Design and Research of Unequal Distance Fan

Shufeng Zhai¹* and Qian Yao²

¹Guangzhou Civil Aviation College, Guangzhou, Guangdong, 510403, China
²South China University of Technology, Guangzhou, Guangdong, 510641, China

*Corresponding author’s e-mail: 254503665@qq.com

Abstract. In this paper, the blade angle modulation method is used to design the unequal distance fan, and three unequal-distance fans with different blade spacing angles are designed. The aerodynamic noise and aerodynamic performance of three unequal-distance fans are analyzed and studied by CFD simulation method. The results show that with the increase of the uneven distribution of blades, the total A-weighted sound pressure level of the fan and the discrete noise of the fan at the passing frequency decrease significantly. The difference between the main aerodynamic performance parameters of three types of non-equidistant fans and equidistant fans is small, which shows that the unequal distance distribution has little effect on the aerodynamic performance while reducing the noise.

1. Introduction

The characteristics of vehicle noise with different properties and the percentage of total sound energy are different, among which the noise produced by cooling fan in engine is the most important[1]. In order to ensure the heat dissipation effect of the engine and prolong the service life of the engine, major manufacturers and engineers are constantly studying the effective noise reduction measures and performance improvement of cooling fans.

The existing design methods for unequal distribution of cooling fan blades can be divided into the following four categories: the first method, proposed by Mellin and Savran[2], is an intuitive model based on the sound field generated by the rotor. They studied the spectral characteristics of modulated noise with unequal pitch distribution in the blade circumference, deduced the formula for calculating the discrete noise of the axial fan with unequal pitch, and gave the optimum circumferential distribution of the blade with 4 to 15 blades. Mellin's method seems to be widely used by designers, possibly because of its instantaneity, but because of its limitations and specificity, it cannot meet the applicability of the standard and can only be used as a reference method. The second method is proposed by Dobrzynski[3] and Léwy[4]. In order to ensure the balance of the rotor, the research is limited to the propeller with uniform blade number z, so that the propeller can be considered to be composed of z/2 symmetrical double-blade propeller. Therefore, the possibility of any unbalance can be ruled out, regardless of the interval between the secondary propellers, the pressure will be generated. The results show that the optimum spacing angle almost depends on the Mach number of the tip of the propeller, and it is confirmed that the aerodynamic performance of the propeller with circumferential asymmetric blade spacing does not decrease. This method has the disadvantage of maintaining a certain degree of symmetry, and its limitation lies in the limited universality of the spacing method. The third method, called sinusoidal curve modulation method, is proposed by Ewald et al.[5]. Based on the design formula $\phi_n = \phi_n + A \sin N\phi_n$, the method determines the corner
coordinates of each blade by taking the hub center of the unequal-distance fan as the origin and the angle coordinates of the z-th blade as the reference $\theta_0$. Fiaqbedzi Y.A.[6] made a thorough mathematical analysis of the method, and obtained a clear formula for reducing the sound pressure level at the blade fundamental frequency and its harmonics, which shows that the more significant the harmonics are, the more obvious the modulation effect is. This method can produce balanced fan rotor and allow rigorous analysis, but it still retains a certain degree of symmetry, which may lead to the emergence of specific harmonics of rotating frequency. The fourth method can be called objective function optimization method. Firstly, the angular coordinates of $z - 2$ blades are determined arbitrarily, and then the angular coordinates $\theta'_{z-1}$ and $\theta'_z$ of the remaining two blades in the coordinate system are solved according to the equilibrium constraint equation set[7], so as to ensure the dynamic balance of the fan. Several objective functions based on radiation power are designed, and each objective function is optimized. Finally, the optimal circumferential distribution of blades is obtained by calculating the minimum noise threshold according to the most suitable objective function. Although this method reduces the randomness of choosing the circumferential angle and considers all-round factors, it has too many combinations of functions and complex calculations, which are more suitable for computer programming.

The larger the maximum modulation angular displacement is, the more uneven the circumferential distribution of the axial fan blade is, and the bigger the performance gap between the axial fan and the equal pitch fan is. Therefore, considering the static characteristics and aerodynamic noise of the fan, and the advantages and disadvantages of different design methods of fans with unequal pitch, this paper adopts blade angle modulation method to design fans with unequal pitch. In this paper, three kinds of unequal blade fans are designed and studied. The modulation angles $A$ are 0.1rad and 0.15rad, and the cycles of modulation $N$ are 1.2 and 2. The three design schemes are as follows: scheme 1, $A = 0.1$, $N = 1$; scheme 2, $A = 0.1$, $N = 2$; scheme 3, $A = 0.15$, $N = 2$.

2. Analysis of results of fan aerodynamic noise
Aerodynamic noise simulations of three unequal distance fans are carried out. The sound pressure level-frequency curves of the three fans are shown in Figure 1, Figure 2 and Figure 3.
From the sound pressure level spectrum of scheme 1, scheme 2 and scheme 3, it can be seen that the total sound pressure level of the three unequal-distance fans is lower than that of the equal-distance fans, which indicates that the rotating noise of the unequal-distance blades is reduced obviously at the passing frequency. However, the total sound pressure level noise of scheme 1 and scheme 2 is higher than that of prototype non-equidistant fans, the main reason is that some turbulent noise is higher in middle and high frequency band, and the total sound pressure level of discrete noise cannot be improved by non-equidistant fans with too small blade modulation angle.

The relationship between the sound pressure level (A weighting) of fans and 1/3 frequency doubling band has been obtained after processing to analyze whether the disturbance to human ear caused by rotating noise of non-equidistant fans has been improved. In order to better compare the difference of five fans in A-weighted sound pressure level, noise data of five fans are derived and compared in the same figure, the curves are shown in Figure 4. The unequal distance fan can distribute the sound energy of the fundamental frequency to a wider frequency band, and make the peak value of the fundamental frequency disperse near the original peak value. With the increase of the modulation angle and the number of cycles of the modulation amount, that is, with the increase of the non-uniformity of the fan blade, the total A-weighted sound pressure level of the fan decreases, especially the discrete noise of the fan at the passing frequency.
3. Analysis of aerodynamic performance simulation results

The aerodynamic performances of three schemes of unequal-distance fans are simulated, and the main aerodynamic performances parameters of equidistant fans and three unequal-distance fans are obtained. The performance parameters of the three schemes are plotted as the performance curves of unequal and equidistant fans as shown in Figure 5, Figure 6 and Figure 7. It can be seen from the figures that the static pressure, static pressure efficiency and shaft power of the three schemes are worse than those of the prototype non-equidistant fans, but the differences of all performance values between non-equidistant fans and equidistant fans are less than 8%, which can still be considered that the unequal distribution has no significant impact on aerodynamic performance.
The unequal distribution of blades can indeed reduce the noise interference to human ears. The total sound pressure level of unequal-distance fans is 2.29 dB lower than that of equidistant fans. The total sound pressure level of unequal-distance fans in scheme 3 is 2.96 dB lower than that of equidistant fans. The results show that the more uneven the distribution of blade pitch is, the more obvious the effect of noise reduction is. But $A$ too small does not improve the total acoustic energy of the fan, too large will affect the aerodynamic performance of the fan, so it is necessary to give appropriate constraint value of $A$ value. In this range, the best blade distribution mode of the fan can be selected by considering the aerodynamic noise and aerodynamic performance of the fan comprehensively. It is considered that the unequal-distance fan designed according to the circumferential angle distribution of the blade of the prototype unequal-distance fan is the best. The optimum circumferential angles of the 7-blade non-equidistant fans are 53.5°, 103.5°, 149.5°, 210.5°, 256.5°, 306.5° and 360°.

4. Conclusion
According to the merits and demerits of unequal distance blade design, three unequal distance fans with different blade spacing angles are designed by using the method of sinusoidal modulation of blade angle. It is found that with the increase of unequal distribution of blades, that is, with the...
increase of the number of cycles of modulation angle and modulation amount, the total A-weighted sound pressure level of the fan decreases and its aerodynamic performance deteriorates. The aerodynamic performance of equidistant fans is calculated. By comparing the performance curves of different-distance fans and equidistant fans, it can be seen that as long as the relative variation of blade uneven distribution is within a certain range of constraints, the aerodynamic performance of different-distance fans will not be greatly affected. Even in some flow areas, the aerodynamic performance of fans is slightly improved, so it is necessary to rationally design the partition of unequal-distance blades. Aerodynamic noise of the corresponding equidistant fan is calculated. By comparing the noise spectrum of the unequal-distance fan with that of the equidistant fan, it can be seen that the unequal-distance distribution of the blades causes the fan to modulate at the passing frequency. That is, the peak acoustic energy corresponding to the fundamental frequency is symmetrically distributed on both sides of the fundamental frequency, and so is the previous harmonics. Therefore, the unequal-distance blade fan can decrease noise to the human ear by reducing discrete noise in sensitivity range.

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