An Experimental Study on Noise Reduction of Axial Flow Fans

(1st Report, Effects of some parameters on blade elements)

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Study on noise reduction of the axial-flow fans was carried out, varying principal assumed parameters such as the chord length of the blade, the camber of the airfoil, the position of maximum camber, and the surface pressure distribution of the airfoil. A separated flow on the surface of the two-dimensional airfoil was observed with use of the Schlieren device, and measurements were made of the strength of turbulence with use of a hot wire probe so as to determine their correlation with fan noise. The airfoil profile was determined by calculation using an optimum pressure distribution. As a result, the relations between the parameters and fan noise reduction have been clarified.

1. Introduction

Axial fans without a stationary blade are widely used in cooling towers and for ventilation in factories. The static pressure required of most of the fans of this type is as low as around 20 mmHg and even if they are equipped with a silencer for noise reduction, pressure loss will amount to several mmHg. This brings about a great decrease in the wind velocity in the silencer and as a natural result, silencers are increasing in size recently. For this reason, there is a strong demand to dispense with a silencer for the axial fans of this type or to reduce the noise of the fans themselves in order to decrease their load.

Generally, noise emitted from axial fans is composed of a rotational noise having discrete components at a blade passing frequency (number of blades x rotating speed) and at its higher harmonic and a continuous broad band noise caused by random pressure fluctuations. Therefore, overall noise is the synthetic noise of these two kinds of noises.

As the rotational noise of the axial fan without a stationary blade is low at blade passing frequency as the number of blades is small (this tendency is more remarkable in larger-sized fans as the rotating speed also decreases), the band sound pressure level of Net A is low and makes little contribution to the overall level of the fan noise. Therefore, the reduction of the continuous broad band noise caused by random pressure fluctuations becomes a subject for study.

The broad band noise is caused by unsteady fluctuations of the forces acting on the blades. Sharland classified the noise into the following three kinds: (1) noise due to fluctuations of lift caused by the turbulent component of the flow entering the blades, (2) noise due to pressure fluctuations resulting from the growth of a turbulent boundary layer on the blade surface, and (3) noise caused by fluctuations of lift due to the vortex of wakes emitted from the trailing edge.

Sharland also made clear that among the three kinds the noise (3) is predominant and that sound intensity is proportional to the sixth power of the representative velocity (for example, the peripheral velocity of the impeller). From the above the following two items become subjects for study: (a) reduction of the peripheral velocity of the impeller and (b) reduction of turbulent fluctuations of the forces acting on the blades. Most of the past studies on noise reduction concerned the rotating noise of axial fans with stationary blades, in which the researchers tried to reduce noise by adjusting the relative distance between the rotor and stationary blades or the angle of intersection. However, concerning the studies on the reduction of noise of the blade elements there are practically no data. In the present study, the authors conducted in connection with (a) and (b) mentioned above experiments on the elements of the rotor blade by changing the chord length of the blade, the camber of the blade profile, the position of the maximum camber and pressure distribution on the blade surface in order to make clear the effects of the blade elements on the reduction of noise. Furthermore, by use of a wind tunnel they observed a separated flow on the surface of the single blade with a Schlieren device and measured the intensity of turbulence with a hot-film probe to investigate the correlation between these elements and fan noise. In this paper the results are reported.
2. Symbols

The following symbols are used in this paper:

\( Q/Q^* \) : air flow rate m³/min (or m³/s)
\( Q^* \) : air flow rate at maximum efficiency point m³/min
\( P_T \) : flow rate ratio
\( P_{Tmax} \) : total pressure kgf/m² (mm Hg)
\( P_{T0} \) : shut-off total pressure m³/kgf
\( L_s \) : shaft power kW
\( L_o \) : shut-off shaft power kW
\( Z \) : total pressure efficiency %
\( Z_{max} \) : maximum efficiency %
\( SPL(A) \) : mean value of noise levels at three points (A, B, C) dB(A)
\( k_s \) : specific noise level = SPL(A) - 10log(GAPT) dB
\( SPL(A)_{rb} \) : noise level at reference dB(A)
\( f_r \) : blade passing frequency Hz
\( f_c \) : center frequency of 1/3 octave band including \( f_r \) Hz
\( L \) : chord length mm
\( t \) : pitch of cascade mm
\( x_f \) : position of maximum camber of blade profile %
\( t_a \) : maximum thickness of blade profile %
\( \alpha \) : angle of attack
\( C_p \) : pressure coefficient = \( (p/p_0)/\rho U^2 \)
\( P_0 \) : pressure at uniform flow kgf/m²
\( p \) : pressure at an arbitrary point on blade surface kgf/m²
\( U \) : velocity at uniform flow m/s

3. Testing Apparatus and Test Method

3.1 Principal particulars of test fan

A fan without a stationary blade was used for the test. Its principal particulars are as follows: outside diameter \( D_o \) of impeller = 600 mm, hub ratio \( r = 0.25 \), tip clearance \( s = 2 \) mm, \( M/T = 0.0032 \), speed 1500 rpm (n=25 Hz), specific speed \( N_s = 2 \) 300, flow pattern = semi-free vortex type. Table 1 shows the principal particulars of rotor blades and the main dimensions of corresponding blade profiles. The chord length of the blade was 143 mm (fixed) with the root-mean-square radius \( r_m = 218 \) mm and the blade setting angle was 25°.

In the present study, the following four items were investigated experimentally in connection with (a) and (b) mentioned above:

(1) Effect of chord length
(2) Effect of the camber of blade profile
(3) Effect of the position of the maximum camber of blade profile
(4) Effect of pressure distribution on blade surface

The object of the investigation of items (1) and (2) is to reduce the peripheral speed of the rotor blade by increasing the blade load coefficient \( C(t)/t \) and that of items (3) and (4) is to reduce turbulent noise by shifting the separated flow on the blade surface as much as possible to the trailing edge side and reducing its scale to the smallest possible. As a method of investigation for the test fan, its performance and noise were measured and as for the elements of the test moving blade separated flows were investigated with use of a wind tunnel and their correlations were compared.

3.2 Performance and noise testing apparatus and test method

Performance test was carried out in accordance with the fan test method specified in the JIS B 8330 (Fig. 1). Air flow rate and pressure were obtained by the pitot tube method and its moving and static pressures were measured with a precision inclined manometer. The number of revolutions was read by a digital speed meter by installing a magnetic pick-up on the shaft end of a DC electric dynamometer. Adjustment of air flow rate was made by changing the throttle plate. To measure the noise of the test fan, it was installed at a place with a considerably open space around and noise levels at three points (A, B, C) were measured with a condenser microphone with a nose cone, and their frequency analysis was performed at D point. Attenuation of noise with distance was over 5 db/Db in all the three directions. Prior to measurement it was confirmed that background noise made a difference of over 15 db. The instruments used for noise measurement were as follows:

![Fig. 1 Test apparatus](image_url)
Precision sound level meter:  
10Hz - 18 kHz (manufacturer: B & K)  
Frequency analyzer:  
2 Hz - 45 kHz (manufacturer: B & K)  
Level recorder:  
10Hz - 200 kHz (manufacturer: B & K)  
3.3 Aerofoil testing apparatus and test method  

The solidity $t$ of the blade element of the test fan is less than 0.7, which is within the range where the characteristic value of the aerodynamic force of the independent blade can be used without considering the interference of the cascade. Therefore, an aerofoil with a chord length of 120 mm and a blade width of 200 mm, made of BK was mounted on the test section (200(W) x 400(H)) of the wind tunnel (Fig. 2) as a single blade (Fig. 3) and the condition of the flow on the blade surface was observed using a Shierien device and also photographed. Further, the intensity of turbulence was measured with a constant-temperature anemometer and a hot film probe (0.5 Hz - 30 kHz).  
The wind tunnel used was of nozzle type with a maximum wind velocity of 90 m/s with a deviation of 0.8 percent. The intensity of turbulence was 0.4 percent and uniform over the section. The blade pro-
files used were 11 kinds as shown in Table 1: N-1, N-9, G-1, G-2 and E-1 corresponding to the symbols of the blade profiles. The instruments used were as follows:  
Shierien device: Manufacturer: Ito-Koken  
Light source:  
Superhigh voltage mercury lamp 100 W  
Turbulence measuring instruments:  
55 A 01 type, 55A 83 type  
(manufacturer: DISA Co.)  

4. Test Results and Discussion  
4.1 Effect of chord length  
Rotor blades used for the test were 5 kinds, types A 100 - A 200, and the aerofoils of the blade elements were of N-1 type. The chord lengths of A 125, A 150, A 175 and A 200 types can be expressed as 125, 150, 175 and 200 percent respectively if the chord length of A 100 type at the root-mean-square radius is given by 100%. Fig. 4 shows an example of the results of investigation using these rotor blades on the effect of chord length on the performance and noise of the fan. Total pressure changed in proportion to chord length, but noise level SPL(A) remained almost unchanged. From this result it is found that specific noise level is reduced with an increase in chord length. There was no change in the value of $f_{max}$ even when chord length was doubled. Fig. 5 shows a
noise spectrum for the case where chord length was changed. On the axis of ordinate, \(\text{SPL}(A) = 10 \log_{10} QP^2\) is taken in place of \(\text{SPL}(A)\). This represents a quantity taking a change in total pressure into account and indicates a band specific sound pressure level (A).

Discrete noise at \(f = 100\) Hz is the fundamental rotational noise. It does not contribute to the overall level, its difference from the overall level being 25 dB. However, the effect of chord length is remarkable in the case of broad band noise over 500 Hz: band specific sound pressure level (A) is lower as chord length is larger. This was compared between the rotor blades of A 100 and A 200 types and it was found that there was a difference of 6 dB between their band specific sound pressure levels (A) both at 1 kHz and 2 kHz. A 200 type is also smaller than A 100 type in overall level by 4 dB. In the example shown in Fig. 4, solidity differs with rotor blade as the numbers of blade are the same. However, if the numbers of blades are 6, 4 and 3 for A 100 type, A 150 type and A 200 type respectively, solidity \(\pi/t\) takes the same value, i.e., 0.417. In this way, their \(\text{Ca}(\pi/t)\) becomes the same, their performances almost coincide at \(\gamma_{\text{max}}\) point and only their specific noise levels become different (figure is omitted). We investigated the relation between specific noise level \(K_s\) and solidity \(\pi/t\) in the range from 0.2 - 0.6 by varying \(\pi/t\) by various combinations of rotor blade and number of blades, the result of which is shown in Fig. 6. When \(\pi/t\) was 0.417, the A 200 type which has a larger chord length than the A 100 type had a smaller \(K_s\) by 5 dB and when \(\pi/t\) was 0.56, the \(K_s\) of the former was smaller by 6 dB than that of the latter. It seems from these results that this tendency has no relation with the value of \(\pi/t\).

### 4.2 Effect of camber of blade profile

Fig. 7 shows the performance and noise curves of four kinds of rotor blades with different cambers. As \(\text{Ca}\) changes according to camber, pressure is naturally affected by camber. However, cambers of 9 percent and 12 percent made only a small difference in pressures, but they made a big difference in noise levels. The noise levels of the four kinds of rotor blades were almost the same when cambers were 3, 6 and 9 percent. From this result it is clear that their specific noise levels differ according to camber. Fig. 8 shows the result of measurement of the various numerical quantities at \(\gamma_{\text{max}}\) point. Ti is found that specific noise level was the lowest when camber was 9 percent and was 2.5 dB lower than when it was 3 percent and 12 percent. Their efficiencies were higher when camber was smaller in relation to drag coefficient. Fig. 9 shows a noise spectrum with camber parameter, in which broad band noise higher than the medium frequency range was predominant. The maximum value of band specific noise level was 500 Hz or 630 Hz, indicating an attenuation characteristic of about 5 dB/OCF toward the high frequency range. Band sound pressure level in the frequency range from 500 to 8000 Hz became the highest when camber was 12 per-

![Fig. 6 Relation between \(K_s\) and \(\pi/t\)](image)

![Fig. 7 Performance and noise curves](image)

![Fig. 8 Relation between SPL(A) and \(f\)](image)

![Fig. 9 Noise spectra](image)
cent and became the lowest when camber was 9 percent. If 9 percent and 12 percent cambers are compared with respect to band sound pressure levels at 500 Hz and 2000 Hz, the former is lower by 4.2 dB and 5.5 dB respectively than the latter.

Fig. 10 shows an example of a separated flow on the blade surface photographed by Shliere method. It is found from the photo that separation started at a point a little toward the trailing edge from the middle of the chord length and grew gradually. For the evaluation of the separated flow, separation point, thickness of separated flow at the trailing edge, \(\delta_{z} = 0\) (Fig. 11) and intensity of turbulence in the trailing edge part, \(\sqrt{u'^{2}}\) were used.

Fig. 12 compares separated flows in four kinds of blade profiles at different angles of attack \(\alpha\). When the attack of angle was small, separation point approached the trailing edge with an increase in camber and the value of \(\delta_{z} = 0\) also increased. When the attack of angle was increased to 14.7°, the blade profile with a camber of 3 percent began separation at the leading edge and fell into stall state, while the blade profile with a larger edge did not start a leading edge separation yet.

Fig. 13 shows the relation between \(\delta_{z} = 0\) and camber. When camber was 3 and 6 percent, \(\delta_{z} = 0\) showed almost the same value but when it was larger than 6 percent, \(\delta_{z} = 0\) increased gradually. \(\delta_{z} = 0\) has a close relation with drag and in consequence \(\frac{C_{d}}{C_{d}}\) reach the maximum when camber was 3 and 6 percent and the maximum values in these two cases were almost the same (Fig. 8). When camber was 12 percent, on the other hand, the maximum value of \(\frac{C_{d}}{C_{d}}\) was smaller by about 8 percent. \(\delta_{z} = 0\) is in proportional relation with the intensity of turbulence and it is considered that it has a correlation with noise in relation to the area of separation point, that is, separated region. It may be understood from this fact why the aerofoil with a camber of 12 percent has such a large SPL(A) (refer to Fig.7).

### Fig. 11 Measurement of separated flow

- \(\alpha = 14.7°\)
- \(\alpha = 10.7°\)
- \(\alpha = 3.7°\)
- \(\alpha = 14.7°\)

### N-2 type (\(\frac{f}{c} = 3\%\))

### N-3 type (\(\frac{f}{c} = 6\%\))

### N-4 type (\(\frac{f}{c} = 9\%\))

### N-5 type (\(\frac{f}{c} = 12\%\))

### Fig. 12 Relation between \(f\) and separated flow

4.3 Effect of position of maximum camber

As shown in Fig. 14 pressure difference was small independently of the value of \(x_{f}\). However, Fig. 15 shows that specific noise level \(K_{s}\) was the lowest when \(x_{f}\) was 30 percent and efficiency was the highest when \(x_{f}\) was 20 percent. As can be seen from the noise spectrum shown in Fig. 16, the level was the highest in the frequency range over 250 Hz when \(x_{f}\) was 50 percent and the level was the lowest near 630 Hz, playing a predominant role in the overall level when \(x_{f}\) was 30 percent.
From the aforesaid it may be said that the effect of \( x_f \) is not so conspicuous as that of camber but the best result is obtainable when \( x_f \) is 30 percent. There is no noticeable difference in the effect of \( x_f \) on \( \delta_x = 0 \) when the angle of attack \( \alpha \) is 5° (Fig. 17).

Fig. 17 Relation between \( \delta_x = 0 \) and \( x_f \)

Fig. 18 Pressure distribution on blade surface

Fig. 16 Noise spectra

Fig. 19 Performance and noise curves
4.4 Effect of pressure distribution

Fig. 18 compares pressure distribution on the blade surface of N-5 type aerofoil with a sharp pressure gradient and that of G-1 type aerofoil with a comparatively gentle pressure gradient. As shown in Fig. 19 there was little difference in their pressure curves. This is because the lift coefficients of the two aerofoils are equal. However, the GR-2 type was about 3 dB lower in SPL(A) and 2 percent higher in $t_{\text{max}}$ than the GR-2 type. It is considered that the GR-2 type has a higher efficiency due to a smaller drag coefficient and the more gentle pressure gradient is responsible for the higher efficiency. Fig. 20 is a noise spectrum comparing the two kinds of aerofoils. The GR-2 type has a lower band specific noise level than the NR-5 type in all frequency bands including the rotational noise. It is presumed that the reason for this is that when pressure distribution curve is gentle, lift fluctuation is small, which not only gives an influence on rotational noise but also makes a great contribution to the reduction of turbulent noise. Fig. 21 shows the states of separated flows on the blade surface at various angles of attack. It is found from the figure that in the N-5 type, separation point is a little toward the leading edge and $\delta_0$ is larger than in the GR-2 type.

It is learned from the above that noise reduction may be attained by obtaining a blade profile with a proper surface pressure distribution. As an attempt, we obtained a blade profile in accordance with the flow chart shown in Fig. 23 by Kikuchi's method and using a computer, gave a pressure distribution as shown in Fig. 22. Fig. 25 shows the pressure distribution obtained in this way. Fig. 25 shows the performance of the fan using this blade profile (E-1 type) as blade element. As the estimated lift coefficient was small, pressure became a little lower and even if this point is taken into account, the E-1 type is lower by 4 dB in noise than the NR-5 type and by 1 dB lower than the GR-2 type. However, there seems to be a room for further study about whether the pressure distribution shown here is the most proper one or not.

START

Optimum pressure distribution is given

Speed on symmetrical blade surface Speed on camber line
Expansion in Fourier series (including angle of attack) Expansion in Fourier series (including angle of attack)
Determination of coefficient Determination of coefficient
Thickness distribution is obtained Camber line is obtained

Synthesis

Blade profile on upper & lower surfaces is obtained

END

Fig. 22 Given blade surface pressure distribution

Fig. 23 Flow chart
5. Conclusions

(1) In the present case, the contribution of rotational noise to the overall level was almost nil and turbulent noise was predominant.

(2) When solidity was constant, specific noise was lower as chord length was larger.

(3) There was no decline in efficiency when chord length was doubled.

(4) When camber was 3, 6 and 9 percent, there was little change in noise level when pressure changed. Consequently, specific noise level was the lowest when camber was 9 percent.

(5) The effects of the position of the maximum camber $x_f$ on performance and noise were small. However, when $x_f$ was 30 percent, specific noise level was low.

(6) An aerofoil with a gentle surface pressure distribution gradient has a lower noise level than one with a sharp pressure distribution gradient. Moreover, it is low in all frequency range including rotational noise.

(7) A further noise reduction could be attained by obtaining a blade profile by Kikuchi's method and giving a supposedly proper pressure distribution.

However, there is a room for further study as to the optimum condition.

(8) The thickness of the separated layer in the trailing edge part measured by Shilken device has a correlation with noise.

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References

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