the input can further shorten the period and cost of noise prediction. Accordingly, its generation mechanism and denoise method can be studied.

In this work, NUMECA software is used to simulate the flow field of BUAA TA36 single-stage low-speed axial fan. The parameters required by the broadband noise prediction can be obtained by modeling the flow field result. The three-dimensional fan sound source model developed by Zhang Weiguang is used to solve the distribution of the sound pressure level in the duct at different frequencies, and the prediction result of broadband noise is obtained.

2. Broadband noise model

2.1. Nomenclature

- $\omega$: frequency
- $V$: blade number of stator
- $\rho_0$: air density
- $U$: front axial mainstream velocity of fan rotor
- $m$: circumferential mode
- $n$: radial mode
- $k_{mn}$: eigenvalues of $(m,n)$ mode
- $\psi(k_{mn}r)$: characteristic function of normalized $(m,n)$ order duct
- $k$: wave number
- $M$: Mach number of uniform flow in the main stream inside the duct
- $\mathfrak{Z}(\vec{K}, r', z')$: unsteady load on the blade surface produced by the unit of upwash disturbance $e^{ik_{mn} \cdot s}$ with the wave number of $\vec{K}$
- $\langle W^* \cdot W \rangle$: upwash velocity spectrum

2.2. Broadband noise model

The general expression of the sound power of fan broadband noise in Zhang Weiguang’s three-dimensional sound source model is

$$P_\alpha \pm = \frac{\omega V^2}{2\pi \rho_0 U} \sum_{s=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \left[ \frac{m^2}{4\kappa_{n,m}} \left( \frac{\beta^2 M}{\pm M \kappa_{n,m} - k_0} \right)^2 \right]$$

$$\int \int \int \mathfrak{Z}(\vec{K}, r', z') \mathfrak{Z}^*(\vec{K}, r'_2, z'_2) \psi(k_{mn} r'_1) e^{-i\alpha_1 z'_1} \psi(k_{mn} r'_2) e^{i\alpha_1 z'_2}$$

$$\langle W^* \cdot W \rangle d\vec{K} d\vec{k} \cdot ds_1 ds_2$$

(1)

The prediction of broadband noise ensures that the rotor wake turbulence acts on the stator blade to produce sound. Therefore, the upwash velocity spectrum $\langle W^* \cdot W \rangle$ is important. Its expression is
\[
\left\{ W^* (\overline{K}, \omega, r_j) \cdot W (\overline{k}, \omega', r_j) \right\}_{uu} - \left\{ W^* (\overline{K}, \omega, r_j) \cdot W (\overline{k}, \omega', r_j) \right\}_{uu} \\
+ \left\{ W^* (\overline{K}, \omega, r_j) \cdot W (\overline{k}, \omega', r_j) \right\}_{bb}
\]

where

\[
\left\{ W^* (\overline{K}, \omega, r_j) \cdot W (\overline{k}, \omega', r_j) \right\}_{uu} = \frac{(N_g L u'_w)^2}{2\pi \overline{r}} \sum_{m_n} \sum_{n_r} \sum \pi \delta \left( \omega - \overline{k} \cdot \overline{U} \right) \delta \left( \omega' - \omega - \Omega (m_n) \right) \\
e^{-\frac{1}{2}(m_n)^2} \cdot \Phi \left( \overline{k} - \frac{m_n}{\overline{r}} n_1, \Delta r \right) \\
\delta \left( k_2 - \frac{\pi n_g}{r_j - r_i} \right) \delta \left( k_1 - \frac{m_n + m_b}{\overline{r}} \right)
\]

\[
\left\{ W^* (\overline{K}, \omega, r_j) \cdot W (\overline{k}, \omega', r_j) \right\}_{bb} = \frac{(N_g L u'_w)^2}{2\pi \overline{r}} \sum_{m_n} \sum_{n_r} \sum \pi \delta \left( \omega - \overline{k} \cdot \overline{U} \right) \delta \left( \omega' - \omega - \Omega (m_n) \right) \\
e^{-\frac{1}{2}(m_n)^2} \cdot \Phi \left( \overline{k} - \frac{m_n}{\overline{r}} n_1, \Delta r \right) \\
\delta \left( k_2 - \frac{\pi n_g}{r_j - r_i} \right) \delta \left( k_1 - \frac{m_n + m_b}{\overline{r}} \right)
\]

The solution of the sound power in this model is to integrate along the whole stator blade rather than to stack the sound power on each rectangular cascade similar to the two-dimensional strip theory. At the same time, the acoustic radiation problem in the circular duct is solved on the basis of acoustic analogy theory. Strip theory is still adopted to solve unsteady load on the stator blade, but the unsteady load is solved in the radial and chord directions at the same time on the whole stator blade. Therefore,
radial influence can be considered. The influence of swept-curved blade design on noise can be also considered.

3. Numerical simulation of rotor wake

3.1. TA36 fan/compressor test bench

In this section, rotor wake will be calculated by means of BUAA TA36 single-stage low-speed axial fan test bench. This test bench is shown in Fig. 1. It mainly consists of three parts, namely, air inlet, a row of rotor blades, and a row of stator blades. The main design parameters of TA36 are shown in Tables 1 and 2.

![Figure 1. TA36 compressor test bench.](image)

### Table 1. Geometric parameters of TA36 compressor test bench

| Geometric parameters        | Rotor | Stator |
|----------------------------|-------|--------|
| Blade number               | 20    | 27     |
| Aspect ratio               | 1.18  | 1.40   |
| Tip clearance (mm)         | 0.6   | 0.5    |
| Case diameter (mm)         | 600   | 600    |
| Hub diameter (mm)          | 346   | 401    |
| Installation angle of hub position (°) | 45   | 0      |

### Table 2. Aerodynamic parameters of TA36 compressor test bench

| Aerodynamic parameters     |       |
|----------------------------|-------|
| Design rotation rate (rpm) | 2930  |
| Design point-mass flow (kg/s) | 6.5  |
| Overall pressure ratio     | 1.026 |
| Efficiency                 | 85%   |

3.2. Calculation method of three-dimensional fan rotor wake

In this section, a commercial software called NUMECA is used to calculate the flow field of TA36 three-dimensional fan. The result is compared with the experimental result of its efficiency characteristic line, and the reliability of the rotor–stator interference calculation result is proven. Accordingly, the wake modeling can be prepared and the input parameters of the fan noise prediction program can be extracted in the next step.

NUMECA has high-quality automatic grid division, impeller machine design, and other modules. Given its simple operation, good stability, fast calculation, and good convergence, it is suitable for three-dimensional fan blade calculation. The second chapter that we only have to solve the RANS equation based on the statistical mean of turbulence. In this case, the wake produced from the whole
row of rotor blades can be regarded as the rotational symmetry of the wake generated by a single blade channel in the circumferential direction. Therefore, only single-channel steady calculation is needed for the TA36 three-dimensional blade, which can reduce huge computational amount.

The turbulent kinetic energy is essential for the prediction of fan broadband noise. Thus, a turbulence model with good stability and convergence, as well the calculation results including the turbulent kinetic energy, should be considered. In this work, two turbulence models are selected, namely, $k-\varepsilon$ model and SST model.

### 3.2.1 Grid generation

The IGG-Autogrid module in NUMECA is used to generate the grid of the three-dimensional TA36 blade. The final result is shown in Fig. 2. The total number of grids is approximately 2.66 million.

Notably, different from the conventional flow field for solving the mainstream velocity, the turbulent kinetic energy may decay exponentially to a small amount approaching zero as the axial distance increases. The main reason is the large grid spacing. If so, when the turbulence parameters are solved in accordance with the turbulence kinetic energy, the background turbulence intensity in turbulence input parameters is nearly zero, and the three other turbulence parameters seriously deviate. The axial grids should be properly encrypted to avoid such phenomenon, and appropriate numerical settings should be used in FINE solution module. The topology of the rotor grid is shown in Fig. 3. The number of grids is approximately 1.51 million. The topology of the stator grid is shown in Fig. 4. The number of grids is nearly 0.75 million.

![Figure 2. TA36 calculation grid](image)

![Figure 3. Topology of the rotor grid](image)

![Figure 4. Topology of the stator grid](image)

### 3.2.2 Boundary condition setting

After grid division is completed, the inlet and outlet parameters are set in accordance with the test conditions. The inlet boundary conditions are set as the total pressure, axial intake, and deflection
angle 0; the outlet boundary conditions are set as static parameters; and the static pressure is set at the height of 1/2 blade on the basis of the radial balance equation. To verify the prediction ability of the three-dimensional fan broadband noise prediction program under multiple working conditions, four characteristic lines corresponding to 100%, 90%, 80%, and 70% of rotation rate should be calculated. In accordance with the conditions of characteristic line, the rotation rates are set to 2915, 2624, 2332, and 2041 rpm.

Notably, the turbulence model is $k-\varepsilon$ model or SST model. Thus, the turbulence kinetic energy should be given in the inlet boundary conditions. The intake air in the TA36 single-stage fan test bench is uniform, and the turbulence intensity at the inlet is very small. It is set on the basis of the default value $k = 5$.

The turbulent kinetic energy determines the turbulent fluctuation velocity but is still smaller than the mainstream velocity. Thus, the setting of the inlet turbulent kinetic energy does not affect the mainstream velocity and compressor efficiency.

### 3.2.3 Calculation results

The compressor has a corresponding characteristic line at each rotation rate. The abscissa is the flow, and the ordinate is the efficiency. In this example, the change in the blade load is simulated by changing the static pressure at the outlet continuously, to obtain the flow-efficiency characteristic line at each rotation rate.

The characteristic line diagram calculated by NUMECA should be compared with the test results to verify the reliability of the CFD rotor-stator interference calculation. Figs. 5–8 show the flow-efficiency characteristic line diagrams of TA36 compressor at 70%, 80%, 90%, and 100% rotation rates. The red lines represent the results calculated by NUMECA, and the green lines represent the test results. The figures show that the calculated results of the flow field at four rotation rates are same as the test results. This similarity shows that the CFD calculation results are reliable.

However, further improvements are required. At the peak of four rotation rates, the calculated results are larger than the test results. The main reasons for this difference include the following: 1) The measurement point of the outlet static pressure is on the duct wall, and the calculated outlet static pressure is 1/2 of the blade height. Thus, using the static pressure measured on the wall as the outlet boundary condition for calculation will cause differences between the calculated and test boundary conditions. Finally, it leads to the difference in efficiency. 2) TA36 test bench has been used for more than 15 years. The slight difference between the tip clearance in operation and the designed value will lead to the difference in efficiency.

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**Fig. 5** Comparison result of 70% speed efficiency characteristic lines

**Fig. 6** Comparison result of 80% speed efficiency characteristic lines
4. Rotor wake parameter modeling

4.1. Modeling method

After rotor wake turbulence fluctuation is obtained using CFD, the flow field information cannot be directly used in the broadband noise prediction. Fig. 9 shows the schematic of the change in the two-dimensional plane cascade rotor/stator coordinates. Four turbulence input parameters are required by the fan broadband noise prediction program: turbulence integral scale $\Lambda$, background turbulence intensity $u'_{b}$, central line turbulence intensity $u'_{w}$, and turbulence width $L_{w}$. Except for integral scale $\Lambda$, the three other variables are determined by turbulence fluctuation speed directly.

The turbulence flow has Gaussian distribution. Background turbulence intensity $u'_{b}$ is the minimum value of Gaussian distribution; central line turbulence intensity $u'_{w}$ is the difference between the maximum and minimum values of Gaussian distribution; and turbulence width $L_{w}$ is the width of Gaussian distribution at semicentral line intensity $u'_{b} + \frac{u'_{w}}{2}$.

![Fig. 9 Rotor/stator coordinate transformation diagram](image-url)
Based on the isotropic turbulence hypothesis, the relationship between turbulence fluctuation velocity and turbulence kinetic energy is

\[ u'_{\text{RANS}} = \sqrt{\frac{2}{3} k_{\text{RANS}}} \]  \hspace{1cm} (6)

where \( k_{\text{RANS}} \) refers to the turbulence kinetic energy solved using the RANS equation in NUMECA and \( u'_{\text{RANS}} \) refers to the turbulence fluctuation velocity.

If the turbulence kinetic energy in rotor wake is calculated by means of \( k - \varepsilon \) model, then integral scale \( \Lambda \) can be obtained from Eq. (7):

\[ \Lambda = C_\varepsilon \frac{k_{\text{RANS}}^{\frac{3}{7}}}{\varepsilon} \]  \hspace{1cm} (7)

where \( C_\varepsilon = 1 \) and \( \varepsilon \) refers to the dissipation factor. Then, the integral scale \( \Lambda \) from \( k - \varepsilon \) is

\[ \Lambda = \frac{k_{\text{RANS}}^{\frac{1}{7}}}{\varepsilon} \]  \hspace{1cm} (8)

If the turbulence kinetic energy in rotor wake is calculated using SST model, which is transformed from \( k - \omega \) model, then the following can be obtained:

\[ \varepsilon = 0.09 k_{\text{RANS}} \omega \]  \hspace{1cm} (9)

After substituting Formula (9) into Formula (8), the expression of integral scale corresponded by SST model is

\[ \Lambda = \frac{k_{\text{RANS}}^{\frac{1}{7}}}{0.09 \omega} \]  \hspace{1cm} (10)

So far, the four turbulence parameters of the two turbulence models have been modeled, and the CFD wake can be transformed into the input parameters of the three-dimensional fan broadband noise prediction program through this transformation relationship.

4.2. TA36 rotor wake modeling result

The actual working condition of the fan is complex and diverse. The rotation speed, the inlet-to-outlet pressure ratio, and the inlet distortion will cause different working conditions, which will lead to the changes in the rotor wake flow field. In this work, the fan rotor wake flow field at 70%, 80%, 90%, and 100% rotation velocities is calculated with the working condition for the maximum fan efficiency as the reference.

After acquiring the flow field information of rotor wake by CFD method, turbulence integral scale, background turbulence intensity, and central line turbulence intensity and turbulence width can be obtained on the basis of Eqs. (6), (8), and (10). Geometric and mainstream parameters can be obtained directly from TA36 blade information and flow field information.

On the basis of the selection of the turbulence kinetic energy and turbulence model, the turbulence parameters of the rotor wake are as follows. Tables 3 and 4 show the rotor wake turbulence parameters of SST and \( k - \varepsilon \) models at the inlet turbulence kinetic energy \( k = 5 \text{kg} \cdot \text{m} / \text{s}^2 \); Tables 5 and 6 show the rotor wake turbulence parameters of SST and \( k - \varepsilon \) models at the inlet turbulence kinetic energy \( k = 50 \text{kg} \cdot \text{m} / \text{s}^2 \).

**Table 3** Rotor turbulence parameter of the inlet turbulent energy \( k = 5 \text{kg} \cdot \text{m} / \text{s}^2 \) by SST model
### Table 4 Rotor turbulence parameter of the inlet turbulent energy $k = 5\text{kg} \cdot \text{m} / \text{s}^2$ by $k-\varepsilon$ model

| Rpm/ (rpm) | Ma   | $L_w / m$ | $u'_w / (\text{m/s})$ | $u'_b / (\text{m/s})$ | $\Lambda (m)$ |
|------------|------|-----------|-----------------------|-----------------------|--------------|
| 2915       | 0.0889 | 0.02916   | 5.121                 | 0.2983                | 0.003554     |
| 2624       | 0.0816 | 0.02886   | 4.450                 | 0.2770                | 0.003400     |
| 2332       | 0.0715 | 0.02904   | 3.998                 | 0.2618                | 0.003512     |
| 2041       | 0.0622 | 0.02816   | 3.485                 | 0.2448                | 0.003630     |

### Table 5 Rotor turbulence parameter of the inlet turbulent energy $k = 50\text{kg} \cdot \text{m} / \text{s}^2$ by SST model

| Rpm/ (rpm) | Ma   | $L_w / m$ | $u'_w / (\text{m/s})$ | $u'_b / (\text{m/s})$ | $\Lambda (m)$ |
|------------|------|-----------|-----------------------|-----------------------|--------------|
| 2915       | 0.0891 | 0.02719   | 5.722                 | 0.002582              | 0.005747     |
| 2624       | 0.0794 | 0.02731   | 5.088                 | 0.002582              | 0.005471     |
| 2332       | 0.0694 | 0.02727   | 4.545                 | 0.002582              | 0.005657     |
| 2041       | 0.0604 | 0.02691   | 3.987                 | 0.002582              | 0.005769     |

### Table 6 Rotor turbulence parameter of the inlet turbulent energy $k = 50\text{kg} \cdot \text{m} / \text{s}^2$ by $k-\varepsilon$ model

| Rpm/ (rpm) | Ma   | $L_w / m$ | $u'_w / (\text{m/s})$ | $u'_b / (\text{m/s})$ | $\Lambda (m)$ |
|------------|------|-----------|-----------------------|-----------------------|--------------|
| 2915       | 0.0834 | 0.02997   | 5.088                 | 2.281                 | 0.02180      |
| 2624       | 0.0811 | 0.02869   | 4.460                 | 2.219                 | 0.02319      |
| 2332       | 0.0712 | 0.02997   | 4.030                 | 2.031                 | 0.02399      |
| 2041       | 0.0621 | 0.02914   | 3.585                 | 1.882                 | 0.02488      |

5. TA36 broadband noise prediction result

The sound power level of the noise in the duct can be obtained by substituting the above-mentioned turbulence, geometric, and mainstream parameters into the three-dimensional fan broadband noise prediction program. The sound wave in the duct is assumed to be plane wave, which can be converted as follows:

$$SPL = SWL - 10 \log A$$  \hspace{1cm} (11)

The left of Eq. (11) refers to sound pressure level, $A$ refers to the area of duct, and $A = \pi r_d^2$, $r_d = 0.3m$. 

10
After converting the sound power level to sound pressure level based on the aforementioned relationship, the sound pressure level spectrum of broadband noise, as shown in Figs. 10–13, can be obtained.

**Fig. 10** Broadband noise spectrum of imported turbulent kinetic energy by SST

**Fig. 11** Broadband noise spectrum of imported turbulent kinetic energy $k = 5kg \cdot m/s^2$ by $k-\varepsilon$ model

**Fig. 12** Broadband noise spectrum of imported turbulent kinetic energy $k = 5kg \cdot m/s^2$ by SST model

**Fig. 13** Broadband noise spectrum of imported turbulent kinetic energy $k = 5kg \cdot m/s^2$ by $k-\varepsilon$ model

Comparing Fig. 10 with Fig. 11 reveals that, except for some differences near 2500 Hz at 100% rotation velocity, the broadband noise spectra obtained from the two turbulence models are nearly the same. This result further verifies the correctness of the previous CFD wake results and indicates the reliability of the three-dimensional fan broadband noise prediction program.

Figs. 12 and 13 show that, when the inlet turbulence kinetic energy is increased, the noise prediction results of different turbulence models are still consistent, but the differences become evident. This observation indicates that the selection of turbulence model and inlet turbulence kinetic energy has very important influence on fan broadband noise prediction.

5.1. **Effect of inlet turbulence kinetic energy**
The setting of inlet turbulence kinetic energy and the selection of turbulence model will lead to the difference in rotor wake turbulence kinetic energy in the flow field and finally lead to the difference in fan broadband noise prediction.

The reason is that the inlet turbulence kinetic energy and the turbulence model determine the distribution of the turbulent kinetic energy in the wake of the rotor. Eq. (4.1) shows that the turbulence kinetic energy determines the turbulence parameters directly, which is further reflected in the noise prediction.

Comparing Fig. 10 with Fig. 12 shows that the increase in inlet turbulence kinetic energy will lead to the overall increase in the sound pressure level of the sound field by SST model. This result is consistent with the common sense. Comparing Fig. 11 with Fig. 13 shows that the increase in turbulence kinetic energy will lead to the increase in low-frequency sound pressure level and the decrease in high-frequency sound pressure level by k – ε model. Therefore, when the turbulent kinetic energy increases, the noise prediction results obtained by SST model are highly regular.

5.2. Effect of turbulence model

Comparing all parameters in Tables 3 and 4 reveals that the background turbulence intensity by k – ε model is two orders of magnitude smaller than that by SST model, and the turbulence integral scale is doubled. The results of parameter analysis indicate that the fan broadband noise increases with the increase in background turbulence intensity and decreases with the increase in turbulence integral scale. At $k = 5kg \cdot m / s^2$, the sound pressure level of the sound field obtained by k – ε model is considerably smaller than that by SST model only from the angle of independent change in parameters. However, comparing Fig. 10 with Fig. 11 indicates that, below 3000 Hz, the sound pressure level by k – ε model is approximately 2dB larger than that by SST model; above 3000 Hz, the sound power levels of both models are nearly the same. This result indicates that k – ε model will make the turbulence parameters change unevenly, but the total sound pressure level by this model is the same as that by SST model.

Comparing Table 5 with Table 6 shows that the parameters are not very different. From the perspective of the independent change in parameters, the corresponding sound power levels of both models should be similar. However, comparing Fig. 12 with Fig. 13 reveals that, if the inlet turbulence kinetic energy is $k = 50kg \cdot m / s^2$, then the sound field by k – ε model is generally 5 dB smaller than that by SST model.

Observing the background turbulence intensity obtained by k – ε model in Table 4 indicates that the final prediction result is the same as that by SST model. However, the turbulence fluctuation decays too quickly from the inlet $k = 5$ to rotor wake $k = 0.002582$. This finding does not conform to the rules from parameter research.

The above-mentioned phenomena show that the turbulence model slightly influences the prediction results of broadband noise when the inlet turbulence kinetic energy is very small. However, when the inlet turbulence kinetic energy is large, the differences in different turbulence models are reflected. SST model conforms to the laws from parametric research for sound field prediction by flow parameters. Therefore, SST model should be preferred.

6. Conclusions

A fast prediction method of broadband noise based on three-dimensional sound source model is proposed, and the application of single-stage TA36 fan is analyzed. The following conclusions are drawn:

(1) This method can be applied to predict fan broadband noise. Noise characteristics can be obtained in the early stage of blade design. Thus, we can effectively save time and cost and shorten the design cycle of blade.
(2) The prediction results of broadband noise are influenced by the turbulence model and inlet turbulence kinetic energy. The result by SST model is more in line with the cognitive law than that by $k-\varepsilon$ model.

Notably, this study only analyzes the influence of the turbulence model preliminarily. In-depth study on the effect of the turbulence model on the turbulence parameters should be conducted to further improve the accuracy of noise prediction.

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