Turbulent Noise Generated by a Jet Fan

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There are two mechanisms giving rise to the dipole-type radiation of the turbulent noise generated from Jet fan. One is the strong turbulence induced by a front rotor which flows into the rear rotor, which, in turn, random force fluctuation on a rear rotor blade. Another is shedding of vortices from the trailing edge of the both front and rear rotors. In this paper, we take these two mechanisms into consideration to theoretically estimate the turbulent noise level. The estimated values agree well with the measured levels of turbulent noise generated by the Jet fan. It is theoretically clarified that the noise generated by the rear rotor is higher than that from the front rotor. The noise due to the turbulent flow is higher than that due to the vortex shedding from the trailing edge of the rotor.

***Key words*:** Fluid Machine, Fan, Turbulent Noise, Specific Noise Level, Acoustic Power

1. Introduction

As one of the features of a jet fan, it is raised to that in the both case of positive and reverse rotation, the characteristic of the fan becomes the same. Therefore, the usual jet fan is installed one rotor at the upstream side another at the downstream side of the motor. In connection with such a two-stage system jet fan, authors made cleared that the jet fan noise consists of a discrete frequency noise and a turbulent noise. In this case, a discrete frequency noise generates mainly by interaction between the rotor and distorted flow, power cord.

The authors were clarified that when the frequency of discrete frequency noise agreed with the air column resonant frequency in a duct, the sound pressure level of a discrete frequency noise is magnified further(1). In a two-stage system jet fan, the turbulent flow produced by the front rotor flows into the rear rotor. Therefore, a steep increase in the turbulent noise resulting from the turbulent flow originate from front rotor is expected. Moreover, if the blades are cambered, the flow into the rear rotor will not be flowed along the blade than that of front rotor. Then the width of wake of rear rotor becomes wider than that of front rotor. And the turbulence noise based on the vortex shedding from the trailing edge of the blade increases as the wake width is increasingly.

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A symmetrical blade rotor can be considered as the policy which reduces such the turbulent noise. And if the aerodynamic performance of the single-stage jet fan which installed the symmetrical blade rotor is the same as that of the two-stage system jet fan, the specific noise level of single-stage jet fan will be lower than that of two-stage system jet fan.

On above mentioned background, in this research we experimented and considered on the aerodynamic characteristics and noise of the airfoil and symmetrical bladed two-stage system jet fan, and symmetrical bladed single -stage system jet fan.

Moreover we carried out theoretical prediction of the turbulent noise due to the vortex shedding from the trailing edge of the blades and large-scale turbulence in the flow. In addition to the theoretical prediction of the overall turbulent noise to the L characteristic was performed. The agreement between the predicted and measured values was fairly satisfactory.

2 Main symbols

a : Radius of vortex core m or mm
a_0: Sound velocity m/s

B : Number of rotor blades
C : Chord length m or mm
C_L : Lift coefficient
C_t : Chord length at the blade tip m or m
D : Width of wake m or mm
ΔD : Amount of increases of the width of wake by the effect of a leakage vortex m or mm
D_1 : Inner diameter of the rotor m or mm
D_2 : Outer diameter of the rotor m or mm
d : Longitudinal scale of the vortex measured from the leading edge m or mm
E : Total sound power W
E_t : Sound power due to turbulent flow W
Ev : Sound power due to vortex shedding W
F : Frequency Hz
K_{sA} : Specific noise level based on A characteristic SPL dB
K_{sL} : Specific noise level based on L characteristic SPL dB
L : Electric motor input W
: Turbulent scale m or mm
n : Harmonic number(n=1 for fundamental)
N : Number of rotations rpm
$\overline{(p^2)}^{1/2}$: Mean square average of sound pressure Pa
p_o : Minimum audible pressure Pa
P_T : Total pressure Pa
Q : Flow rate m^3/s
R : Radius of rotor m or mm
Rec : Reynolds number based on chord length
r : Radial distance m or mm
SPL_A: Sound pressure level based on the A characteristic dB

SPL_L: Sound pressure level based on the L characteristic dB

$\bar{s}$: Average value of tip clearance mm

T: Turbulent intensity %
t : Pitch mm
u_2: Circumferential speed at the tip of rotor m/s
W : Representational relative velocity m/s
W_1 : Relative velocity at a rotor inlet m/s
$\overline{(w^2)}^{1/2}$:Velocity fluctuation m/s
x : Axial distance mm
y : Radial distance from the wall surface mm
z : Distance between a sound source and an observation point m
β_2: Flow angle at a blade outlet deg.
$\Delta\beta_2$: Deviation angle in air flow angle deg.
γ_1: Blade inlet angle deg.
γ_2: Blade outlet angle deg.
η : Fan efficiency
: Ratio of the chord length to vortex scale
σ : Solidity
ν : Hub-tip ratio
ξ : Stagger angle deg
ρ : Air density kg/m^3
λ : Input power coefficient
ϕ : Flow coefficient
ψ : Pressure coefficient

3 Theoretical analysis of turbulent noise

The turbulent noise generated from a fan is mainly on the turbulent flow incomming blades and vortex shedding at trailing edge of the blade.

3.1 Turbulent noise resulting vortex shedded from trailing edge

Authors were introduced a equation(1) as sound power E_V of the turbulent noise based on the vortex shedding from the trailing edge of blades.

$$E_V = \pi B \rho \int D W^6 dr / (2400 a_o^3) \qquad (1)$$

Where B is the number of blade, ρ is the air density, D is the width of wake, W the relative velocity, r the radial distance and a_o velocity of sound.

3.2 Width of wake

The wake width contained in equation (1) is one of the important parameters of turbulent noise. **Fukano** and **Kodama** are clarified [3]that the turbulent noise due to the vortex shedding is estimated by equations(1) and (2) with sufficient accuracy, when the fan is operating near the maximum efficiency point.

$$D = D_t + 0.093\, C\, Rec^{-0.2} + \Delta D \qquad (2)$$

$$\Delta D = C' \tan(\Delta\beta_2) \qquad (3)$$

Where D_t is the blade thickness of trailing edge, and C is the chord length and Rec is the Reynolds number based on chord length and ΔD is the amount of increases of the width of wake by the effect of a leakage vortex. C' is the distance from point A to the trailing edge B.

$\Delta\beta_2$ is the deviation angle in flow angle at outlet, and is given by the equation (4).

$$\Delta\beta_2 = \arctan\left[0.25(C_t/t)C_L\{1-(y-\bar{s})/a\}\right] \quad (4)$$

Where C_t is the chord length at the blade tip, C_L the lift coefficient, t the blade pitch, y the radial distance inward from the inner surface of the duct, and $\bar{s}$ the tip clearance. The term a is the radius of the vortex core and defined by the next equation.

$$a = 0.14\bar{s}\left[d(C_L)^{1/2}/\bar{s}\right]^{0.85} \quad (5)$$

Where d is the longitudinal scale of the vortex measured from the leading edge.

3.3 Turbulent noise due to the turbulence flowed into the rotor blades

In the case of obstacles, such as a stator and strut, for the upstream of rotor, the large-scale turbulent flow flows into the down-stream rotor.

Sharland has discussed the turbulent noise due to the turbulent flow which flow into the rotor blades and introduced the equation (6) as the output power of sound [3].

$$E_T = B\rho \int \phi^2 C W^4 w^2 dr/(48\pi a_o^3) \quad (6)$$

Where ϕ is a lift curve slope, C the chord length and $(w^2)^{1/2}$ the mean square velocity fluctuation.

3.4 Lift curve slope

Liepmann is related turbulent strength and turbulent scale of main flow with the lift curve slope, and argues about it, and introduces the equation(7)[4].

$$\phi^2 = 2\pi^2[(4\eta-\pi)/\{2\pi(\eta^2+1)\} + (\eta^2+3)/(\eta^2+3)/(\eta\log\eta^2+\pi)\{2\pi(\eta^2+1)^2\}] \quad (7)$$

$$\eta = \pi C/L \quad (8)$$

L is the turbulent scale and C is the chord length of blade.

Therefore we can be obtained the value of ϕ by use of equations(7) and (8), if the turbulent scale of the main flow can predict (measurement). The turbulent noise due to the turbulent main flow can be predicted by equation(6) by use of the value of ϕ and the mean square velocity fluctuation.

3.5 Turbulent scale

The turbulent flow generated by front rotor blades flows into the rear rotor. And the turbulent scale is spread with the distance from the trailing edge of the front rotor blades. It is related the wake width D near the trailing edge of blade with the turbulent scale L in the axial distance X, and it is connected by a equation (9)[5].

$$L = 0.19(DX)^{1/2} + 0.5D \quad (9)$$

3.6 Turbulent noise of jet fan

In regard to two-stage system and upstream supporting-plate (introduction strut) type jet fan of a single-stage system, as mentioned above, the vortex shedding from the trailing edge of the blades and the large scale turbulence in the main flow generate. These can become the sources of turbulent noise. On the other hand, in the case of downstream supporting plate type (postpositing strut type) jet fan of the single-stage system the turbulence which flows into rotor blades is small. Therefore, we will be just to take a chisel into consideration of the source based on the vortex shedding as the source of turbulent noise.

The sound source based on vortex shedding and the turbulence in the main flow became independent mutually. If it assumes, the sound power of the turbulent noise is expressed by equation (10) as the sum of the sound power E_V due to vortex shedding and E_T due to the turbulence in the main flow, in the case of two-stage system and introduction strut type single-stage jet fan.

$$E = E_V + E_T \quad (10)$$

On the other hand, the relationship between the sound power E and sound pressure level SPL of the measuring point in the axial distance of z from a bellmouth end is expressed by equation (11).

$$SPL = 10\log_{10}\{3\rho a_o E/(8\pi z^2 p_o^2)\} \quad (11)$$

Where, p_0 is minimum audible pressure(=0.00002Pa).

4 Experimental apparatus and method

Fig. 1 shows the outline of the experimental apparatus of the two-stage system jet fan. The total length of the experimental apparatus is 2250 mm ,the outer diameter of duct is 630mm. And the axial distance between the trailing edge of front rotor and leading edge of rear rotor is 500mm. The details of the experimental apparatus the matter about explanation and measurement of sound level has given detailed in reference (1), therefore that of the experimental apparatus omit in this paper.

Fig. 2 shows an example of the rotor. The number of blades used in this experiment is four kinds of 3, 5, 6 and 7, and blade cross section shape is two kinds of the airfoil and symmetrical blades. Each diameter of these rotor is 624 mm and the average tip clearance is about 4mm. In addition the rotor with six and seven-blade is only used at the time of an experiment of a single-stage jet fan. The rotational frequency of each rotor is about 1960rpm, and the average axial velocity in flow rate at maximum fan efficiency is about 30m/s.

The main dimensions of the rotor used for two-stage system jet fan in this experiment are shown in table 1. In addition, for the single-stage jet fan, the rotor with symmetrical blades is used. In this case, the stagger angle of blades was installed in 49.5 degrees as the flow rate of single-stage fan was the almost same that as two-stage.

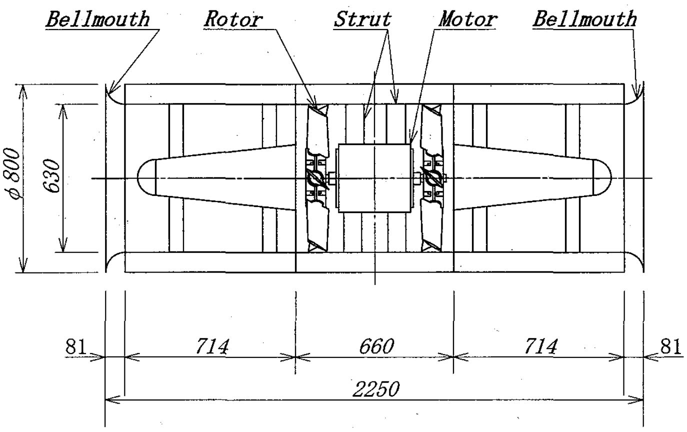


Fig.1 Experimental apparatus

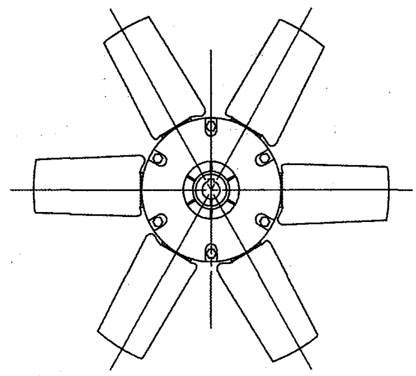


Fig.2 Test rotor

Table 1 Main dimensions of the impeller

Blade profile	Airfoil			Symmetrical		
B	3	5	6	3	5	6
D_o[mm]	624	624	624	624	624	624
D_i [mm]	250	250	250	250	250	250
ξ [deg.]	46.9	46.9	46.9	47.5	47.5	47.5
γ_1 [deg.]	41.2	41.2	41.2	47.5	47.5	47.5
γ_2 [deg.]	50.6	50.6	50.6	47.5	47.5	47.5
C[mm]	436	262	218	436	262	218
σ	0.67	0.67	0.67	0.67	0.67	0.67

5 Experimental results and discussion

5.1 Aerodynamic characteristics

The aerodynamic characteristic was investigated by each fan. The flow coefficient, ϕ is within the limits of 0.495～0.515, pressure coefficient, ψ is 0.261～0.294 and fan efficiency, η is 0.620～0.654. In addition, it is checked that a design point is mostly in agreement with a maximum efficiency point.

ϕ, ψ and η are expressed as follows.

$$\psi=2P_T/(\rho u_2^2),\quad \phi=4Q/\{\pi(1-\nu^2)D_2^2u_2\}$$
$$\lambda=8L/\{\pi\rho(1-\nu^2)D_2^2u_2^3\},$$
$$\eta=\phi\psi/\lambda \quad (12)$$

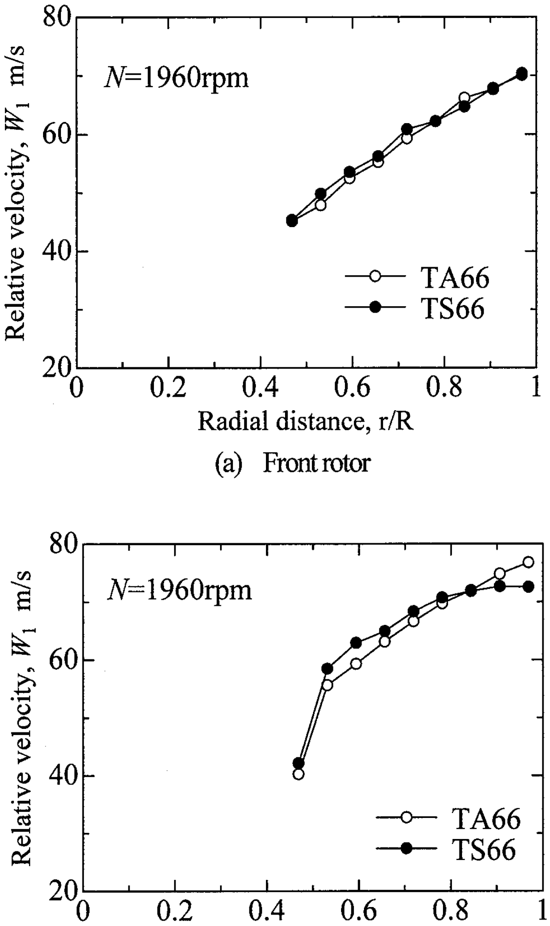
Where P_T is the total pressure(Pa) and u_2 is the circumferential speed at the rotor perimeter(m/s) and ν is the hub-tip ratio and D_2 is the outer diameter of rotor(m), and L the electric motor input(W) and λ the input power coefficient.

In this experiment, it is checked that the flow rate of a design point is almost in agreement that of the maximum efficiency point. The characteristics of these fan are expressed in table 2.

5.2 An aspect of flow

Sharland, Fukano and Others are predicted the turbulent noise of the axial fan. In these researches, it is assumed that the representational relative velocity W is almost the same as the inlet relative velocity W_1(2) - (4). In any case, the agreement between the predicted and the measured values are satisfactory. Therefore in this research, we adopt also inlet relative velocity as representational relative velocity.

Fig. 3 shows the inlet relative velocity W_1 of the two-stage system jet fan such as TA66 fan(○mark) and TS66 fan(● mark). A difference is not looked between front rotor and rear rotor except that the inlet relative velocity, W_1 of rear rotor is larger than front rotor in the range which the radius r/R is between 0.6~0.8. However in the rear rotor, the difference is looked that the inlet velocity of the airfoil blade rotor larger than the symmetric blade rotor between 0.4~0.7.



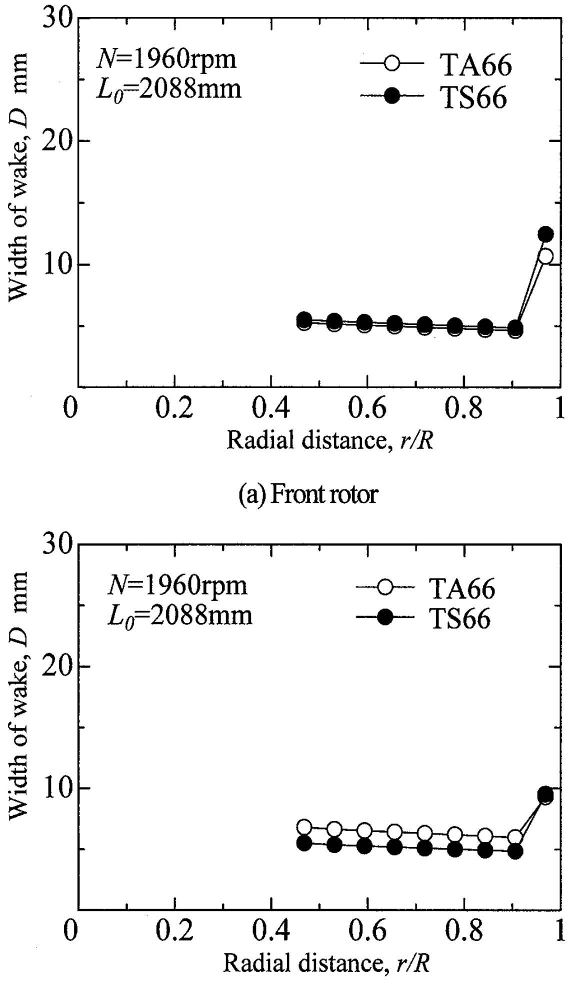
(a) Front rotor

(b) Rear rotor

Fig.3 Radial distributions of the inlet relative velocity of the rotor

Fig. 4 shows the radial distribution of wake width obtained by equation (2) for TA66 and TS66 fan. In the case of symmetrical blade rotor(● mark), there is little difference of wake width between front and rear rotor. However, in the case of airfoil blade rotor(○ mark), the width wake of rear rotor become wider), the width wake of rear rotor become wider than that of front rotor. This tendency is much the same for another fan with different number of blades.

The radial distribution of turbulent scale L at inlet of the rear rotor was obtained by equation (9) is shown in Fig.5. The turbulent scale L of 3-5 fan (○, ● marks) is larger than that of 5-3 fan(△, ▲ marks). This reason is that the more blade chord length is long, the more the boundary layer on the surface of blade is development.



(a) Front rotor

(b) Rear rotor

Fig.4 Radial distributions of the wake width

Moreover, if L of symmetrical blade fan is compared with that of airfoil blade fan, the former is slightly smaller than the latter.

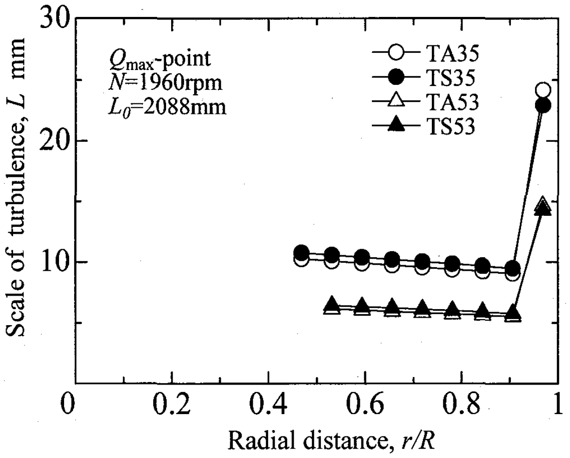


Fig.5 Radial distributions of the turbulent scale

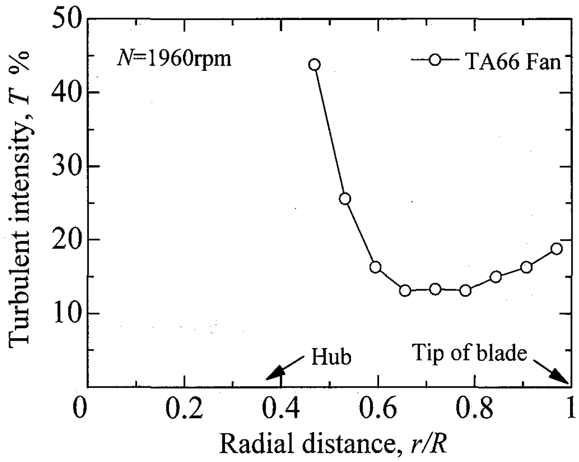
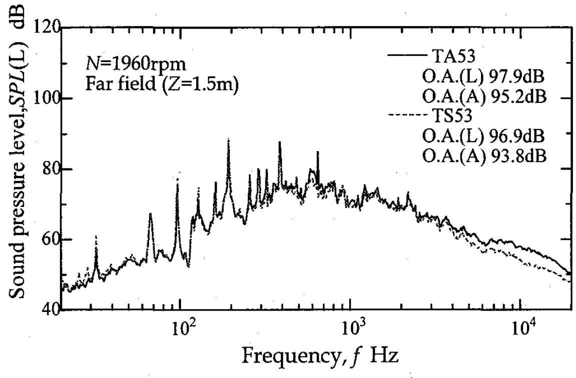


Fig.6 Radial distributions of the turbulent intensity

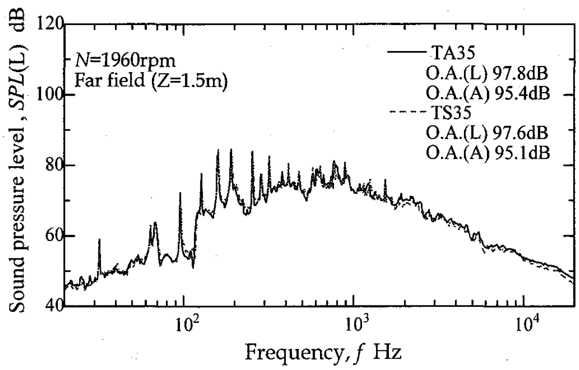
Fig.6 shows the radial distribution of turbulent intensity of TA66 fan measured at inlet of the rear rotor. The turbulent intensity begins to reduce abruptly with increasing radial distance and which has minimum point at about r/R=0.7, then the value of turbulent intensity increase again with going toward r/R=1.0.

5.3 Spectral distribution of fan noise

An example of the spectral distribution of Fan Noise is shown in Fig. 7. Fig. 7 (a) and 7(b) show the 5-3 fan and 3-5 fan expectantly. In these figures, a solid line and a broken line express the results of airfoil and symmetric blade fan. In the comparison of overall noise, in the case of 3 blade, there is little difference between airfoil and symmetric blade. In the case of 5 blade front rotor, the noise generated by the symmetric blade fan becomes slightly lower than that of airfoil blade fan.



(a) TA53 and TS53 fan



(b) TA35 and TS35 fan

Fig.7 Spectral density distributions of the two-stage fan noise

Moreover, the generation of a discrete frequency noise is seen also in each fan. This is due to the interaction between a power cord and rotor, a main flow distortion and rotor (1). In the case the experimental value of turbulent noise is computed, which is obtained by subtracted sound power of these discrete frequency noises from the overall sound power (7).

Fig.8 shows the spectral distribution of fan noise for single stage type jet fan with 6 blade (SR6). In this figure, the solid line and the dashed line express the case when the struts are located downstream of the rotor(postpositive strut type, SF6) and upstream of the rotor(,introduction strut type, SR6) respectively. The generation of interaction noise is seen in both. These discrete frequency noise of SR6 fan is higher than that of SF6 fan.

This cause is due to the interaction between the power cord and rotor. In introduction strut type fan, the power cord (ϕ=28mm) of a motor is located upstream of the rotor. Therefore the interaction noise generates because the rotor cut the wake of power chord and the wake does almost not decay as the distance between power cord and leading edge of the rotor blade increase.

On the other hand, the case of the postpositive strut type, the interaction noise will be generates also because the wake of the rotor run into the power cord. However the wake width of rotor is about 1/3 of power cord.

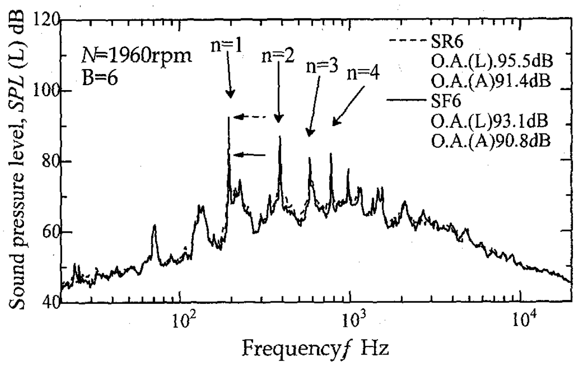


Fig.8 Spectral density distributions of the single-stage fan noise

And the distance between trailing edge of the rotor blades and power cord is longer than introduction type because the flow of this type fan flow out with some angles for rotor axis. Therefore the interaction noise of postpositive strut type fan become lower than introduction type fan.

The possibility of reducing interaction noise appears to be a combination of power cord shape and the distance between power cord and rotor. In addition, Some relief would also be gained by tilting the power cord and dividing into three power cord.

On the other hand, the turbulence noise of postpositive strut type fan become lower than introduction type fan because in the latter, the wake of struts flow into the rotor blade which relative velocity is larger than that of struts.

5.4 Specific noise level

To judge the quality of a fan from the viewpoint of noise reduction, the specific noise level, K s, has been used. It is defined by

$$K s = SPL - 10\log10(QPt\,2) + 2 \qquad (13)$$

Where SPL is the overall sound pressure level in dB, and Q is the fan flow rate in m 3/s and P t is the total pressure in Pa., which has been conventionally used.

Table 2 Specific noise level (Two-stage fan)

Fan	TA66	TA53	TA35	TS66	TS53	TS35
SPL_L	98.6	97.9	97.8	99.9	96.9	97.6
SPL_A	95.9	95.2	95.4	96.3	97.8	95.1
K_{sL}	35.2	34.5	34.5	36.5	33.4	34.4
K_{sA}	32.5	31.9	32.1	32.9	30.3	31.9

Table 3 Specific noise level (Single-stage fan)

Fan	SF7	SR7	SF6	SR6	SRD6
SPL_L	93.5	96.5	93.1	95.5	93.5
SPL_A	91.3	93.0	90.6	91.4	90.8
K_{sL}	30.9	34.0	30.5	33.0	31.0
K_{sA}	28.7	30.5	28.0	28.9	28.3

From a viewpoint to discuss the quality of a fan, we take the overall sound pressure level in which both the turbulent noise and the interaction noise are contained. The specific noise level of fan used in this experiment is shown in table 2. Subscripts L and A means the measuring value used sound level meter with L and A characteristics. From Table 2, in relate with the two-stage system jet fan, the specific noise of symmetric blade fan is lower than that of airfoil blade fan generally. Therefore it seems that the symmetric blade fan is more suitable than the airfoil fan as the two-stage jet fan. Moreover, in the specific noise level, TS53 fan is lowest among all fans.

From the comparison of the sound pressure level and the specific noise level for TS53 with TS35 fan, the former is lower about 1.5 dB than latter. Moreover, in relation to maximum fan efficiency, the former is higher about 4.5 % than latter. Therefore it is desired to arrange the rotor with short chord length and much number of blades in the upstream side as a rotor combination.

On the other hand, the specific noise level of the symmetrical blades jet fan of the single- stage is shown in Table 3, the specific noise level of the postpositive strut type fan (SF6) is lowest among all fans. It is the reason that the overall noise of SR6 fan is higher than that of SF6 fan, in the former, the turbulent flow generated from the power cord and struts located upstream side of rotor flow into the rotor blades. The overall noise of single-stage type fan is lower than that of the two-stage type fan. Therefore the merit using the single stage fan is expectable.

Fig. 9 shows the comparison of the predicted sound pressure level due to the vortex shedding from the trailing edge using equation (1) and the turbulence flow into the rotor blades using equation (2). From this figure, the overall noise is lower in order two-stage fan , introduction strut type single-stage fan, postpositive strut type single-stage fan. It suggests that the noise based on the turbulence flow into the blades is problem in two-stage type fan.

On the other hand, the interaction noise due to the interact between power cord with rotor and the turbulent noise due to turbulent flow generated by cord and strut become problem in the single stage introduction strut type fan.

Fig. 10 shows comparison between the measured and predicted value of the overall sound pressure level of turbulent noise. A 45-degree thick solid line shows a line which connected the point coincided between measured and predicted value. A thin solid line is the line which shows a ±2dB error. The accuracy between the measured and predicted values of overall turbulent noise is in less than about ±2dB.

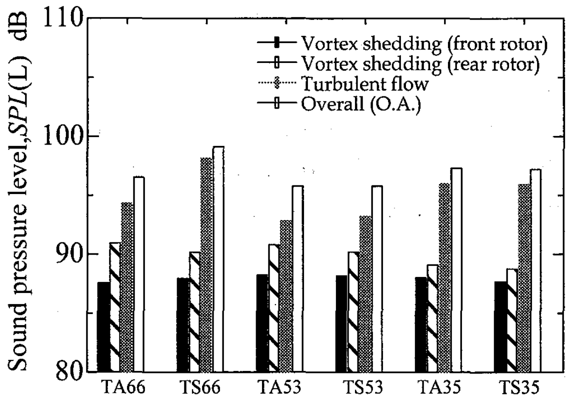


Fig. 9 Comparison of the two different sources

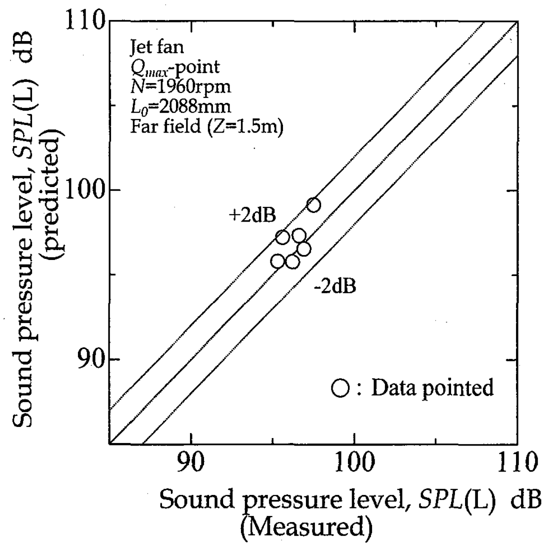


Fig.10 Comparison of predicted and measured sound pressure level of the turbulent noise

6. Conclusion

The effects of number of blades and the number of stages on the aerodynamics and noise were investigated experimentally. Moreover theoretical and experimental investigations are performed to make clear the turbulent noise due to the turbulent into the rotor blades.

Consequently, the following conclusions were obtained.

(1) From the experiment for the two-stage system jet fan, it is advantageous from a view point of aerodynamics, noise characteristics and specific noise level that the rotor with numerous number of blades is arranged upstream side and that with few blades to the down stream side.

(2) In the case of a single stage system, between postpositive strut type and introduction strut type fan, the fan characteristics is different drastically. Namely, in the case of the former, interaction noise of

hig sound pressure level occurs. If suitable processing of a cord is performed, as tilting the cord divided into three. Interaction noise can be reduced . Therefore the single stage jet fan is superior to the two-stage jet fan.

(3) In present research range, among the factors which contributes to turbulent noise, the factor with the largest influence is turbulent flow which flows into blades. For this reason, the turbulent noise of rear rotor becomes higher than that of front rotor.

(4) If the method of predicting the width of wake proposed by present research is used, overall turbulent noise level can be predicted with accuracy within about ±2dB in this experiment.

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