Development of Sirocco Fan Featuring Dragonfly Wing Characteristics

トンボの翅形状を応用したシロッコファンの開発

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Sharp Co. has developed high-performance electric fans by applying features of the wings of living creatures. This paper proposes an air purifier sirocco fan blade that mimics the wings of a dragonfly. Air quality has increasingly attracted attention in Japanese homes, and one or more air purifiers are installed in almost 40％ of all houses in the country. The purpose of an air purifier is to maintain air cleanness, and it is operated overnight. There is, however, the problem of the loud noise created by the fan, which also makes overnight operation inconvenient. To solve this problem, we adopted the shape of the dragonfly wing in the sirocco fan blade of an air purifier. As a result, a maximum reduction of 2.5dB was achieved.

シャープではこれまで，生物の有する形状要素を応用することによる高性能の白物家電の開発を行ってきた。これらのうち，本稿では，トンボの翅形状を模した空気清浄機用シロッコファンの開発について報告する。日本国内において，住環境の空気の質へのこだわり意識は上昇しており，国内では40％近くの家庭に空気清浄機が１台以上設置されている。空気清浄機は主に，家庭の空気をきれいな状態を維持するという目的で，夜中でも使用したいという一方，ファン騒音がうるさく，夜通しつけっぱなしにすることができないという問題があった。この問題を解決するため，空気清浄機用シロッコファンに，トンボの翅形状を応用することとした。その結果，最大で2.5dBの騒音低減に成功した。

1. Introduction

The cross section of an ordinary sirocco fan blade is a circular arc, and this affords a simple structure that is easy to fabricate. Moreover, a fan blade that has a circular-arc wing section is often used as the blade of the blower because it is easy to configure by setting the inlet and outlet angles according to the ratio of the inside and outside diameter. By setting these three values, the blade shape can be determined. However, when the blade shape is set to only a circular arc, the camber of the blade is also determined automatically. In this case, the efficient generation of lift is hampered and the performance of the fan is impaired.

To warp the shape of a blade, a thickness distribution is added to the camber line of a basic airfoil. When using this method in aeronautical engineering, the cross section of the blade is the aircraft airfoil and hence lift is easily generated. This basic aeronautical principle has been widely applied in the design of fans. There is, however, a limit to how a fan blade can be designed on the basis of aeronautical principles. Many aircraft wing sections, including those developed by NASA and NACA, are assumed to operate with high Reynolds numbers (greater than 10^7). Such values are, however, not suitable for blower fans, which typically operate with Reynolds numbers of 10^2–10^4. In addition, the required motor torque and power consumption of a fan is increased by the weight of the blade. A high efficiency can therefore not be achieved, and the targeted performance and efficiency are often not achieved.

2. Cross Section Of The Dragonfly Wing

The wings of a flying creature are designed to be strong, light, and to minimize the energy expended during flight. Moreover, they have a small wake and generate little noise. The efficiency of a fan can therefore be increased by decreasing the weight without decreasing the strength with regard to the motor torque and the axial bearing loss. In other words, the wing shape of a flying creature should be adopted in the design of a fan. For this purpose, we considered a dragonfly. The dragonfly is small and flies with a Reynolds number close to 10^3, which is comparable

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to that of the sirocco fan of our study. The specifications of the general sirocco fan used in an air purifier are as follows: diameter of ≈200 mm, height of 60–100 mm, rotational speed of 1200 rpm (circumferential speed of approximately 10 m/s), and volume flow rate of 6–8 m^3/min. The chord length and span are close to that of a dragonfly, and the circumferential speed of the blade is also close to the flight speed of the fly.

The Reynolds number of an air purifier sirocco fan is thus close to that of a flying dragonfly. As shown in **Fig. 1**, the Reynolds number of a dragonfly (especially the Anax parthenope) is about 3.1×10^3 [1] and that of a sirocco fan [2] (diameter: 200 mm, blade-to-blade gap: 5 mm, rotational speed: 1200 rpm, and temperature: 20°C) is 4.16×10^3. Among insects having a Reynolds number close to that of a sirocco fan, many studies have been conducted on the wings of a dragonfly with a flying prowess. Hertel [3] described that the wings of a dragonfly generate a lift higher than the wing of a plane, at a low Reynolds number. Many research results on the flight of a dragonfly have been published. Therefore, we considered that these results could be applied to the blade of a sirocco fan operating at a low Reynolds number.We therefore decided to apply the structure of the dragonfly wing to the sirocco fan blade. An ordinary fan for the air purifier is used as a sample fan. The inlet and outlet angles were 94° and 164°, respectively. We tried to decrease the noise of the fan installed above the air purifier by applying the dragonfly wing to it.

The wing of the dragonfly is a film with a non-streamlined and jagged cross section. It is known that vortexes are generated in the jags and the frictional drag between the air and the blade is reduced by the vortexes. The vortexes function as a ball bearing, and the strength of the thin blade is significantly increased by the jags [4]. We applied these features of the dragonfly in developing the shape of the air purifier sirocco fan blade.

3. Parameter Selection For The Determination Of The Optimum Cross Section

To determine the optimum blade shape, 37 prototypes were fabricated. In this paper, we will focus on describing 16 prototypes that have a high impact on performance. The noise was measured using experimental apparatus for noise measurement. The volume flow rate was fixed at 6.5 m^3/min by changing the rotational speed of the fan. Further, the power consumption was measured using a wattmeter.

The volume flow rate was measured using experimental apparatus, for measuring the aerodynamic characteristics. These values were measured using a built air purifier, rather than a fan. We set the following parameters in determining the optimum cross section of a fan that mimics the wings of a dragonfly:

- Inlet and outlet blade angles: To optimize the incidence and deviation angles, the inlet and outlet blade angles were optimized.
- Blade camber: The blade was cambered—something that could not be realized with a circular arc blade—and the effect on performance was examined. The blade camber is defined by the distance from the centerline of the ordinary circular arc blade to the jagged shapes on the pressure side.
- Jag depths: The effect of the jag depths on performance was examined. The jag depth is the amplitude of a jag from the ordinary circular arc.
- End position of the jags: The effect of the jag range on performance was examined by changing the end position of the jags.
- Number of jags: The effect of the number of jags on

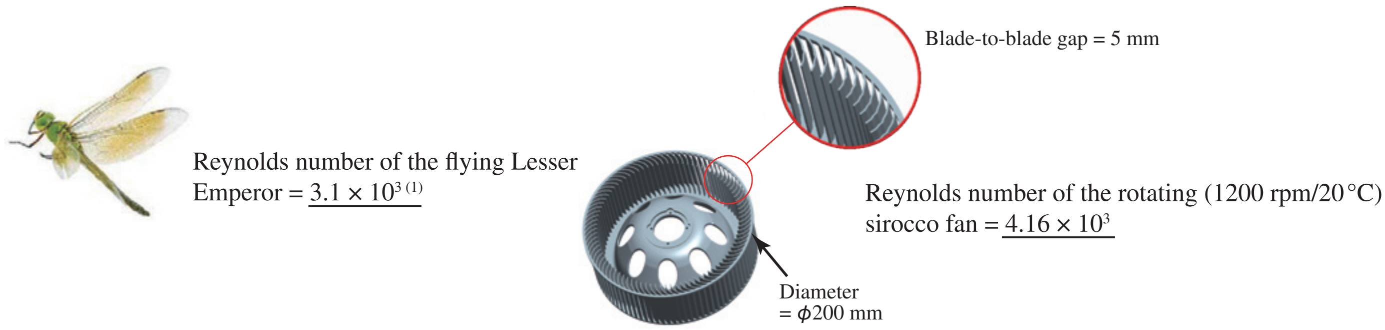

Fig. 1 Reynolds numbers of dragonfly and sirocco fan.

performance was examined.

- Virtual airfoil cross section: When vortexes were generated between the jags, the pattern of the virtual airfoil was changed several times and the effect on performance was examined.

3.1 Optimization Of The Inlet And Outlet Blade Angles

In applying the jagged cross section of the dragonfly wing to the air purifier fan blade, the following assumptions were made: 1) Resistance is reduced by the vortexes generated between the jags. 2) The flow pattern around the dragonfly after vortex generation forms the airfoil shown in Fig. 2 [4]. 3) When the jags are set as shown in Fig. 3, the thickness at the position 0.3C (C: chord length) from a leading edge is maximum, and the thickness is 0.12C. The cross-sectional shape of the wing of the sirocco fan is determined by referring to Fig. 2, and it is shown in Fig. 3.

To realize these assumptions, the performance of the fan was examined in terms of the inlet and outlet angles of the blade for a fixed jag form (jag position, depth, etc.). Fig. 4 shows the positions of the inlet and outlet angles.

Firstly, the volume flow rate, power consumption, and noise were measured with the inlet angle fixed at 94° and the outlet angle changed from 150° to 170°. The noise measurement condition is as follows. Noise is measured when the volume flow rate is 6.5 m^3/min. The measurement method conforms to JISC9615, and noise is measured at a point 1 m in front of the central portion of the body of the air purifier. As a result, a positive correlation was observed between the outlet angle and power consumption. It is expected that the volume flow rate will be maximum and that the noise minimum for an outlet angle is 160°, as shown in Fig. 5. Next, the outlet angle was fixed at 160° and the inlet angle changed from 80° to 105°. The power consumption, volume flow rate, and noise for these conditions are shown in Fig. 6. A positive correlation was again observed between the inlet angle and power consumption. Negative correlations were, however, observed between the inlet angle and both the volume flow rate and noise, as shown in Fig. 6. As noted earlier, one of the objectives of this study is the reduction of the air noise. Although we expected that the noise would be reduced by increasing the inlet angle, this also increased the power consumption. It was therefore necessary to define a weighting factor to determine a suitable relationship between power consumption and noise.

Because the purpose of an air purifier is to maintain air cleanness, and it is operated overnight, for a Japanese user, the demand for noise reduction is overwhelmingly greater than that for reduced power consumption. For this reason, we established weighting factors of 0.85 and 0.15 for noise and power reductions, respectively. The measured values of the noise and power consumption were nondimensionalized, multiplied by the weighting factors, and respectively totaled. The total was denoted by S, a small value of which indicated a demand for high performance by users. If an approximate line is drawn on Fig. 7 (a) using the least-squares method, S is expected to be minimized when the outlet angle is 160°.

Similarly, in case an approximate line is drawn on Fig. 7 (b), S is expected to be minimized when the inlet

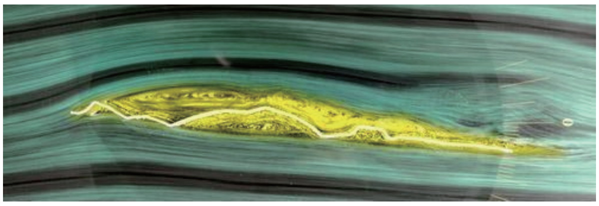

Fig. 2　Flow pattern around the dragonfly's wing [4].

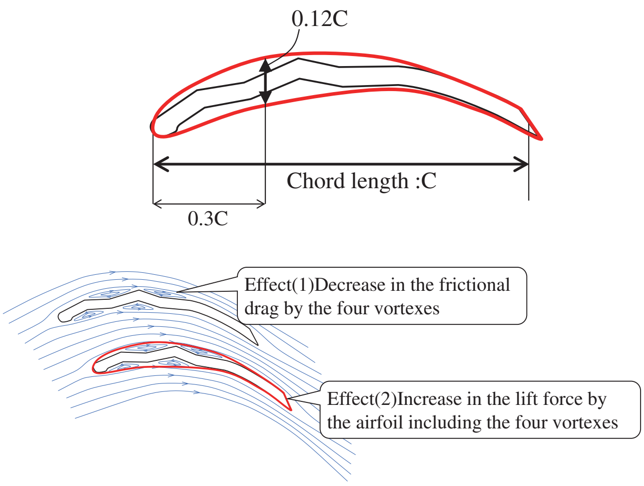

Fig. 3　Blade of sirocco fan and flow pattern around a sirocco fan blade with the shape of a dragonfly wing.

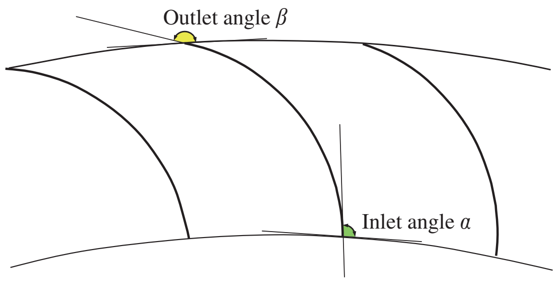

Fig. 4　Inlet and outlet angles of sirocco fan blade.

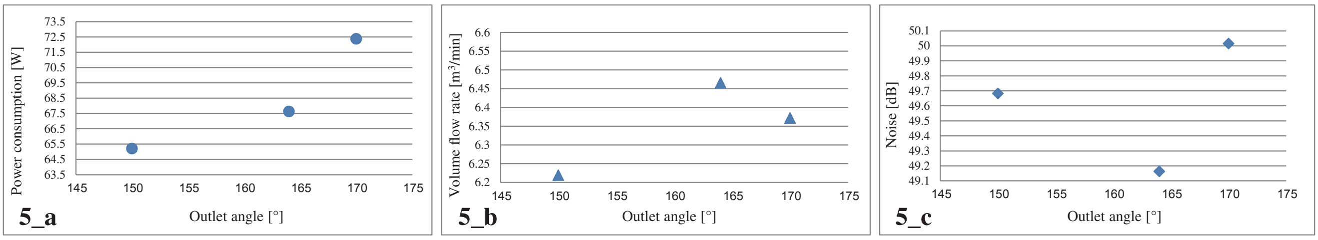

Fig. 5 Relationship between the outlet angle and performance of the fan; (a) power consumption, (b) volume flow rate, and (c) noise.

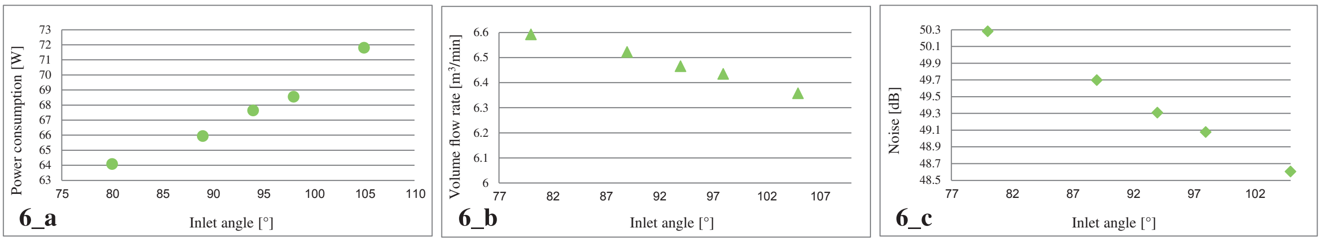

Fig. 6 Relationship between the inlet angle and performance of the fan; (a) power consumption, (b) volume flow rate, and (c) noise.

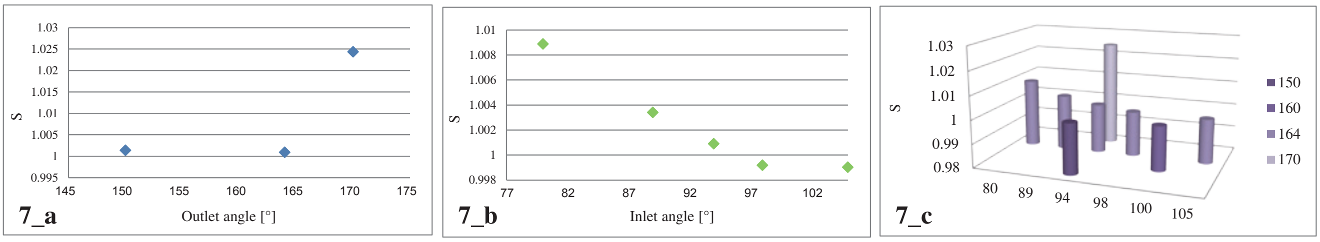

Fig. 7 Relationship between the inlet and outlet angles and S; (a) inlet angle and S, (b) outlet angle and S, and (c) inlet and outlet angles and S.

angle is 100°; using these results a prototype was then made, and a measurement was performed. Based on these results, the performance was again determined using inlet and outlet angles of 100° and 160°, respectively. All the data are presented below. Consequently, S was reduced further, and it was confirmed that the expectation was right. The optimal inlet and outlet angles of 100° and 160°, respectively, were used for all the experiments of the next section.

3.2 Effect Of The Blade Camber On Perormance

The effect of the blade camber on the performance of the fan was examined. As shown in Fig. 8, the jagged shape of the blade is defined as convex or concave depending on the distance from the centerline of the arc blade (L1). A concave shape represents the distance from the centerline (L1) to the jagged shape on the suction side, whereas a convex shape represents the distance to the jagged shape on the pressure side. The jagged shape is defined as convex1, concave1, convex2, and concave2 by the distance from L1 to the midpoint of the jagged shape. The midpoint of convex1 and concave1 is identified as center1, and the midpoint of convex2 and concave2 is identified as center2. The camber is defined by the distance from the centerline of the ordinary circular arc blade to center1 and center2. The three patterns described in Table 1—for which the sum of the deviations of L1 from the

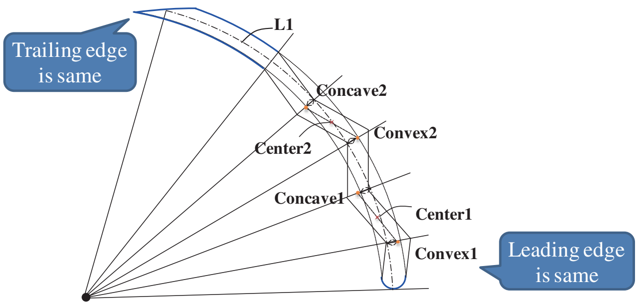

Fig. 8 Convex and concave portions of the jagged blade.

Table 1 Camber and noise.

Case	Camber [mm]	Noise [dB]
No. 2	0.1	48.92
No. 3	0	49.23
No. 4	0.2	49.12

ordinary circular arc blade centerline are respectively 0, 0.1, and 0.2—were examined.

As noted earlier, it is not possible to simultaneously optimize the incidence angle, deviation angle, and camber for a circular arc blade section. There is therefore a limit to the performance, efficiency, and noise reduction that can be achieved for a circular arc blade. However, the incidence angle, deviation angle, and camber can be simultaneously optimized using the jagged form of the dragonfly wing as a parameter. This is a secondary effect of applying the dragonfly wing; that is, it affords noise reduction that could not be achieved by the ordinary circular arc blade.

3.3 Effect Of Jag Depth On Performance

Next, the effect of the jag depths on performance was examined. The rear and front positions of the jags were fixed while the depths were varied. With the positions of center1 and center2 fixed, the eight prototypes were examined while varying the jag depths, as shown in **Table 2**, where the amplitude is the sum of the jag depths.

It was observed that the volume flow rate (6.5 m^3/min.) and power consumption (about 62 W) did not change, but the noise changed with the jag depth, as shown in **Fig. 9**. An amplitude of 1.1 mm was found to be ideal. However, the noise rapidly increased after a certain point, as shown in **Fig. 9**. The flow separation was considered to be the reason for this. **Fig. 10** shows the flow pattern diagrams of the phenomenon. The figure on the left-hand side of **Fig. 10** shows the flow pattern diagram when the flow did not separate because the amplitude of the jag was lower than that of case No. 8 in **Fig. 9**. The figure on the right-hand side of **Fig. 10** shows the flow pattern diagram of case No. 9 or No. 10 when the flow separated from the blades because the amplitude of the jag was too high and the noise increased.

It was observed that the jags could be used to reduce the noise to a certain degree, although very deep jags increased the noise.

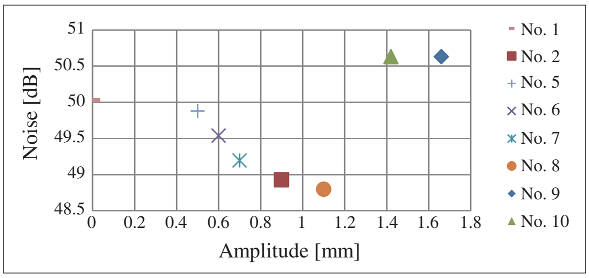

Fig. 9 Relationship between the amplitude and noise.

Table 2 Amplitude and noise.

Case	Amplitude [mm]	Noise [dB]
No. 1	0	50.03
No. 5	0.5	49.87
No. 6	0.6	49.53
No. 7	0.7	49.19
No. 2	0.9	48.92
No. 8	1.1	48.79
No. 10	1.4	50.63
No. 9	1.7	50.63

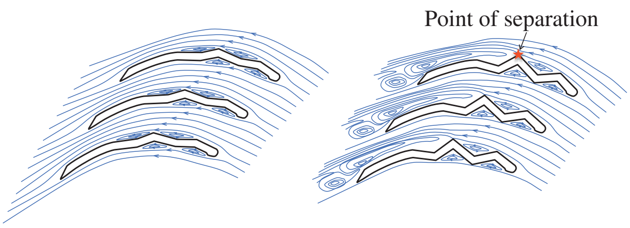

Fig. 10 Pattern of the flow separation at the jags.

3.4 End Position Of The Jags

Next, the effect of the end position of the jags on performance was examined. With the starting position of the jag fixed, the end position was varied as 0.65, 0.55, and 0.45 from the front. As seen in **Table 3**, the noise was at a minimum for 0.55. Although the flow around the wings of a dragonfly is similar to that of an airfoil, this observation might be due to the separation of the flow at the jags with respect to their positions. Because the 0.65 point was too close to the rearguard, the flow was considered to separate at this point. Conversely, for the 0.45 point, the imaged wings took on the shape of a tadpole because the jags were excessively concentrated at the front and the drag coefficient might have increased. This showed that the optimal point that could be used to control the flow separation and reduce the drag coefficient was approximately 0.55. The jags must therefore be set at 0.55 in the first half.

Table 3 End position and noise.

Case	End position	Noise [dB]
No. 2	0.65	48.92
No. 11	0.55	48.73
No. 12	0.45	48.97

3.5 Effect Of The Number Of Jags On Performance

Next, the effect of the number of jags on performance was examined using four, five, and six jags. The same thickness and position were used for convex1, concave1, convex2, and concave2, whereas convex3 and concave3 were added behind, as shown in **Fig. 11**.

The noise increased for five jags, as seen in **Table 4**. It was also observed that the side of the last jag (suction or pressure) affected the noise. When the last jag was on the suction side, the flow separated and the noise increased. In addition, the difference between using five and six jags was that concave3 was on the positive pressure side. It is supposed that the jag suppressed the separation at convex3. Moreover, the noise for six jags was lower than that for five jags. Flow separation is expected to occur if the last jag is convex.

The relationships among the rotating speed, volume flow rate, and power consumption were also examined. It was observed that a 0.04 m^3/min (at 1400 rpm) reduction in the volume flow rate was accompanied by a 0.4 W increase in the power consumption for five jags, compared to four and six jags. This is supposed to be a result of flow separation. In this case, because the amplitudes of the jags are small, there were no significant adverse effects; however, for a larger amplitude, a severe increase in noise is expected. Therefore, as previously, the last jag should be set on the positive pressure side.

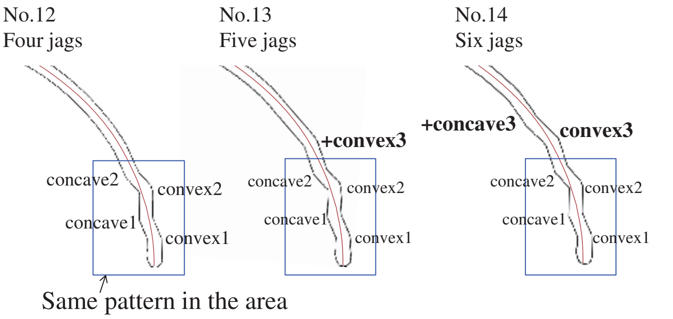

Fig. 11 Blade shape pattern according to the number of jags.

Table 4 Number of jags and noise.

Case	Number of jags	Noise [dB]
No. 12	4	48.97
No. 13	5	49.21
No. 14	6	49.02

3.6 Effect Of The Virtual Airfoil Shape On Performance

Finally, the effect of changing the virtual airfoil shape on performance was investigated. As noted earlier, the virtual airfoil that was considered had a maximum thickness of approximately 0.3 C. The thickness of the rear of the jag was greater than the thickness at the front. **Fig. 12** compares the effects of when the thickness of the front jag is greater, the same, or less. As seen in **Table 5**, there was no significant change in the volume flow rate and noise.

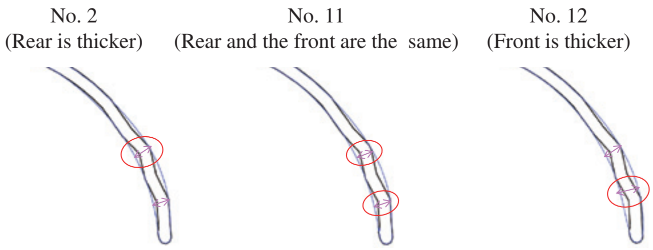

Fig. 12 Three virtual airfoil shapes.

Table 5 Maximun thickness point and noise.

Case	Maximum thickness point	Noise [dB]
No. 2	Rear	48.92
No. 15	Middle	48.94
No. 16	Front	48.98

4. Conclusion

Below are the findings of the study:

- Good performance was achieved for inlet and outlet angles of 100° and 160°, respectively.
- All the jags should be set at 0.55 in the first half of the chord length.
- The last jag should be set on the positive pressure side.

The circular arc blade is weak under pressure because the lift is not efficient, and flow separation and turbulence occur downstream of the suction side of the blade. Because the lift of the newly developed fan is efficiently generated by the airfoil, the flow is smooth downstream of the suction surface of the blade. **Fig. 13** shows the ordinary and newly developed air purifier sirocco fans, as well as

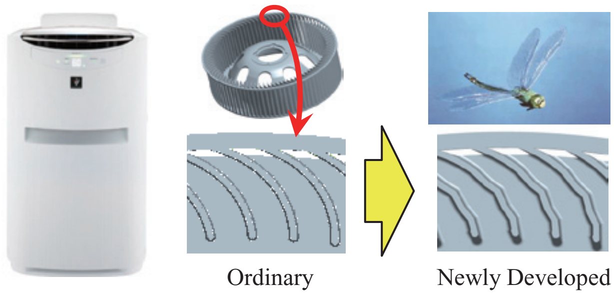

Fig. 13 Ordinary and newly developed fan blades, and end product of the research.

the end product of this research. **Table 6** lists all the prototypes.

5. Summary

Using the cross-sectional shape of a dragonfly wing, the noise of an air purifier sirocco fan blade was reduced. The reduced friction drag of the jagged cross section was used to achieve a noise reduction of 1.3 dB for Q = 6.0 m^3/min compared to an ordinary fan blade. A reduction of 1.3–2.5 dB was achieved over the entire area, as shown in **Fig. 14**.

This study makes a significant contribution to the fan industry because its findings can also be applied to blowers and a broad range of other equipment. The study confirmed that drawing inspiration from nature, particularly the body features of living creatures, is important to technological development. This requires an understanding of the form of the living creature, the pertinent physical phenomena and mechanisms, and the determination of the specific shape that can be used to replicate the performance of the creatures.

We hope for the further development and practical application of bio-mimicking in the future.

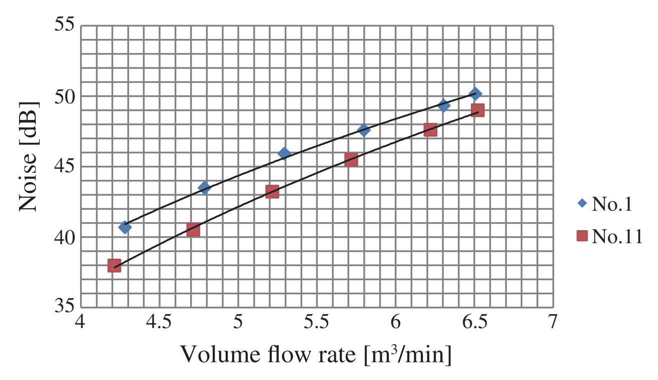

Fig. 14 Noise comparison of ordinary and newly developed air purifiers.

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Table 6 List of all prototypes.

Prototype No.	Camber [mm]	Amplitude [mm]	End-position	Number	Maximum thickness point	Noise [dB]
No. 1	—	0.0	—	—	—	50.03
No. 2	0.10	0.9	0.65	4	0.3	48.92
No. 3	0.00	0.9	0.65	4	0.3	49.23
No. 4	0.20	0.9	0.65	4	0.3	49.12
No. 5	0.60	0.5	0.65	4	0.3	49.87
No. 6	0.00	0.6	0.65	4	0.3	49.53
No. 7	0.10	0.7	0.65	4	0.3	49.19
No. 8	0.10	1.1	0.65	4	0.3	48.79
No. 9	-0.33	1.7	0.65	4	0.3	50.63
No. 10	-0.33	1.4	0.65	4	0.3	50.63
No. 11	0.15	1.0	0.55	4	0.3	48.73
No. 12	0.05	0.9	0.45	4	0.3	48.97
No. 13	0.10	1.1	0.55	5	0.3	49.21
No. 14	0.05	1.3	0.65	6	0.3	49.02
No. 15	0.10	0.9	0.65	4	0.2	48.94
No. 16	0.10	0.9	0.65	4	0.1	48.98