Research on the Noise Reduction and Efficiency Increase for Axial Fan with Wave Leading Edge Blades

Bo Li
University of Shanghai for Science and Technology
Yujing Wu
University of Shanghai for Science and Technology
Dange Guo
University of Shanghai for Science and Technology
Dan Luo
University of Shanghai for Science and Technology
Diangui HUANG (dghuang@usst.edu.cn)
university of shanghai for science and technology

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Research on the noise reduction and efficiency increase for axial fan with wave leading edge blades

Bo Li[1, 2] • Yu-Jing Wu[1, 2] • Dan-Ge Guo[1, 2] • Dan Luo[1, 2] • Dian-Gui Huang[1, 2]

Abstract: This paper imitates the raised structure of the leading edge of the humpback whale fin limbs, designed six bionic blades. The aerodynamic analysis show that: the wave leading edge blade can improve the total pressure efficiency of the axial flow fan, and under off-design conditions, the aerodynamic performance of bionic fan is better than that of prototype fan. The noise analysis shows that: under the condition of constant wave number, increasing wave amplitude can reduce the overall sound pressure level at the monitoring point, in the middle and high frequency range, the sound pressure level of the bionic fan at the monitoring point is significantly lower than that of the prototype fan, and the noise reduction effect increases with the increase of wave amplitude; under the condition of constant wave amplitude, increasing the wave number can reduce the fan noise. At a certain wave number and amplitude, the overall sound pressure level of the bionic fan at the monitoring point is at most 2.91 dB lower than that of the prototype fan. In this paper, the noise reduction effect of increasing wave number is more obvious than that of increasing wave amplitude.

Keywords: Bionic blade • Aerodynamic performance • Off-design • Noise reduction

1 Introduction

The fan will generate noise during operation, which has a certain impact on people's life. In recent years, with the large-scale application of fans and the continuous improvement of people's living environment requirements, it is urgent to reduce the noise of fans and other turbomachinery. Fish and Battle [1] found that the humpback whale had agile maneuverability that was not commensurate with its huge body, and they measured and drawed the different cross-sectional shapes of the fin limbs. Then the hydrodynamic performance of the raised structure of the leading edge of the fin limbs was studied by the wind tunnel test.The results showed that the leading edge bulge (wavy leading edge) structure allowed the airfoil to generate lift at a high angle of attack and delayed the stall. Since then, many scholars have studied the wave leading edge airfoil / blade. Levshin and Custodio [2] applied the leading edge to the NACA 634-021 airfoil. The experimental results show that the leading edge protuberances can delay the stall, and the amplitude of the protuberances had a greater influence on lift and drag. Hansen [3-4] applied the leading edge tubercles to different airfoils, the results showed that the leading edge tubercles could improve the aerodynamic performance of the airfoil, and the larger the amplitude of the leading edge tubercles, the smaller the wavelength and the more obvious the noise reduction effect. Clair [5] studied the effect of wave leading edge on blade noise through the wind tunnel test and numerical simulation. The results showed that the wave leading edge could reduce the blade turbulent interference noise, and the noise reduction can be up to 3 ~ 4 dB. Kim, Haeri, and Joseph [6] numerically studied the influence of the wave leading edge on the flat-plate airfoil turbulent interference noise by solving the full three-dimensional inviscid Euler equation. The results showed that the large the wave amplitude, the more noise reduction; the wave leading edge could reduce the noise in the middle and high frequency bands. Biedermann, Chong and Kameier [7] studied the noise reduction mechanism of the leading edge serrations on the airfoil, it is found that the amplitude of serration was the main parameter to reduce broadband noise. Becker [8-10] applied the leading-edge serrations to axial fans. It was found that whether it was flat-plate axial fan or skewed axial fans, the leading-edge serrations could reduce the noise of the axial

✉ Dian-Gui Huang
dghuang@usst.edu.cn

1 School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai, China

2 Shanghai Key Laboratory of Power Energy in Multiphase Flow and Heat Transfer, Shanghai, China

fans. For rotating machinery, the use of leading-edge serrations for noise reduction is an effective method. Wang [11] took NACA0006 blade as the original blade, and designed three bionic blades with wavy leading edge, serrated trailing edge and ridge structure through blade shape modification. The numerical simulation results showed that the noise of bionic blade was lower than that of original blade. However, when the reynolds number increased to 190,000 and the angle of attack was 10° , due to the interference of the wave leading edge with the flow field, the noise near the leading edge increased, and the noise at the trailing edge still decreased significantly. Finally, the bionic fan and the prototype fan were tested at four voltages of 13V, 16V, 20V and 24V, and the results showed that the acoustic performance of the bionic fan was superior to the prototype fan. Mao et al. [12] used the wind tunnel to study the effect of the wave leading edge on the turbulent interference noise of the swept blade. The results show that the wavy leading edge structure can reduce the leading edge turbulent interference noise in the low frequency range, and the amount of noise reduction can be up to 2 dB.

Imitating the raised structure of the leading edge of the humpback whale fin limbs,the wave leading edge modification was carried out on the straight blade optimized by Wu [13]. Six kinds of fan with bionic blades were designed by changing the wave number and amplitude and the aerodynamic performance and acoustic characteristics of the axial fan with bionic blades were analyzed.

2 3D modeling of fan with wavy leading edge blades

Based on the optimized straight blade, the blades of the fan were modified with wave leading edge. Figure 1 shows the three-dimensional structure of the prototype fan. To make the geometric profile of the original blade change less dramatically, the wave leading edge was only modified within 30% of the chord length from the leading edge of the blade. Connect the leading edge points of the eight airfoils with straight lines, the support surface of the wavy leading edge is generated by the connection line of the leading edge point of the airfoils and the tangent of the mean line of each airfoil section at the leading edge point. Equation (1) is the wavy leading edge function.

$$y = h \sin bx \tag{1}$$

Where h is the wave amplitude and b is the wave number between the two sections. The wave leading edge is generated on the support surface according to the wave leading edge function. Table 1 is the main parameters of the axial flow fan. Table 2 is the geometric parameters of the bionic blade. Figure 2 is the model of six bionic blades.

Figure 1 3D structure diagram of the prototype fan

Table 1 Main parameters of the fan

	Value		Value
Fan diameter (mm)	1800	Hub ratio	0.4
Impeller diameter (mm)	1796	Mass flow rate (kg/s)	60
Rotational speed (r/min)	985	Number of rotors	8

Table 2 Bionic blade geometry parameters

Model No.	Wave amplitude (cm)	Ratio of wave amplitude to average chord length	Wave number	Ratio of wave length to average chord length
1	2	0.0679	3.5	0.5243
2	3	0.1018	3.5	0.5243
3	4	0.1358	3.5	0.5243
4	2	0.0679	7	0.2622
5	2	0.0679	10.5	0.1748
6	2	0.0679	14	0.1311

(a) Model 1 (b) Model 2 (c) Model 3

(d) Model 4 (e) Model 5 (f) Model 6

Figure 2 Wavy leading edge blades model

3 Analysis on the aerodynamic performance of axial fan

3.1 Mesh generation and independence verification

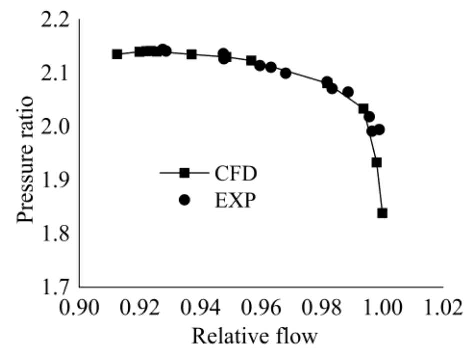
Ansys-CFX is used for numerical simulation of this axial flow fan, and the turbulence model is k-ε model. Table 3 is the grid independent verification result. The results show that when the grid number is 1 million and 2 million, the total pressure efficiency of the fan differs only by 0.02%, and the difference of wind pressure is 1.26 Pa. To balance the calculation accuracy and cost, the third set of grid is used in this paper.

Table 3 Grid independence verification

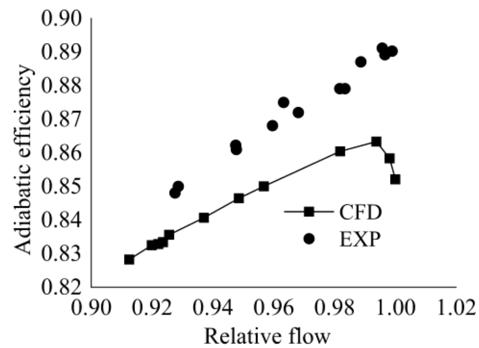
No.	Grid number	Total pressure efficiency (%)	Wind pressure (Pa)
1	250,000	93.62	1504.99
2	500,000	93.60	1493.23
3	1,000,000	93.56	1496.05
4	2,000,000	93.58	1494.79

3.2 Numerical simulation reliability verification

In this section, rotor 37 is taken as the research object, and the reliability of the numerical simulation results are verified by comparing with the test results from the pressure ratio characteristic curve and adiabatic efficiency characteristic curve. Figure 3 shows the comparison between the simulated value and the experimental value [14] of the Rotor 37 performance curve.



(a) Pressure ratio characteristic curve



(b) Adiabatic efficiency characteristic curve

Figure 3 Rotor 37 overall performance curve experiment comparison

Figure 3 shows that the numerical simulation can accurately calculate the limit index value of the compressor, the pressure ratio characteristic curve is roughly similar to the experiment, and the adiabatic efficiency characteristic curve is consistent with the experimental trend. The accuracy of the numerical simulation method used in this paper is proved.

3.3 Effect of wavy leading edge blades on aerodynamic performance of axial fan

The six bionic blades are applied to the axial flow fan, and the full three-dimensional numerical simulation of the axial fan is carried out under the design and off-design conditions

3.3.1 Design condition

The calculation results of the aerodynamic performance of the bionic blades are shown in Table 4, which indicates that under the design conditions, comparing the model 1, 2, and 3 bionic fans with the prototype fan, the total pressure efficiency of the model 1 bionic fan reaches 94.92%, which is the highest among several bionic blade design schemes, and with the increase of wave amplitude, the total pressure efficiency of the bionic fan decreases slightly. Comparing the model 1, 4, 5, 6 bionic fans with the prototype fan, the total pressure efficiency of model 1 bionic fan is still the highest among several bionic fans, and when the wave number increases, the total pressure efficiency of the bionic fan decrease.

Table 4 Simulation results of using several bionic blade fans

	prototype	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Units
Speed	985	985	985	985	985	985	985	[r min^-1]
Volume flow rate	50.96	51.18	51.18	51.18	51.17	51.17	51.17	[m^3 s^-1]
Pressure rise	1496	1400	1398	1397	1397	1393	1390	[Pa]
Total pressure efficiency	93.56	94.92	94.85	94.84	94.89	94.67	94.64	[%]

From the above analysis, it is found that the total pressure efficiency of the fan increases and the aerodynamic performance improves after the modification of the wave leading edge of the blade. However, as the wave amplitude increases or the wave number increases (the wavelength becomes shorter), the total pressure efficiency of the fan gradually decreases, and the aerodynamic performance become worse.

3.3.2 Off-design condition

In actual work, the fan is often operated under off-design conditions. Figures 4 and 5 are the total pressure efficiency curves of several bionic fans under off-design conditions of variable mass flow rate and speed.

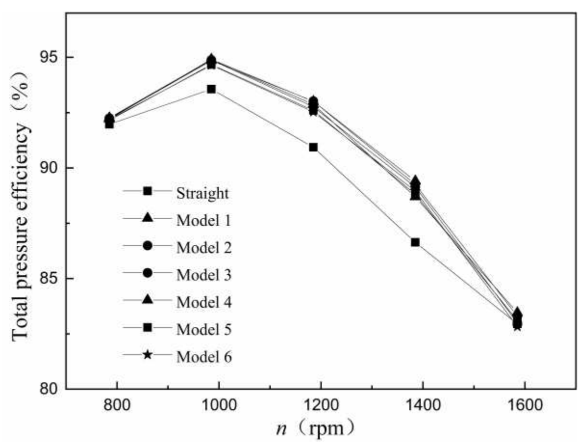


Figure 4 Total pressure efficiency curve of several bionic fans and prototype fan at different speed

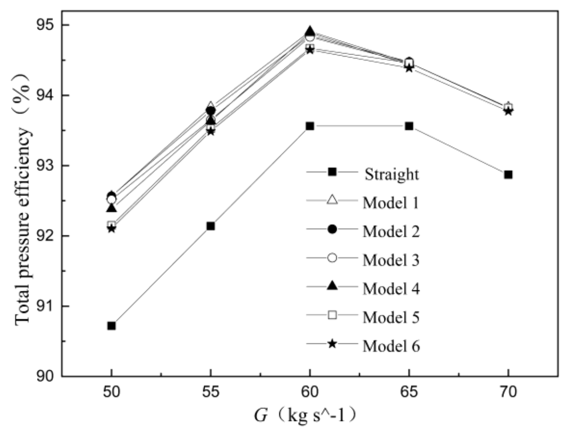


Figure 5 Total pressure efficiency curve of several bionic fans and prototype fan at different mass flow rate

Figure 4 shows that as the speed increases, the total pressure efficiency of the fan increases first and then decreases. At the design speed, the total pressure efficiency of the fan achieves a maximum value; within the variable speed range, the total pressure efficiency of bionic fan is higher than that of prototype fan; under high speed conditions, the aerodynamic performance of bionic fan is much better than that of prototype fan. Figure 5 shows that as the mass flow rate increases, the total pressure efficiency of the fan increases first and then decreases, and the total pressure efficiency achieves a maximum value at the design mass flow rate; among the selected variable mass flow range, the total pressure efficiency of bionic fan is better than that of prototype fan.

4 Effect of wavy leading edge blades on aerodynamic noise of axial fan

The overall sound pressure level and spectrum curve of the noise at the monitoring point of the fan are obtained by FW-H equation and FFT (Fast Fourier Transform) from the sound field information calculated by Fluent.

4.1 Acoustic mesh generation and independence verification

Due to the high requirements of acoustic calculation on grid, the grid for aerodynamic calculation can no longer meet the noise calculation. ATM optimized topology technology in Turbogird is used to mesh the fan, and the thickness of the first layer of the grid on the wall is 1e-5m to ensure y+ is less than 10. Figure 6 is the y+ distribution close the blade suction surface, which shows that the maximum y+ close the blade surface is 7.291, and most of the y+ value is about 1.82.

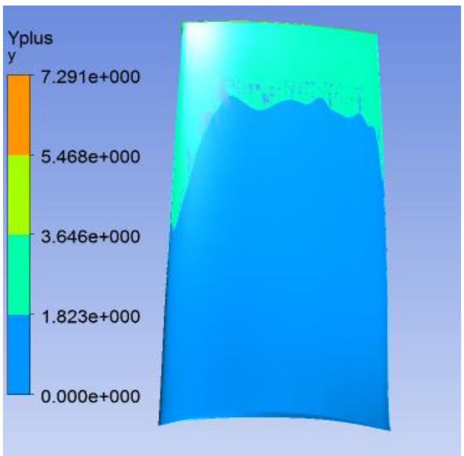


Figure 6 The y+ distribution of the blade suction surface

According to Methods of noise measurement for fans blowers compressors and Roots blowers [15], the layout of noise monitoring points is shown in Figure 7. The angle between the monitoring point and the center position of the fan outlet is 45° and the distance is 1m.

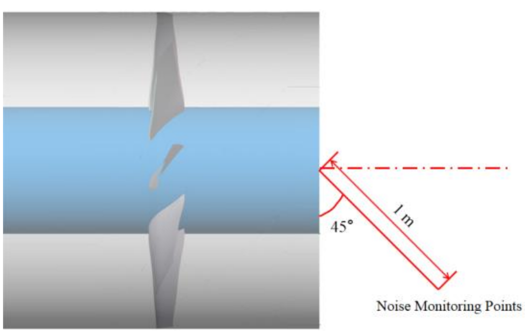


Figure 7 Noise monitoring point layout

In order to ensure the accuracy of the calculation results, the grid independence verification is carried out. Table 5 is the calculation results, it is found that the overall sound pressure level of the monitoring point differs by only 0.48 dB when using the 6.68 million and 10.07 million grid. The second set of grid is used in this paper.

Table 5 Noise Grid Independence Verification

No.	Grid number	overall sound pressure level of monitoring point (dB)
1	3,950,000	76.94
2	6,680,000	79.47
3	10,070,000	78.99

4.2 Effect of wave amplitude on aerodynamic noise of bionic fan

Table 6 is the calculation results of overall sound pressure level at monitoring points of model 1, 2, 3 fans and prototype fan. It can be seen that when the straight blades are modified with a wavy leading edge, the overall sound pressure level of the model 1, 2 and 3 fans at the monitoring point increased by 3.6 dB, 3.47 dB and 2.94 dB compared with the prototype fan; comparing the calculation results of model 1, 2, and 3, it is found that as the wave amplitude increases, the overall sound pressure level at the monitoring point gradually decreases.

Table 6 overall sound pressure level at the monitoring point

No.	Fan	Ratio of wave amplitude to average chord length	overall sound pressure level（dB）
1	Prototype	/	79.47
2	Model 1	0.0679	83.07
3	Model 2	0.1018	82.94
4	Model 3	0.1358	82.41

Figure 8 is the noise spectrum of the prototype fan and model 1, 2, 3 fans at the monitoring point. It is found that in the low frequency range (0-1,000 Hz), the sound pressure level of model 1, 2 and 3 fans are significantly higher than that of the prototype fan, which is the main reason for the noise of bionic fans to increase; in the middle and high frequency range (above 1000 Hz), the sound pressure level of several bionic fans at the monitoring point is lower than that of the prototype fan, which shows that the wave leading edge can effectively improve the vortex noise of the axial flow fan, and the effect becomes better with the increase of wave amplitude.

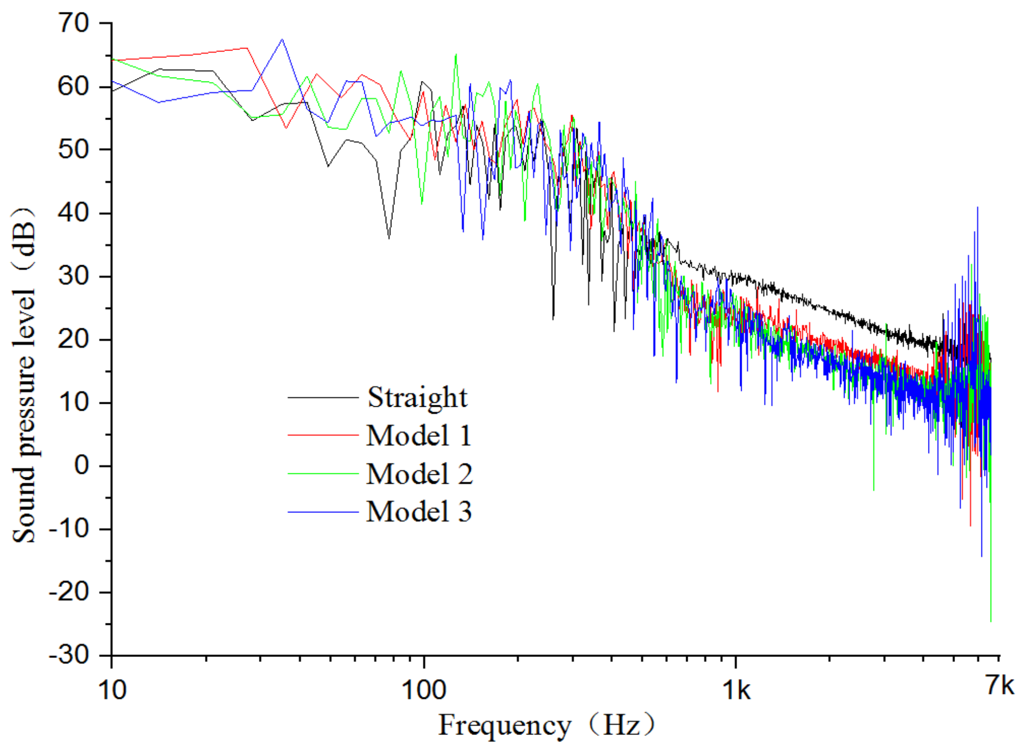


Figure 8 Noise spectrum at monitoring points of bionic fan and prototype fan

4.3 Effect of wave amplitude on aerodynamic noise of bionic fan

Table 7 is the calculation results of overall sound pressure level at monitoring points of model 1, 4, 5, 6 fans and prototype fan. It can be seen that when the straight blades are modified with wavy leading edge, as the wave number increases (wavelength decreases), the overall sound pressure at the monitoring point decreases first and then increases. The overall sound pressure level of model 5 fan is 2.91 dB lower than that of the prototype fan, and the noise reduction effect is obvious.

Table 7 overall sound pressure level at the monitoring point

No.	Fan	Ratio of wave amplitude to average chord length	overall sound pressure level（dB）
1	Prototype	/	79.47
2	Model 1	0.5243	83.07
3	Model 4	0.2622	81.3
4	Model 5	0.1748	76.56
5	Model 6	0.1311	81.4

Figure 9 is the noise spectrum of the prototype fan and model 1, 4, 5, 6 fans at the monitoring point. It is found that in the low frequency range (0-1,000 Hz), the sound pressure level of model 1, 4 fans are significantly higher than the prototype fan, which is the main reason for the noise of bionic fans to increase; in the selected frequency range, the sound pressure levels of models 5 and 6 fans have a certain reduction relative to the prototype fan, which has the effect of reducing noise. In the medium frequency range (1,000 Hz - 3,000 Hz), the sound pressure level of model 4, 5 fans at the monitoring point is lower than that of the prototype fan, but the sound pressure level of model 6 fan is higher than that of the prototype fan, which shows that the wave leading edge can effectively improve the vortex noise of the fan within a certain wave number range, but not the more wave number is, the better. In the high frequency range (above 3,000 Hz), the sound pressure level of the model 4, 5 fans at the monitoring point has an increasing trend, and the sound pressure level of the model 6 fan is higher than that of the prototype fan.

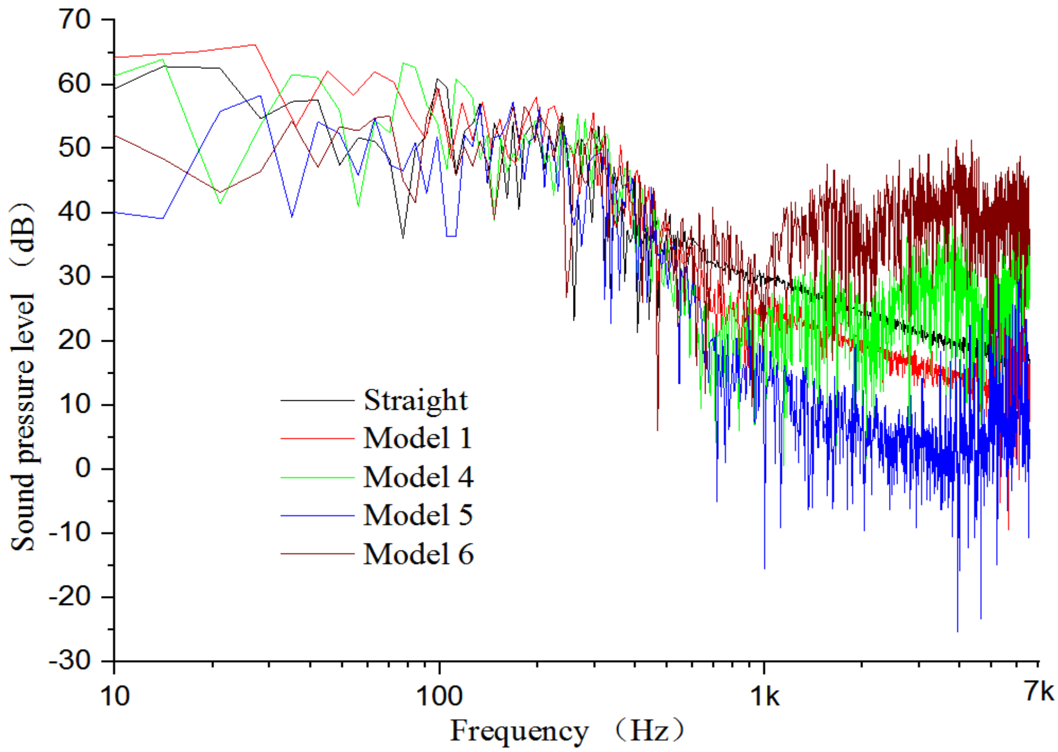


Figure 9 Noise spectrum at monitoring points of bionic fan and prototype fan

5 Conclusions

(1) Under the design condition, after the modification of the wave leading edge of the straight blade, the total pressure efficiency of the fan is increased and the aerodynamic performance is improved; however, with the increase of wave amplitude or number (shorter wavelength), the total pressure efficiency of bionic fan gradually decreases.

(2) Under the conditions of variable speed and mass flow rate, the aerodynamic performance of the bionic fan is better than that of the prototype fan; but under low speed conditions, the total pressure efficiency of the bionic fan and the prototype fan are not much different.

(3) The noise calculation results show that when the wave number is fixed at 3.5 and the amplitude is changed, the overall sound pressure level at the monitoring point of the bionic blade fan is increased compared with the prototype fan. However, with the increase of wave amplitude, the overall sound pressure level at the monitoring point decreases continuously. The spectrum analysis shows that the wave leading edge of blade increases the sound pressure level in low frequency range, which is the main reason for the increase of noise. However, in the medium and high frequency range, the sound pressure level of bionic fan at monitoring point is significantly lower than that of the prototype fan, and the effect is better with the increase of wave amplitude.

(4) When the wave amplitude is fixed at 2 cm and the wave number is changed, it is found that when the wave number increases to 10.5, the overall sound pressure level at the monitoring point of the bionic fan is 2.91 dB less than that of the prototype fan; when the wave number increases to 14, the overall sound pressure level of the bionic fan at the monitoring point is higher than that of the prototype fan. It is found that as the wave number increases (wavelength decreases), the overall sound pressure level of the fan at the monitoring point decreases first and then increases. When the wave number is 10.5, bionic blade fan has the best noise reduction effect.

(5) For the wavy leading edge design, increasing the wave number has a more significant effect on reducing noise than increasing the wave amplitude.

6 Declaration

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Authors' contributions

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Competing interests

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Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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Figures

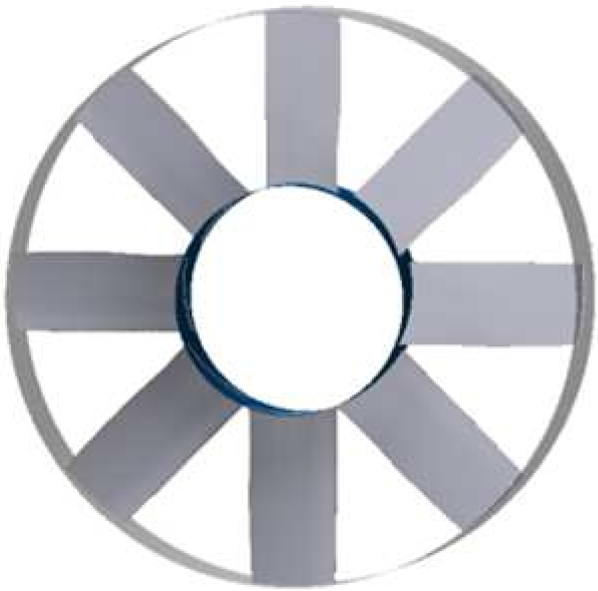

Figure 1

3D structure diagram of the prototype fan

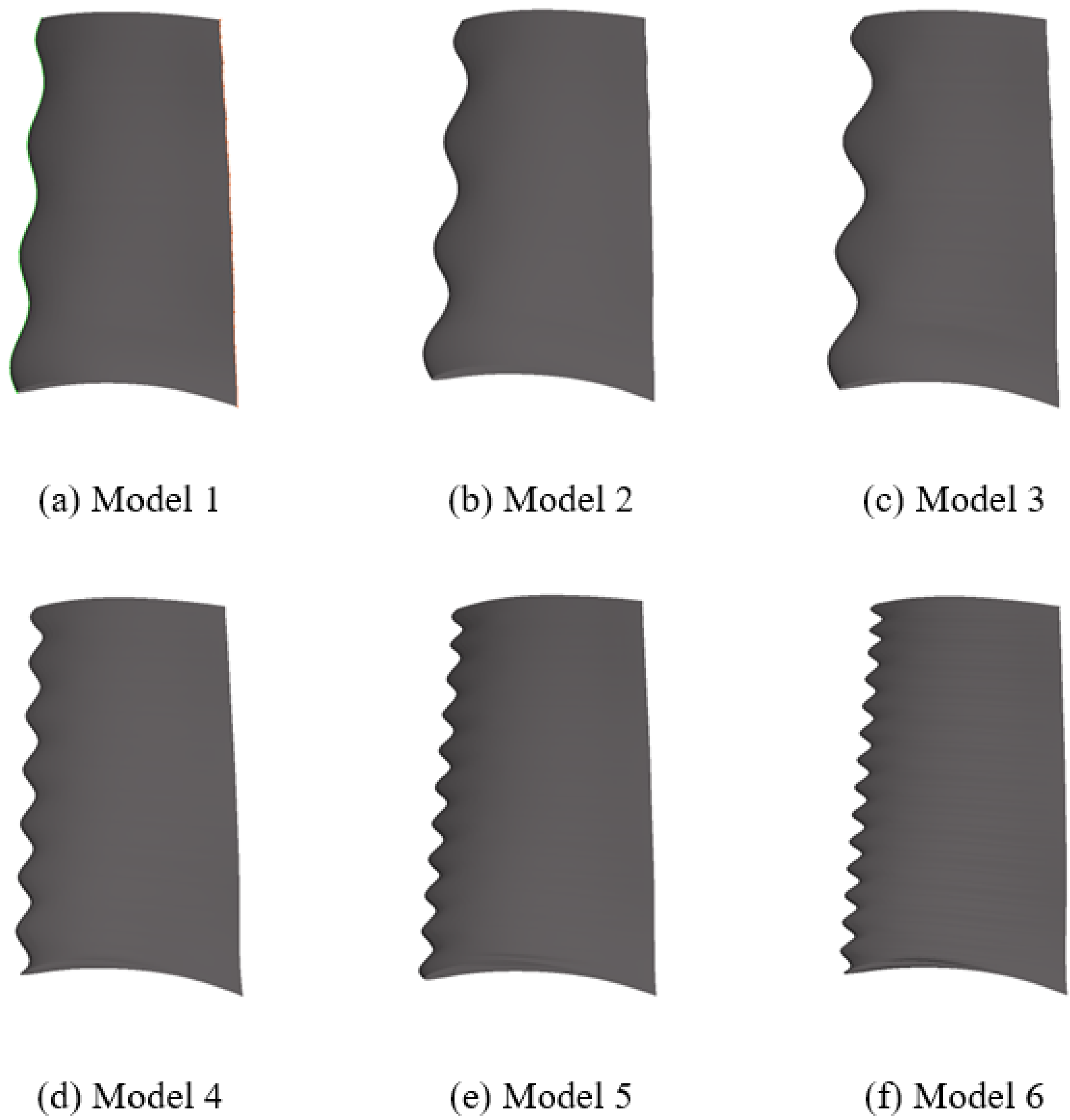

Figure 2

Wavy leading edge blades model

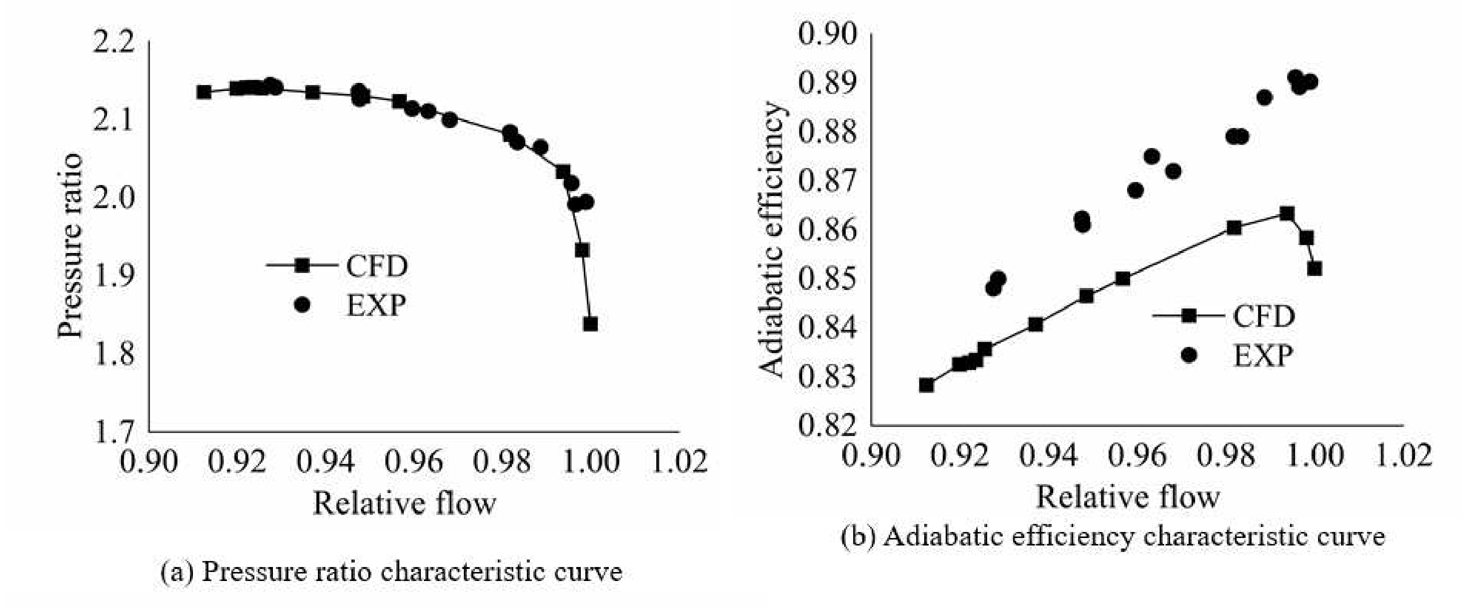

Figure 3

Rotor 37 overall performance curve experiment comparison

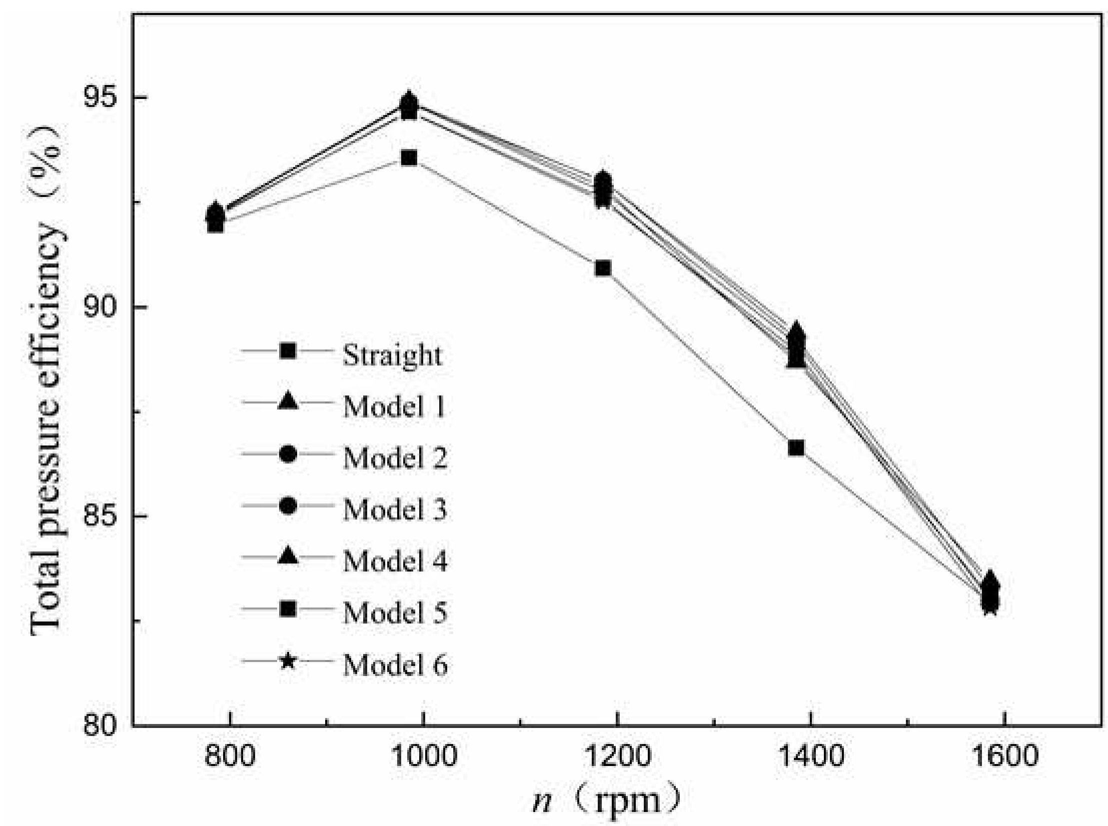

Figure 4

Total pressure efficiency curve of several bionic fans and prototype fan at different speed

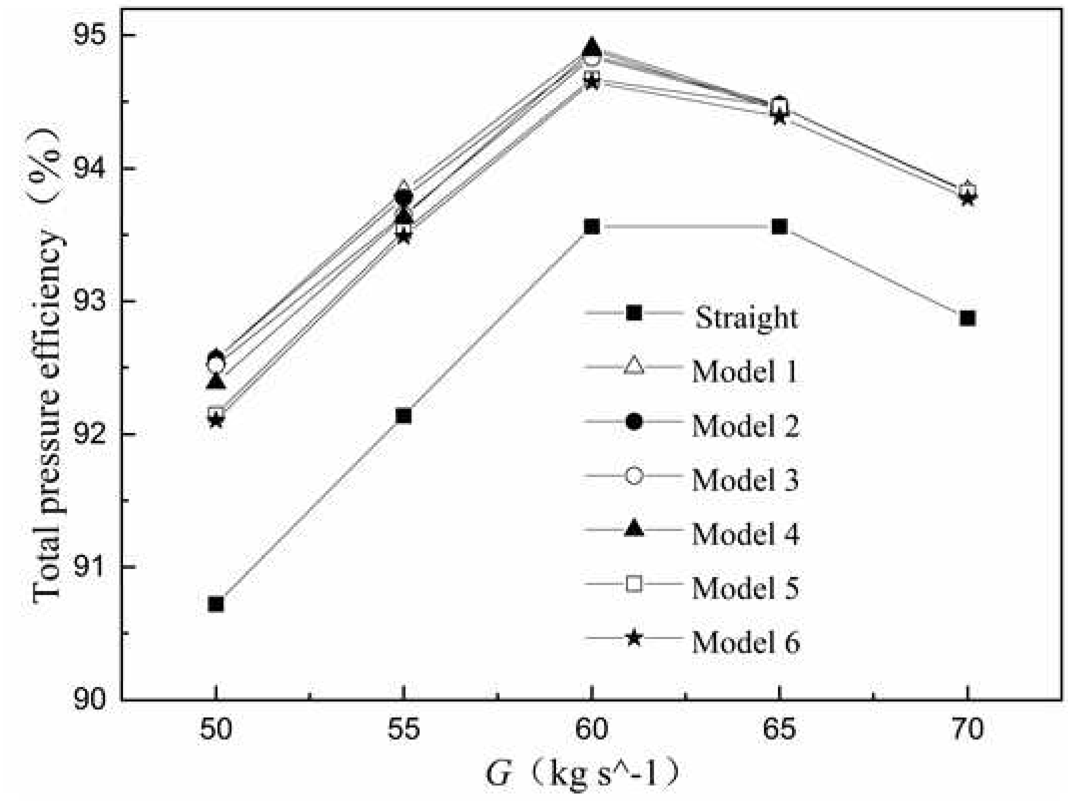

Figure 5

Total pressure efficiency curve of several bionic fans and prototype fan at different mass flow rate

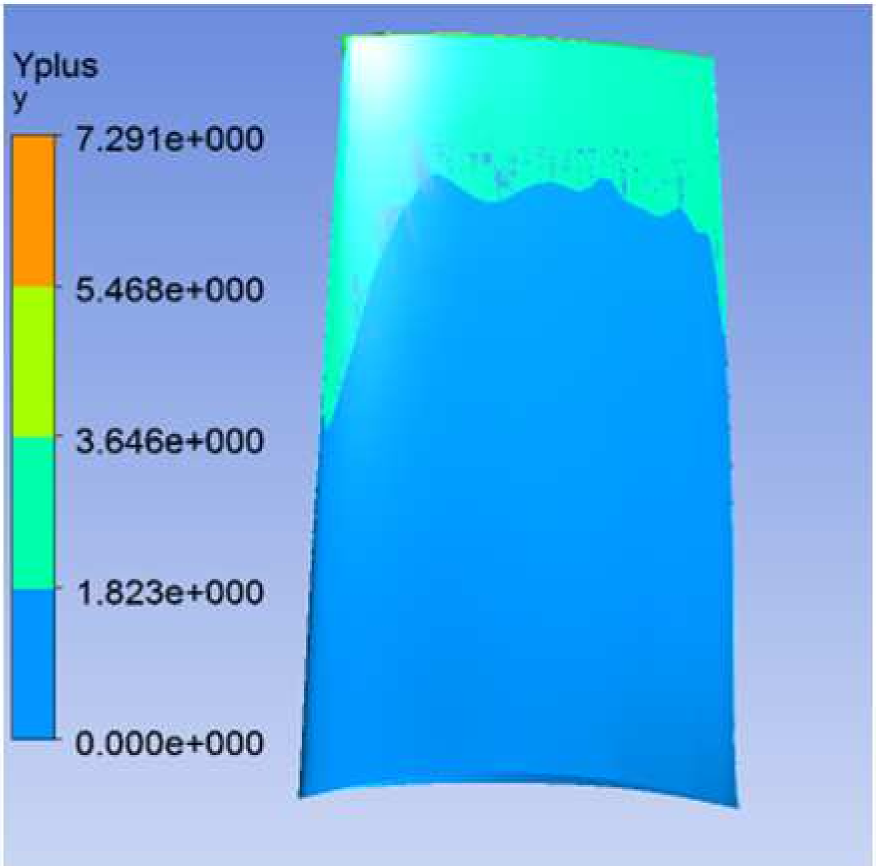

Figure 6

The y+ distribution of the blade suction surface

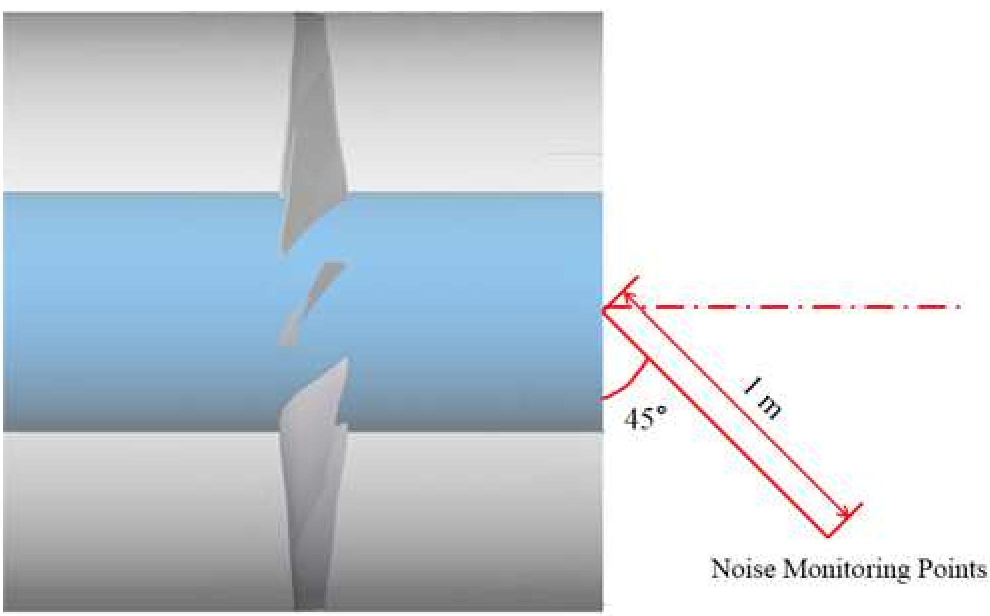

Figure 7

Noise monitoring point layout

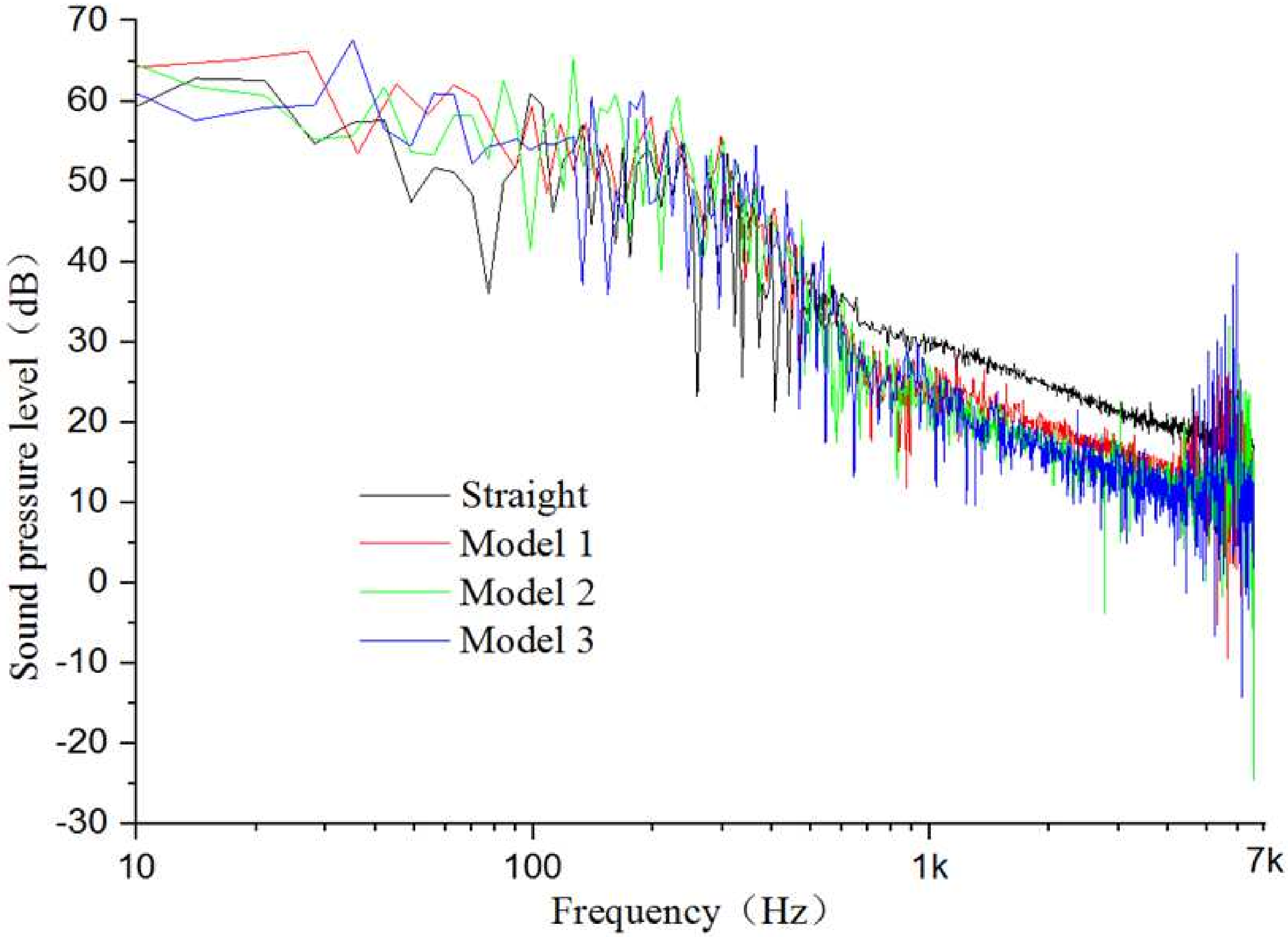

Figure 8

Noise spectrum at monitoring points of bionic fan and prototype fan

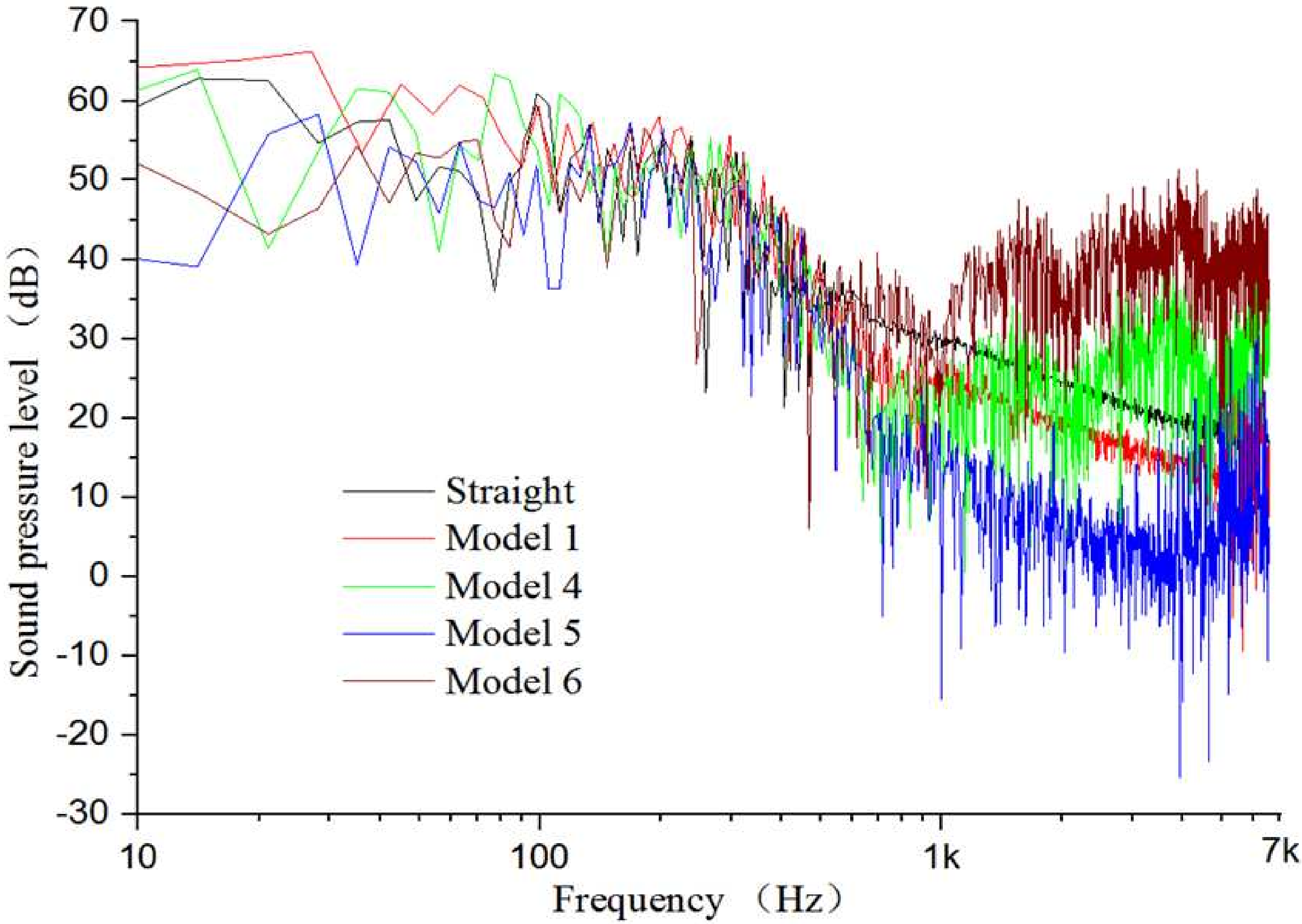

Figure 9

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