論文

Development of Electric Fan Propeller Featuring Chestnut Tiger Butterfly Wing Characteristics

アサギマダラ蝶の翅形状を応用した扇風機用プロペラファンの開発

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Sharp Corporation has been developing high-performance electric fans by applying the characteristics of wings of living creatures. This paper describes an electric fan having a propeller that mimics the shape of the wings of a Chestnut Tiger butterfly. Most electric fans generate a nonuniformly distributed wind velocity, which cause an uncomfortable feeling for the user. If the number of fan blades was increased, the wind generated would be smoother; however, the efficiency of the propeller itself would decrease. To solve these problems, we have modeled prototype electric fan propeller blades based on the shape of a Chestnut Tiger butterfly wing.

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。本稿では，数千キロも海を渡るアサギマダラ蝶の翅形状を模したプロペラファンの開発について報告する。プロペラファンが生成する風速分布は不均一であり，不快感の原因となる。羽根枚数を増やせば，ムラの少ない滑らかな風を生成することができるが，ファン効率が悪化するという問題がある。この問題を解決するため，アサギマダラ蝶の翅形状を模してプロペラファンの設計を行った。

1. Introduction

The wind generated by most electric fans is nonuniform, which gives an uncomfortable feeling to the user. There are two reasons for this.

The first derives from the property of the propeller fan itself. In general, propeller blades are mounted on a boss at the center of a fan. Around the boss, a wind is barely generated or a backward flow is generated, and it is only at the blade tips that an effective wind is generated, where there is an adequate rotational speed. The second reason is the relationship between the efficiency and number of propeller fan blades. As the number of blades increases, the wind velocity distribution becomes smoother, but the efficiency of the fan decreases and the noise increases. In other words, a trade-off relationship is established between comfort and performance.

The wind that an electric fan generates is felt by the user directly; therefore, the quality of the wind is very important. Given this background, we decided to develop a fan blade that generates a comfortable, uniformly distributed wind. To achieve this, we sought to enhance the diffusion of wind by redesigning the outer part of the fan blades and increase the wind velocity at center part of the fan by redesigning the blade near the boss.

2. Chestnut Tiger butterfly

The Chestnut Tiger butterfly (**Fig. 1**) is the only migratory butterfly in Japan. When Chestnut Tiger butterflies travel thousands of kilometers across the sea to escape the cold, they do not flap their wings repeatedly, instead they ride the air currents. Many other butterflies maneuver their bodies and fly in complex patterns to escape predators, but the Chestnut Tiger butterfly prefers to glide.

We started our study with certain expectations for the characteristics of the wing of a butterfly. The specification of a standard propeller fan used for electric fan is as follows: the diameter is about 300 mm, height is 40−55mm, and velocity of the wind is 3 m/s at low speed (many users always use the fan at low speed). The Reynolds number of the propeller for an electric fan is close to the Reynolds number of the Chestnut Tiger butterfly. The Reynolds number of a butterfly (especially the Chestnut Tiger butterfly) is about 6.6×104 (flying velocity: 8.3 m/s, forewing width: 120 mm, temperature: 20°C), and the Reynolds number of the propeller fan (specifications: diameter: 320 mm, wind velocity: 3 m/s, temperature: 30°C) is 6.0×104. Therefore, we decided to apply the structure of a butterfly’s wing to the propeller fan blade, opting for the Chestnut Tiger butterfly.

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3. Mimetic of the constriction shape of the outer part

We decided to improve the comfort factor by mimicking the constriction shape of the outer part of the wings of the Chestnut Tiger butterfly in the propeller fan, which has proved to be a high efficiency fan for outdoor air conditioners. “Constriction shape” is a shape in which there is a convex area between the leading and trailing edges of the blade, by an edge getting in the trailing edge side outside a fan inward. A constriction shape that evenly divides the front and back of a wing, like the wings of a butterfly, was used in a four-blade propeller fan (**Fig. 2**) (diameter of fan: 320 mm, height of fan: 55 mm, diameter of fan guard: 360 mm). The appearance of the fan is important for the user.

As the NZ noise caused by the rotation of the propeller increased, the total noise emitted by the fan increased. NZ noise is a resonance noise resulting from the rotational speed and number of fan blades (narrow band noise with the frequency [Hz] = NZ/60, N: rotational speed [r/min], Z: number of blades). It occurs because of the periodic pressure fluctuations from the rotating fan. Because it is a resonance noise, it can be decreased when the number of fan blades is a prime number. By installing a vibration pick-up immediately behind the outer part (constriction shape) of a fan, the pressure fluctuations in the wind is measured, and the frequency data are analyzed by a fast Fourier transform [2].

The noise waveform of this propeller fan is similar to that of an 8-bladed fan. It is found that the comfort factor provided by an 8-bladed fan could be obtained by a 4-bladed fan. The constriction shape of the wing shape of the butterfly is applied to the outer part of the fan blade. As a result, one blade produces the pressure fluctuations of two blades, and the pressure fluctuation on the downstream side of the fan is reduced by half. However, the efficiency does not decrease and the noise does not increase because the blade is actually a single blade. Accordingly, we achieved a high comfortfactor. The constriction shape decreased the wing area of the outer part, which relaxed the peak and smoothened the distribution of wind velocity. **Fig. 3** shows the noise waveform when the rotational speed of a prototype with a constriction shape is 800 rpm. The noise is supposed to have the peak of NZ noise at (4×800/60) 53 Hz, but the peak is 106 Hz. This shows that the 4-bladed fan behaves like an 8-bladed fan. **Fig. 4** shows the noise waveform when the rotational speed of a standard 5-bladed fan is 520 rpm (**Fig. 5**). The noise is supposed to have the peak of NZ noise at (5×520/60) 43 Hz. Next, the number of blades of the fan was increased to enhance the comfort factor. As shown in **Fig. 6**, the number of blades selected was seven, which is a prime number, to enhance the comfort factor while controlling the generation of NZ noise. The shape of the outer part is modified by following the actual shape of a Chestnut Tiger butterfly’s constriction. The area of the wing of the leading-edge side is greater, whereas the area of the trailing edge is smaller, and the shape is constricted to a greater degree inside the trailing-edge side. As a result, the generation of NZ noise was decreased. The wind velocity distribution was measured in the radial direction (measuring device: anemometer measuring method: At 30 mm downstream from the fan guard, wind velocities are measured at 10-mm intervals in the radial direction). By using a propeller fan with a constriction shape, the peak outside of the fan was reduced compared with standard fans.

Fig. 1 Chestnut Tiger butterfly.

There is another important point regarding the wind generated by an electric fan−the diffusion of the wind. At low speed (volume flow rate = 27 m^3/min), an electric fan can provide a wind for a few people by using the sweeping function, or spread a wind gently throughout the room. At low speed, the fan is required to deliver two functions. One is to generate a gentle wind with little feeling of discomfort even over a long period, and the other is to generate a wind that is diffused more widely. At high speed (volume flow rate = 50 m^3/min), the electric fan is used after bathing or to concentrate the wind at only one user, or it is used to agitate the air of the entire room by using it with an air conditioner to conserve energy. In other words, it is desirable to generate a highly convergent wind that suppresses the diffusion of the wind for the electric fan. However, this idea generates a conflict with standard wind generation using a rotator. This is because at low-speed rotation, the centrifugal force generated by the rotation of the fan is small and the wind converges.

In comparison, at high-speed rotation, the centrifugal force generated by the rotation of the fan is large and the wind spreads outward. The measured result for the diffusion angleof a standard fan and the prototype fan is shown in Table 1. Fig. 7 shows the definite of the diffusion angle, which is defined as the angle 1 m downstream of the fan guard; in other words, the angle is extended from the edge of the fan guard on one side. At low speed, the diffusion angle on one side of the propeller fan with a constriction shape was 169%, and at high speed, it was 135%, compared with a standard fan. The catchment area at low and high speeds was 167% and 153%, respectively, as shown in Table 1. By using the Taft method, the behavior of the wind at the outer part of the fan was confirmed in detail. As a result, it was found that the behavior of the wind at the constriction depends on the rotational speed, and the position of the separation of the horseshoe vortex from the wingtips of the fan blades depends on the rotational speed [2][3]. It was found that the angle of diffusion of the wind differs significantly according to the rotational speed, and it was suggested that the flow pattern becomes as in Fig. 8. The catchment area

Fig. 2
4-blade prototype.

Fig. 5
Standard fan.

Fig. 6
7-blade prototype.

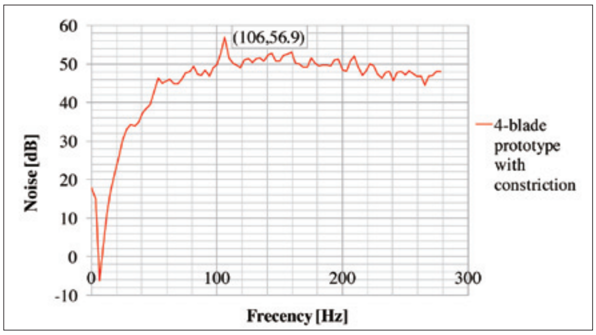


Fig. 3 Noise waveform of prototype with constriction shape.

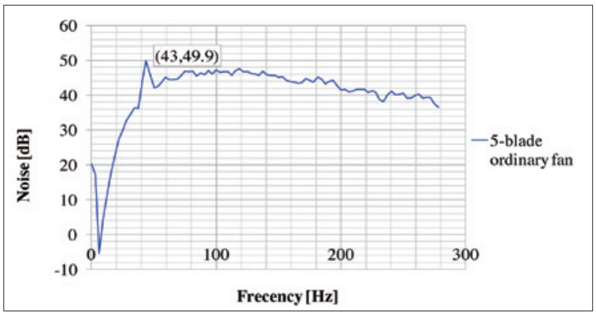
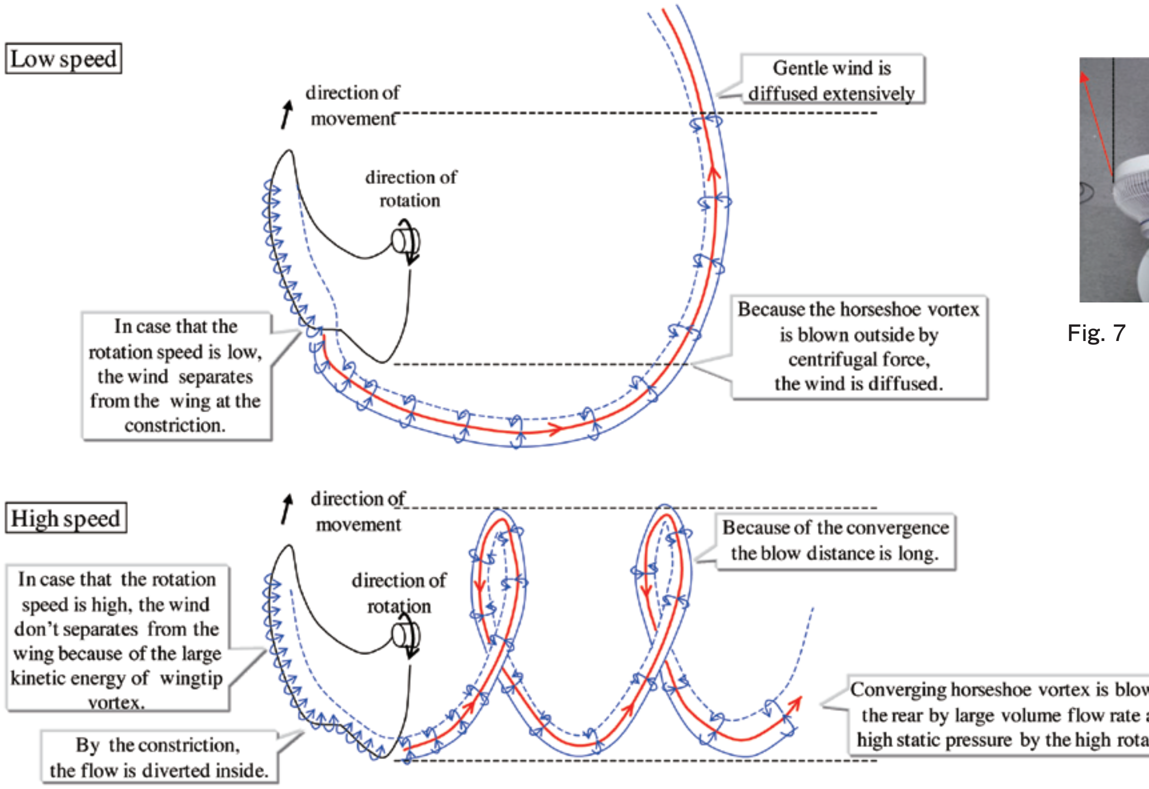


Fig. 4 Noise waveform of standard 5-bladed fan.



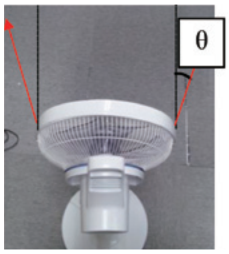


Fig. 7 Definite of the diffusion.

Fig. 8 Flow pattern diagram at low and high speeds.

means that the passing area of the wind is calculated using the diffusion angle at 1 m downstream from the fan guard. The expected flow pattern diagram by the measured result is shown in Fig. 8. When the fan is rotating at low speed, because of small kinetic energy, the separation of the horseshoe vortex is promoted by the shape of constriction of the wing, and the wind is diffused by centrifugal force. By using this phenomenon, we can increase the diffusion area at low speed. When the fan rotates at high speed, the flow is grabbed by the constriction shape and not diffused because of high kinetic energy.

The separation of a horseshoe vortex is not promoted by the shape of constriction of the wing, and the wind is not diffused by centrifugal force.

As a result, the convergence performance of the wind is increased. Therefore, it was understood that the wind spreads smoothly at low speeds and does not spread at high speeds. Moreover, flow separation is not promoted by the shape of constriction of the wing, and the wind is not diffused by centrifugal force. A horseshoe vortex accompanies the trailing edge of the fan blade and is separated from the blade at the end of the trailing edge. At this position, the diameter of the fan is slightly smaller and the direction of separation of the horseshoe vortex is taken inward. Thus, the spread to the outside of the horseshoe vortex is reduced, and the convergence performance is more advanced.

In addition, by measuring the velocity of the wind, it was confirmed that the range of reach of the wind with a velocity of 0.3 m/s (threshold: one can feel the wind) is equivalent to a standard fan, although the wind becomes softer and wider. The measured results are shown in Fig. 9.

4. Mimetic of the swell shape of center part of the wing

If only the constriction shape discussed above is adopted, the volume flow rate is decreased, which leads to a decrease in fan efficiency. Without reducing the volume flow rate, the wind velocity distribution should be made uniform and the peak velocity in the outer part of the wing should be reduced. The uniformity of wind cannot be achieved without considering the central part of the fan. In other words, it is necessary to generate the wind from this part effectively. Here we focused on the deformation of the wing of the Chestnut Tiger butterfly during flight, which bends significantly. We applied this shape to the blade shape of the central part of the propeller fan (near the boss). In a standard fan, the volume flow rate of the central part is lower than that of the outer part; i.e., the wing area is reduced to trim the weight of the fan. Therefore, a method to improve the volume flow rate of the central part was examined by increasing the angle of attack around the root of the blade, which was done by mimicking the swell shape of the wings of the Chestnut Tiger butterfly.

In this case, deterioration in the fan performance was anticipated because of the flow separation resulting from increasing the angle of attack significantly. To find the appropriate an gle of attack, we constructed prototypes of the fan and conducted experiments (Fig. 10). To define the shape of the blade, we considered three parameters height of propeller H, height at 0.3R $hr1$, and height at 1R (the wingtip) $hr2$. The variable ha ($=\frac{hr1}{H}$) is treated as a parameter for how the base part of the blade is raised:compared with the height of the fan. hb is treated as a parameter for how the wingtip of blade is raised compared with the height of fan.

In addition, by comparing ha and hb ($=\frac{hr2}{H}$), it is possible to understand the appropriate relationship between the base part and outer near-edge part of the fan. Table 2 shows the tested prototypes expressed using ha and hb. Fig. 11 (a, b, and c) show the wind distribution, volume

Table 1 Comparison of diffusion of standard fan and prototype fan.

Diffusion angle on one side θ [°]	Low speed	High speed
Standard fan	6.3°	13.8°
Prototype fan	10.6°	18.6°
Ratio of the prototype to standard fan of the diffusion angle	169%	135%
Ratio of the prototype to standard fan of the size of passing area of the wind	167%	153%

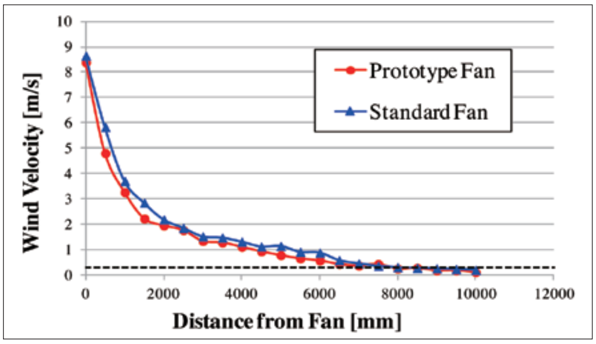
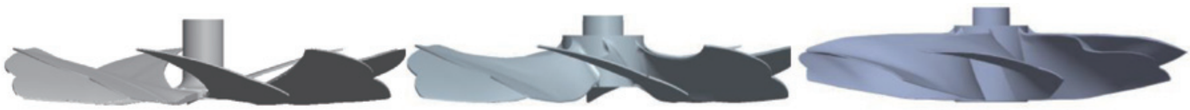


Fig. 9 Wind velocity of standard and prototype fans.

flow rate and electric power consumption of prototypes 1 and 2. In Fig. 11 (a), the horizontal axis is a radial dimensionless distance from the rotating axis at the center of the boss, 0 is at the center, and 1 shows the outer edge of the blade. The vertical axis represents the dimensionless wind velocity; the total sum of each dimensionless velocity in the area under the line is 1. If this wind velocity distribution is uniform (the plots are "flat"), which means that a smooth wind is generated from the entire fan. The velocity for nondimensionalization is always defined by the sum of the wind velocity of the 12 points in Fig. 11 (a). It was confirmed that the distribution does not change because of the rotational speed. The wind velocity of outer part of standard fan is fast, and slow at inner part. To obtain the same volume flow rate compared to prototype fan, there is the spot that the wind velocity is fast locally. To obtain the same volume flow rate, the maximum wind velocity of new prototype fan is small.When the skin of human body exposed to a strong wind, its temperature is lowered. It is well known, that a thermal comfort is correlated with temperature of body, in the condition of low temperature, the comfort is reduced.

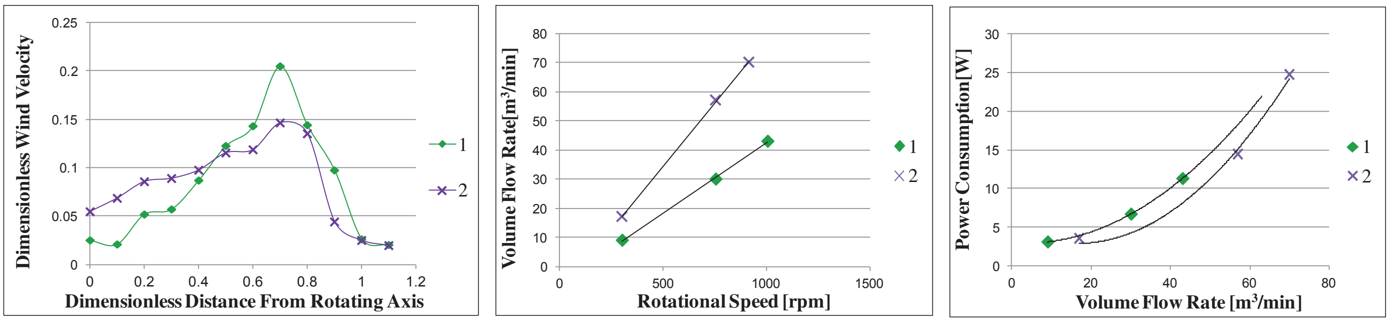
Fig. 11 (b) and (c) show a comparison of prototypes 1 and 2 from the viewpoint of the volume flow rate and electric power consumption. The difference in these prototypes is only the existence of a swell on the root of the blade; they have the same height and projected shape.

Accordingly, it is also known that the blood flow of capillary at the outer layer of skin is suppressed, autonomic nervous system rises, and the fatigue increases. [4] By suppressing the nonuniformity of the wind and reducing the maximum wind velocity, the effect of suppressing a decrease the temperature at the outer layer of the skin of the human body and reducing the fatigue by weakening the rise of the autonomic nervous system. [5] Fig. 11 (b) and (c) show a comparison of prototypes 1 and 2 from the viewpoint of the volume flow rate and electric power consumption. The difference in these prototypes is only the existence of a swell on the root of the blade; they have the same height and projected shape. Despite this being



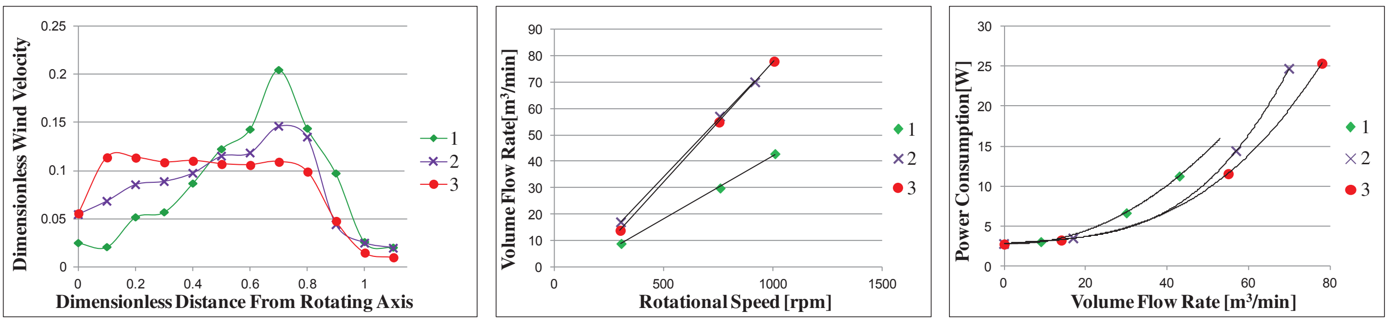
a) Prototype 1 **b) Prototype 3** **c) Prototype 10**

Fig. 10 Prototypes.



a) Radial wind velocity of prototypes **b) Volume flow rate** **c) Electric power consumption**

Fig. 11 Performance of prototypes 1 and 2.



a) Radial wind velocity of prototypes **b) Volume flow rate** **c) Electric power consumption**

Fig. 12 Performance of prototypes 1, 2, and 3.

the only difference, the volume flow rate generated by prototype 2 is more than 30% better than that generated by prototype 1.

From another viewpoint, the rotational speed and power consumption of the fan could be reduced. In addition, the fan efficiency is expected to be highest when *ha* = 1; this means that the height of the blade root is the same as that of the blade itself. However, as shown in **Fig. 11 (a)**, the wind distribution is still nonuniform and the comfort factor has not been improved yet. Therefore, an improvement of the comfort factor is necessary. Therefore, prototypes 2-1 to 2-4 were made, as *ha* was increased and *hb* was decreased to increase the comfort factor. **Fig. 13** shows the wind distribution measurement on one side of the six prototypes. In prototype 2-4, the comfort factor was improved greatly, but the wind velocity was very small at x = 0.8. As a result, a decrease in the volume flow rate is expected. This derives from significantly decreasing hb. To solve this problem, prototype 3 was constructed. **Fig. 12 (a)** shows the wind velocity distribution on one side of prototypes 1, 2, and 3. Without decreasing the wind velocity at x = 0.8, the plots became flat. From the result of measurements, we found that when *ha* is near 1 and *hb* is near 0.6, the distribution of wind velocity from the center to the wingtip becomes uniform, resulting in the comfort factor being the highest. **Fig. 12 (b)** and **(c)** show the volume flow rate and electric power consumption of three prototypes, respectively.

The volume flow rate is increased without increasing the electric power consumption by prototypes 2 or 3.

Next, the comfort factor, which is improved by mimicking the constriction and swell of the wing of the butterfly, is discussed here in detail. **Fig. 14** shows the measured results of wind speed distribution in the radial direction of a standard and prototype fan (prototype 10) at low speed. The horizontal axis is a dimensionless distance from the center, 0 is the rotational axis at the center, and 1 is the wingtip. The vertical axis represents the wind velocity.

In addition, the value of the slope of the wind distribution is calculated by inserting the straight line of a first-order approximation to the measured data; the slopes (coefficient) of the straight line were considered to show one of the indexes of uniformity of wind. Moreover, the index of drift, which is the index representing the nonuniformity of the flow, was also calculated and compared. Here the index of sinuosity (S) is an index of nonuniformity; i.e., it shows the roughness of the wind. When S takes a small value, the flow is uniform. Its definition is as follows: S = (Vmax－Vmin)/Vave. As shown in **Fig. 13**, a standard fan's slope of distribution of wind velocity and the value of S are large－between 1/3 to 2/3 of its width－and the difference between the fast and slow areas is large. The prototype fans have a small slope and slight bump in the distribution of the wind velocity.

As a result, the slope of wind distribution is less than1/100 and the index of drift is about 1/40 the drift indexes. With the fan guard, there is a windless boss at the center of the fan, and the outer part of the fan is also subject to erosion. Moreover, the wind speed is lowered significantly; therefore, these areas are outside the scope of application. These values have been evaluated in the range that the wind blows as expected, i.e., between the inner 1/3－2/3 of the fan diameter, as shown in **Table 3**. By the swell and constriction shapes of the fan, the wind velocity in the radial direction becomes completely uniform. In other words, the velocity of the wind is the same everywhere; the wind brings a comfort feeling. By applying the deflection shape of the wing of the flying Chestnut Tiger butterfly, the fan performance and comfort factor were greatly improved.

5. Performance of prototype fan

We validate the effect of the constriction and swell mimicking the butterfly's wing from the viewpoint of the entire electric fan system. **Table 4** shows the data of the specifications of two standard electric fans (one selected for efficiency, the other for comfort factor) and the developed fan with new wing shape. Model A, the efficiency model, has five blades of standard shape.

Model B, the comfort model, has seven blades of standard shape. Their blades do not have swell or constriction shapes. One of the characteristics of the electric fan is the trade-off between efficiency/noise and comfort factor: when the blade number of the fan is small, its efficiency is high and the noiseis low. However, the wind on the downstream side of the fan becomes complex and unpleasant because of the fluctuations in pressure. On the other hand, when the blade number of the fan is large, its efficiency is low and the noise is large, and the wind on the downstream side of the fan becomes comfortable and gentle because of the small fluctuations in pressure. Then, the constriction shape is applied to the fan blade, which halves the pressure fluctuation on the downstream side of the fan.

As a result, we achieved a high efficiency and high comfort factor simultaneously. This table shows that the volume flow rate decreased by concentrating on the comfort factor; however, to obtain the desired volume flow rate, we must abandon the comfort factor provided by the standard technology. With the developed electric fan containing a new wing shape, the uniformity and comfort factor of the wind was increased greatly without compromising the basic performance of the fan blower. From the table, the trade-off between the comfort factor and performance is solved by the development of a fan inspired from the shape of a butterfly's wing. Finally, a product as shown in **Fig. 15** was developed by this study.

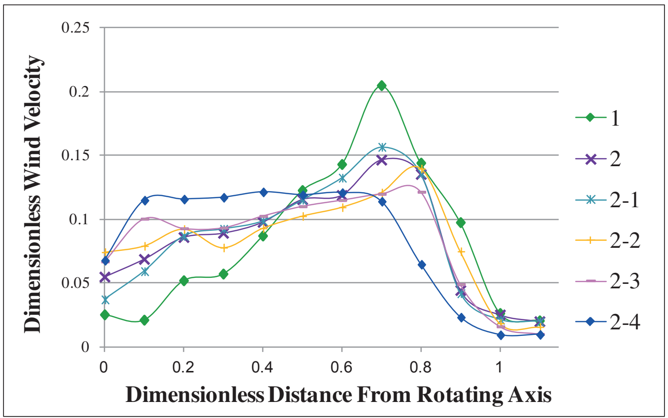


Fig. 13 Radial Wind velocity of all prototypes.

Table 2 Parameters of swell.

Prototype No.	$ha = \frac{r1}{H}$	$hb = \frac{r2}{H}$
1	0.24	0.91
2	0.58	0.91
2-1	0.63	0.91
2-2	0.74	0.91
2-3	0.95	0.71
2-4	0.98	0.50
3	1.00	0.63

6. Conclusion

In existing electric fans, there is a trade-off relationship between the comfort factor and performance. To resolve this problem, we developed a propeller fan inspired by the shape of a butterfly's wing, and evaluate the fan from the viewpoint of the comfort factor and efficiency.

The results are listed below.

1) By applying a constriction shape to the tip of the fan blade by mimicking a butterfly's wing shape, the wind generated by the tip of the fan becomes very smooth.
2) By applying a swell shape to the root of the fan blade, a contribution by the central part of the fan to the entire wind generation was achieved.
3) An electric fan with fan blades of this design can generate a comfortable wind at high efficiency.
4) Biomimetics for home electronics are effective.

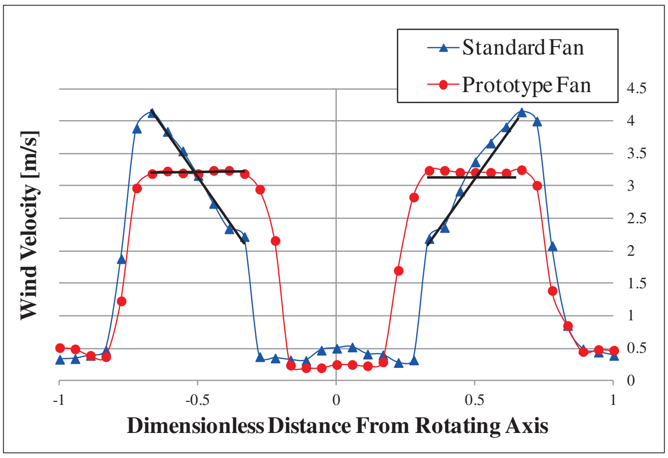


Fig. 14 Wind distribution of standard and prototype fans.

Table 3 Slope of wind distribution and index of drift.

	Slope of wind distribution	Index of drift (S)
Standard fan	0.341	0.604
Prototype fan	0.00214	0.0155
Improvement	1/159	1/39

Table 4 Specification of two standard fan models and a prototype fan.

	Specification				Comfort factor	
	Volume Flow rate [m³/min]	Rotational speed [rpm]	Noise [dB]	Power consumption [W]	Slope of wind distribution	Index of drift
Model A	51	950	47	16	0.341	0.604
Model B	31	1000	46	16	0.0369	0.2787
Comparison	▲40%	▲42%	Equivalent	Equivalent	1/10	1/2
Prototype fan	50	800	46	15	0.00214	0.0155

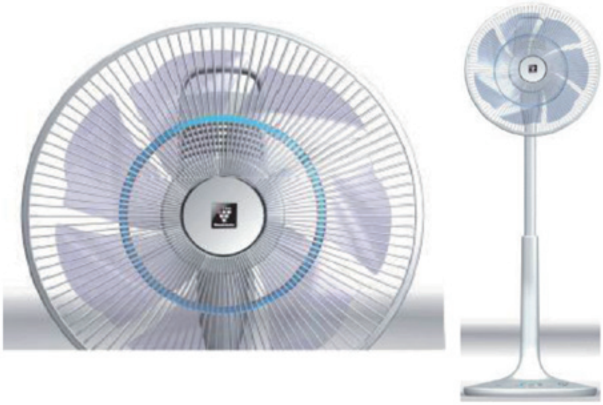


Fig. 15 Electric fan featuring Chestnut Tiger Butterfly wing.

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