Application of Arbitrary Vortex Method in Wind Tunnel Axial Fan Design

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Abstract. The flow axial velocity is assumed equal everywhere in free vortex design method, and the pressure rise of flow pass through fan is assumed also equal at different radial height. But in arbitrary vortex design method, on the assumption that axial velocity along radial is variable, the flow rotational velocity along radial is not must an inverse distribution. Therefore, arbitrary vortex design method could have a more uniform axial velocity at the outlet of fan system by regulating the rotational velocity distribution. In the numerical simulation, the fan of a pilot wind tunnel is used as physical model. By comparison with the experimental data the reliability of the numerical simulation could be verified. Two fan physical models are established which are based on the designs of arbitrary vortex method and free vortex method. The result of numerical simulation indicated that compared to the free vortex method, the arbitrary vortex fan minimized the separation on the tip and root of blade, obtained a more well uniform axial velocity distribution at the outlet of fan system. And the efficiency of blade is also increased by arbitrary vortex method.

1. Introduction

The energy which keeps air flow running in low speed wind tunnel is provided by fan. The energy loss of air flow in wind tunnel is in the shape of pressure drop. The function of fan is increasing the pressure of air flow. The power of large low speed wind tunnel was usually very high, which required the efficiency of fan was also very high; otherwise huge energy loss would be produced. And the low efficiency of fan indicated that the working condition of the fan was not good, which may generated big noise and the operation of wind tunnel would be affected. So as one of the core sections in wind tunnel, the performance of fan was very important. The fan design technique which could obtain high aero efficiency and low noise was one of the most important techniques in high quality wind tunnel design.

The most widely used fan design method was free vortex method which was based on 2D blade element theory in wind tunnel axial fan design. The assumptions of free vortex method were that the axial velocities of flow were equal everywhere and the pressure rise of flow passed through fan was also equal at different radial height. The calculation process of free vortex method was simple, and the method itself was verified by many engineering projects.

But in arbitrary vortex method, there was no such assumption. On the assumption that axial velocity along radial was variable, the flow rotational velocity along radial was not must an inverse distribution, and the pressure rise of air flow passed through the fan was not uniform. In arbitrary vortex design process the axial velocity distribution of incoming flow could be obtained by the
measuring result of pilot facility or similar equipment. The rotational velocity distribution could be pilot calculated and optimized which depended on the experience of designers. When the axial velocity distribution of incoming flow was decided, different rotational velocity distributions corresponded to different axial velocity distributions of fan outlet. Therefore, there would always be a specific rotational velocity distribution which could meet the design requirement, when the uniformity of axial velocity distribution at fan outlet was one of the major objectives [1-2].

The blade aerodynamic load also would be change with different rotational velocity distribution. So some specific rotational velocity distribution could be selected to optimize blade aerodynamic load. In a pilot wind tunnel, for example, it was always required high aerodynamic efficiency of fan and low aero noise. Therefore, one of the basic design principles was avoiding blade stall, which was contradictory with raising efficiency. Arbitrary vortex method could adjust blade aerodynamic load according to the pilot calculation and performance of blade airfoil profile, so blade stall might be avoid meanwhile obtaining high efficiency. Arbitrary vortex method could predict blade load distribution along the blade radial direction more precise especially when the wind tunnel had numerous of operating conditions.

Compared to free vortex method, more complex calculation was a defect of arbitrary vortex method. If the uniformity of axial velocity distribution at fan outlet or the blade local stall was not the focus in wind tunnel design, free vortex method was used in most case. But when these were taken into account, arbitrary vortex method was recommended.

2. Calculation of arbitrary vortex method

Contrary to the free vortex design method arbitrary vortex method does not require radial equilibrium. Like the free vortex design method, it is assumed that the flow may be treated in concentric cylinders around the centre axis, whereby the contributions of the relatively small radial components may be neglected. It is further assumed that the flow leaves the stator without tangential components, hence should be essentially swirl free downstream of the fan system [3].

The figure 1 is the sketch map of fan system in wind tunnel. Position 1 is upstream of rotor, position 2 is between rotor and stator, position 3 is downstream of stator. Taking an infinitesimal circular passage, the radius is \( r \), and \( dr \) is the width. According to the assumption of no radial flow, the air flow in infinitesimal circular passage does not mix with neighbouring flow.

\[
\begin{align*}
H_1 &= p_1 + \frac{1}{2} \rho u_1^2 \\
H_2 &= p_2 + \frac{1}{2} \rho u_2^2 + \frac{1}{2} \rho (\omega_1 r)^2 \\
H_3 &= p_3 + \frac{1}{2} \rho u_3^2
\end{align*}
\]
The affix s refers to the position between rotor and stator. The power applied to the shaft for that part of the flow may be expressed as (Q torque):

\[
dQ = \rho u_i^2 2\pi dr\omega r^2
\]

(4)

\[
\Delta h_{h2} 2\pi dr u_i = \Omega dQ
\]

(5)

\[\Delta h_{h2}\] is theoretical total pressure rise, and can be inferred as:

\[
\Delta h_{h2} = H_2 - H_1 = \rho \xi \omega r^2
\]

(6)

For the following calculations dimensionless quantities are introduced such as the local induced tangential rotation speed \( \varepsilon_s \), the local advance ratio \( \lambda \) and the local dimensionless pressure ratio \( k \).

Substitution in equation (6) gives

\[
\varepsilon_s = \frac{\omega r}{u}, \quad \lambda = \frac{u}{\Omega r}, \quad k = \frac{\Delta h}{\frac{1}{2} \rho u^2}
\]

\[
k_{h2} = \frac{\Delta h_{h2}}{\frac{1}{2} \rho u^2} = \frac{2\varepsilon_s^2}{\lambda_2}
\]

(7)

This formula forms the basis for design of axial fans. For a free vortex design, for which \( \omega_s r^2 \) = constant. In case of an arbitrary vortex design it is customary to start with an estimated linear distribution of \( \varepsilon_s \) with the radius \( r \) [4]. The value of \( \varepsilon_s \) at the "mean" radius can be fixed with expression (7). In order to be able to calculate the mean velocity field in the fan plane, like in the case of a free vortex design, it is necessary to first calculate the velocity distribution downstream of the rotor. Equations (1), (2) and (6) contain 4 unknowns, however, so that for \( p_2 \) an extra relation needs to be found. Wallis states that experience has taught that already close downstream of the rotor a new radial equilibrium develops so that the following expression may be applied [1].

\[
\frac{dp_2}{dr} = \frac{\rho(\omega r)^2}{r}
\]

(8)

To find the axial velocity distribution the following steps are now applied. Equations (1), (2) and (6) give:

\[
\Omega \rho \omega r^2 = p_2 - p_1 + \frac{1}{2} \rho (u_2^2 - u_1^2) + \frac{1}{2} \rho (\omega r)^2
\]

(9)

After dividing these terms by the mean entrance velocity \( U \) and introduction of the mean dimensionless quantities \( F_s \) \( \lambda_s \) and \( \varepsilon_s \) equation (25) may be rewritten as follows:

\[
\left( \frac{u_2}{U} \right)^2 - \left( \frac{u_1}{U} \right)^2 = \frac{2 \varepsilon_s}{\lambda_s} - \varepsilon_s^2 - \frac{p_2 - p_1}{\frac{1}{2} U^2}
\]

(10)

To avoid a laborious trial and error calculation of \( p_2 \), Wallis states that in practice most velocity distributions may be approximated by a linear distribution with radius [1]. It is further recommended to select the radius for which the local axial velocity is equal to the mean velocity [5]. It can easily be shown that this radius is a function of the ratio \( x_b \) between the minimum (boss) and the maximum (house) radius of the annulus. The expression reads:

\[
x_v = \frac{2(1 + x_b + x_b^2)}{3(1 + x_b)}
\]

(11)

For this position \( p_2 \) may be calculated directly from equation (10) and forms thereby the integration limit for solving equation (8).
Finally the axial velocity distribution after rotor can be inferred as follows:

\[
\frac{(u_z U)}{U} = \frac{(u_x U)}{U} + \left( \frac{2e_x}{\lambda_x} - (e_x) \right)^2 - \left( \frac{2e_y}{\lambda_y} - (e_y) \right)^2 \left|_{s_U} \right| - 2 \int\limits_{s_U}^{} (e_y) ^2 dx \left/ x \right.
\]

(13)

Likewise, a similar expression can be derived for the velocity downstream of the stator vanes.

\[
\frac{(u_z U)}{U} = \left( \frac{u_x U}{U} \right)^2 + (e_x) ^2 - (e_x) ^2 \left|_{s_U} \right| + 2 \int\limits_{s_U}^{} (e_y) ^2 dx \left/ x \right.
\]

(14)

3. Numerical simulation
Two fan physical models are established which are based on the designs of arbitrary vortex method and free vortex method. Fan A is a free vortex fan, fan B is an arbitrary vortex fan.

3.1. Physical models
Figure 2 shows the model of fan A. There are 10 blades and 7 stator vanes in fan A. The blade airfoil profile is GÖ 797. Installation angle at root is 44.2°. The chord length at root is 126mm, and 86mm at tip. The stator vane airfoil profile is NACA4415. Installation angle at root is 85.1°. The chord length at root is 66.5mm, and 110.9mm at tip.

Figure 3 shows the model of fan B. There are also 10 blades and 7 stator vanes in fan A. The blade airfoil profile is GÖ 797. Installation angle at root is 38.1°. The chord length at root is 126mm, and 86mm at tip. The stator vane airfoil profile is NACA4415. Installation angle at root is 81.3°. The chord length is 450mm from root to tip.

![Figure 2. Model of fan A](image1)

![Figure 3. Model of fan B](image2)

The parameters of design point are listed in table 1.

| model | blade installation angle (deg.) | rotate speed (rps) | test section wind velocity (m/s) | theoretical pressure rise (Pa) |
|-------|---------------------------------|-------------------|-------------------------------|-------------------------------|
| A     | 44.2                            | 60                | 130                           | 2900                          |
| B     | 38.1                            | 60                | 130                           | 2900                          |

Figure 4 shows the mesh of models.
3.2. Result of numerical simulation

The axial velocity distribution of incoming flow is showed in figure 5, and the distribution at fan outlet is showed in figure 6. From these two figures, it can be indicated that the axial velocity distribution at arbitrary vortex fan outlet is more uniform than free vortex fan in case of the same velocity distribution of incoming flow. As mentioned above, it is because the aerodynamic load of blade is decreased at root and increased at tip. Meanwhile, these results also indicate that it is successful the more uniform axial velocity distribution at fan outlet is obtained by arbitrary vortex method.

![Figure 4. Mesh of models](image)

(a). mesh of fan A rotor  (b). mesh of fan A stator

(c). mesh of fan B rotor  (d). mesh of fan B stator

**Figure 4.** Mesh of models

![Figure 5. Axial velocity distribution of incoming flow](image)

**Figure 5.** Axial velocity distribution of incoming flow
Figure 6. Axial velocity distribution at fan outlet

Figure 7 and figure 8 show oil streamline on blade upper surface of arbitrary vortex fan and free vortex fan respectively. In each figure, the left side is leading edge and the right side is trailing edge. The results indicate that there is no separation on most area of blade upper surface, not only arbitrary vortex fan but also free vortex fan, which prove these two fan design method are both successful. But at root and tip of trailing edge, separations are generated in both blades. The separation in arbitrary vortex fan is less than that in free vortex fan, which infers the performance of arbitrary vortex fan may be better. Because of the viscosity of air flow, there will be separation more and less in the boundary layer of trailing edge.

Figure 7. Oil streamline on blade upper surface of arbitrary vortex fan
Figure 8. Oil streamline on blade upper surface of free vortex fan

4. Conclusion
As the blade aerodynamic load can be adjusted in fan design process by arbitrary vortex method, there always will be a reasonable design. As mentioned above, the flow separation in arbitrary vortex fan is less than that in free vortex fan, and the axial velocity distribution at arbitrary vortex fan outlet is more uniform than free vortex fan in case of the same velocity distribution of incoming flow. The less
separation and more uniform velocity distribution are benefit for improving the performance diffuser which locate downstream of fan, and reducing the noise of fan.

References
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