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Prediction Methodology of Broadband Noise from a Cooling Fan

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ABSTRACT

The experimental prediction methodology of the fan noise as the first step to organize the blade elementary angular momentum theory is proposed. For the prediction equation of the broadband noise, the theory on the acoustic radiation from airfoil with turbulent boundary layer is applied. The broadband noise of the cooling fan is predicted experimentally by using the measured flow regime in the wake of the actual fan based on the results of wind tunnel test on the aerodynamic noise of a flat plate. The prediction by the suggested methodology could explain the reduction of the broadband noise in the low frequency domain in the operation point of the cooling fan is the effect of the reduction of the wake vortex noise made by the pressure side separation.

Keywords: Broadband Noise, Blade Element, Wind Tunnel, Low Pressure Fan

1. INTRODUCTION

Propeller fans are used as a cooling fan for the heat exchangers in HVAC systems (heating, ventilation, air conditioning, systems). For example, in recent years, the R & D of the small output Organic Rankine Cycles using a low-grade heat source such as hot spring water has been promoted [(1)]. In this cycle, the low boiling point refrigerant such as R245fa is used as the working fluid; the cooling fan is used for condensing the working fluid. Because the cooling fan in the HVAC system cools the heating device by its own velocity, it has no duct and is almost no increase the static pressure of the fan. Under such conditions, in the case of the low solidity impeller, the flow passing through the blade can be handled as two-dimensionally.

The blade element momentum theory (BEM) is the theory which is handled the flow passing through the blade element in two dimensions [(2)]. The theory has been practical used to calculate the local forces on the blade on the wind turbine [(3)]. Even in the case of the wind turbine, the static pressure rise of the flow passing through the impeller is small. It makes possible to handle the flow around the blade elements as a simplified two-dimensional flow. Author predicted the broadband noise generated from a horizontal axis wind turbine based on BEM by applying the characteristics of the two dimensional flow [(4)]. An analytical model proposed by M. Roger and S. Moreau was used for the base principal to predict the broadband noise [(5)]. However, there are some difficulties in the handling of the radiation integral and statistical pressure fluctuation model in the practical using for the design of the fan. T. Fukano et al., proposed the prediction theory on the aerodynamic noise generated from an axial fan with the wake characteristics of the impeller [(6)]; however, the theory cannot express the spectral distribution of the broadband noise because the overall noise level is predicted.

By the way, the cooling fan in the HVAC system is also small static pressure rise, so it makes possible to replace the flow in the blade elements as the two-dimensional flow. In the case of the design for the impeller of the fan, the theoretical total pressure based on velocity triangle and their angular momentum is used as the basic principal. If the principal of the velocity triangle and angular momentum is applied to fan noise prediction, it is possible to predict fan noise by the blade element theory. Therefore, in this study, the methodology to predict the fan noise experimentally based on the measurement of the wake as the first step to organize the blade elementary angular momentum theory is proposed. For the prediction equation of the broadband noise, the theory suggested by B. D. Mugridge which is acoustic radiation from airfoil with turbulent boundary layer is applied [(7)]. In the

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suggested methodology, the broadband noise of the cooling fan is predicted experimentally by using the measured flow regime in the wake of the actual fan based on the results of wind tunnel test on the aerodynamic noise of a flat plate.

2. EXPERIMENTAL SETUP

2.1 Experimental Apparatus

The wind tunnel for the measurement of the properties of the flap plate is shown in Fig.1. The size of the square nozzle is 100mm. When the Reynolds number is approximately 2.0×10^5, the turbulence of the main flow within the measurement region is less than 0.5%. The leading edge of the blade is set at 100 mm downstream from the nozzle exit. A 1/2-inch microphone (Ono-Sokki, LA-4350) is set at a distance of 0.5 m from the trailing edge; the angle between the main flow and the microphone is 90°. The signal from the noise level meter is sent to the FFT analyzer (Ono-Sokki, CF5210), and the frequency response characteristics of the noise are analyzed. In this measurement method, we discuss the far field noise properties than the wave length of the point sound source without take into account of the directivity. The blade chord is 40mm, the span length is 100mm, the thickness is the 2mm. The angle of attack is defined as the angle formed by the center line of the blade and the stream line of the main flow.

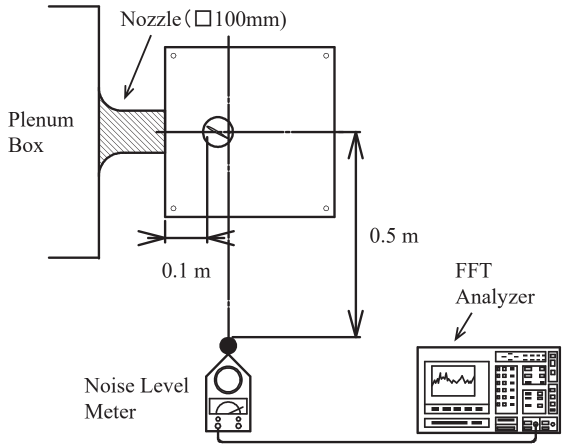
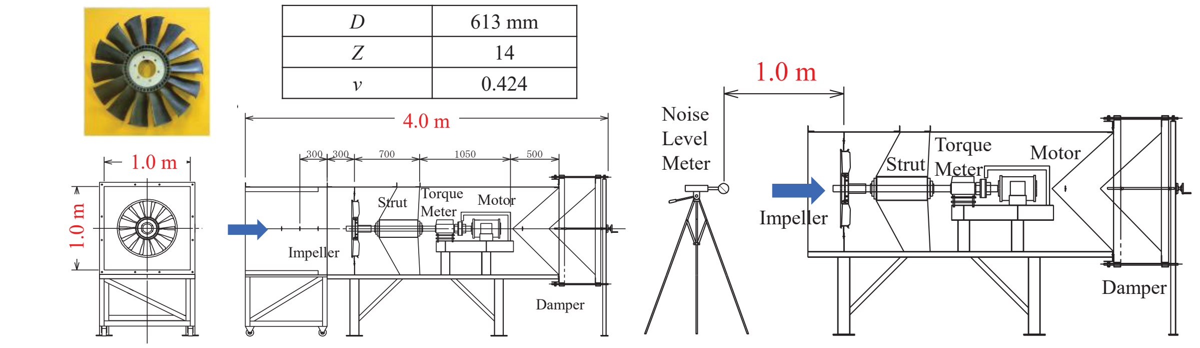


Fig. 1 Experimental setup of the wind tunnel test for the flat plate

In Fig. 2, the schematic diagram of the test bench for the estimation of the fan performance is shown. The diameter of the impeller is 613 mm, the hub ratio is 0.424 and number of blades is 14. The height and width of the duct are 1 m each, while its total length is approximately 4 m. The dynamic pressure is measured 600 mm upstream of the impeller disc using a Pitot tube. From the results of the velocity distribution for the estimation of the flow rate, the flow coefficient was found to be 0.842. The flow rate is deduced from the dynamic pressure. It is controlled by an adjustable throttle at the duct exit. The static pressure of the fan is measured 400 mm upstream of the exit. The rotational speed of the driving shaft is 1200 rpm. I measured the shaft torque of the motor using a torque meter (Ono-Sokki; SS-500), and the efficiency of the fan was estimated based on the ratio of shaft power to theoretical power. The normalized characteristics of the fan are summarized as follows;

$$\varphi = \frac{4Q}{\pi(1-\nu^2)D^2 U}, \psi_s = \frac{2P_s}{\rho U^2}, \lambda = \frac{8L}{\rho\pi(1-\nu^2)D^2 U^3}, \eta = \frac{\phi\psi_s}{\lambda} \tag{1}$$

where the φ is the flow coefficient, ψ_s is the static pressure coefficient, λ is the power coefficient, and η is the efficiency. A 1/2-inch microphone (Ono-Sokki, LA-4350) is set at distance of 1.0 m from the impeller inlet on the rotational axis of the impeller. The frequency response of the measured fan noise is provided by a Fast Fourier Transfer analyzer (Ono Sokki, CF5210).



(a) measurement for the aerodynamic characteristics (b) measurement method for the noise

Fig. 2 Schematic diagram of the test bench for the estimation of the fan performance

In Fig. 3, the measurement method of the flow regime in the wake of the impeller is shown. The wake of the impeller is measured by an X type hot-wire probe (KANOMAX, 0249R-T5). The X type hot wire probe can measure the simultaneously the two velocity components. The hot-wire probe is attached to the traverse machine; the arbitrary flow field is measured by controlling the stepping motor. The flow regime near the blade tip is measured 160 mm in the mainstream directions and 240 mm in the radial directions. The measurement position of the wake is 5mm behind the trailing edge of the blade.

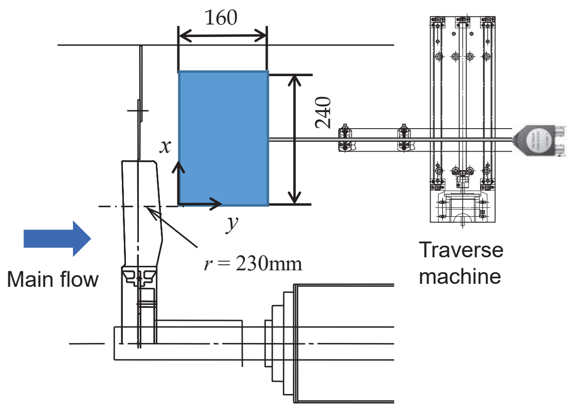


Fig. 3 Measurement method of the flow regime

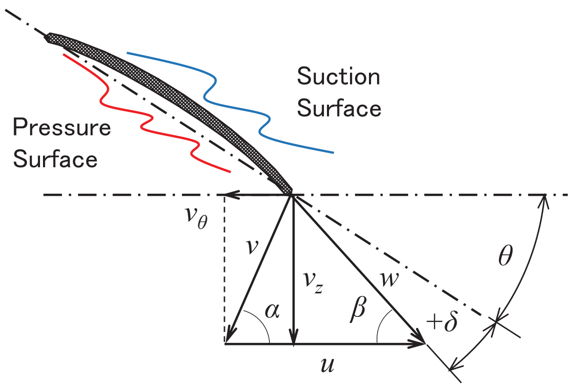


Fig. 4 Velocity triangle in the wake

2.2 Prediction Methodology of Broadband Noise

In Fig. 4, the velocity triangle in the wake of the impeller is explained. The X type hot-wire probe can measure the axial velocity component v_z of the absolute velocity and the circumferential velocity component v_θ. Then, the absolute velocity and the absolute outflow angle are given by equation (2).

$$v = \sqrt{v_x{}^2 + v_\theta{}^2} \quad , \quad \alpha = \tan^{-1}\frac{v_x}{v_\theta} \tag{2}$$

At this time, the relative velocity w and the relative outflow angle β become Equation (3).

$$w = \sqrt{u^2 + v^2 - 2\,u\,v\cos\alpha} \quad , \quad \beta = \cos^{-1}\left(\frac{u^2 + v^2 - w^2}{2uw}\right) \tag{3}$$

When the setting angle θ of the impeller is known, the outlet deviation angle δ is expressed as follows;

$$\delta = \beta - \theta \tag{4}$$

where, the angle of the pressure side is defined as positive. According to reference (7), the sound power radiation by a number of flat plate or airfoils, each having a surface pressure distribution caused by the turbulent boundary layers, may be written as;

$$\frac{dE}{d\omega} = \frac{N\,L\,w^3}{6\,\pi\,\omega\,\rho\,a_0}\phi_{pp}(\omega)\ ,\because 1 > \pi c/\lambda > 0.4M;\, b < \lambda;\, M > 1/14 \tag{5}$$

where, E is the sound power, N is the number of blades, L is the span of the blade element, w is the relative velocity, φ_{pp} is the wall pressure spectrum density. The statistical wall pressure spectrum density suggested by B. D. Mugridge is given as;

$$\phi_{pp} = 10^{-3}\,\rho^2\,\delta\,w^3\ ,\because \delta = 0.093\,c\,R_e^{-0.2} \tag{6}$$

where, δ is the boundary layer displacement thickness. The boundary layer displacement thickness is evaluated by the exponential law. The ratio on the sound pressure p^2 of the measured value of the model in the wind tunnel test to the target value of the blade element in the actual fan is given by;

$$\frac{p_o^{\ 2}}{p_m^{\ 2}} = \frac{N_o}{N_m}\frac{L_o}{L_m}\left(\frac{w_o}{w_m}\right)^3\left(\frac{\omega_m}{\omega_o}\right)\left(\frac{r_m}{r_o}\right)^2\frac{\phi_{pp}(\omega)_o}{\phi_{pp}(\omega)_m}\ ,\because \frac{E}{2} = \frac{4\,\pi\,r^2}{3\,\rho\,a_0\cos^2\theta}p^2 \tag{7}$$

where, subscript m is the model value, o is the objective value of the blade element for the target fan. In the case of the noise level, since decibel notation is common, let me express equation (8) as logarithm.

$$\begin{aligned} L_{p\,o} = L_{p\,m} &+ 10\log\left(\frac{N_o}{N_m}\right) + 10\log\left(\frac{L_o}{L_m}\right) + 30\log\left(\frac{w_o}{w_m}\right) \\ &+ 10\log\left(\frac{\omega_m}{\omega_o}\right) + 20\log\left(\frac{r_m}{r_o}\right) + 10\log\left(\frac{\phi_{pp}(\omega)_o}{\phi_{pp}(\omega)_m}\right) \end{aligned} \tag{8}$$

In the experimental analysis of the broadband noise using this methodology, the target noise level of the fan can be predicted by the model size and test condition in the wind tunnel test and the scale and driving condition of the actual fan.

3. RESURLT AND DISCUSSION

In Fig. 5, the aerodynamic characteristics of the fan is shown. The highest efficiency point of this fan is φ = 0.3. The operating point of the cooling fan is set to φ = 0.43, which is close to the atmospheric pressure. The characteristics of the sound pressure level of the fan is presented in Fig. 6. The fan noise at the operating point of the cooling fan was 0.8 dB greater than that at the highest efficiency point.

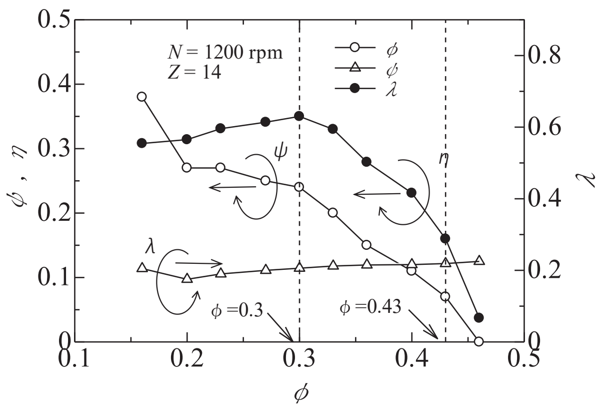


Fig. 5 Aerodynamic characteristics

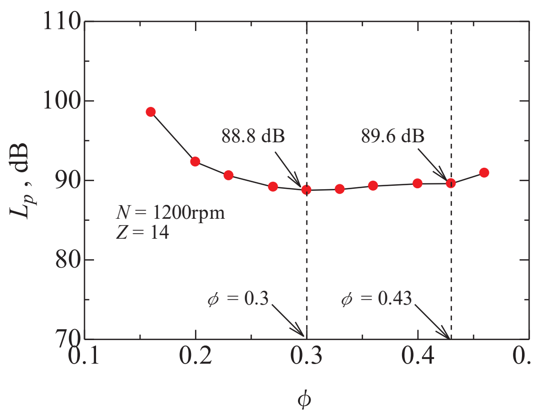


Fig. 6 Noise characteristics

The spectral distribution of the fan noise at the highest efficiency point and the working point is compared in Fig.7. The fan noise at the operating point was increased by 0.8 dB; however, it is the influence on the discrete frequency noise synchronized with the blade passing frequency; whereas, we can notice the sound pressure level of the operation point in the domain lower than 200 Hz became clearly low than that of the maximum efficiency point. In Fig.8, the distribution of absolute velocity in wake measured by the hot-wire anemometer is shown. The absolute velocity is distributed in the axial direction of the impeller. This result indicates that the direction of the momentum of the wake flow is directed in the axial direction; in particular, the velocity distribution gives the information that the two-dimensional flow field is formed in the area of a mid-span.

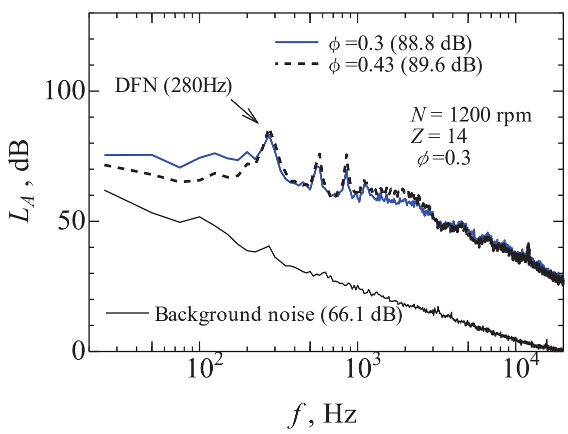


Fig. 7 Spectral distribution of the fan noise

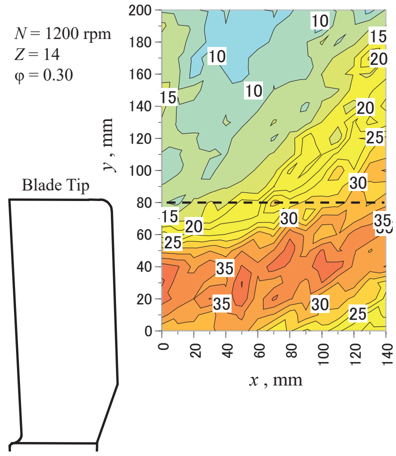
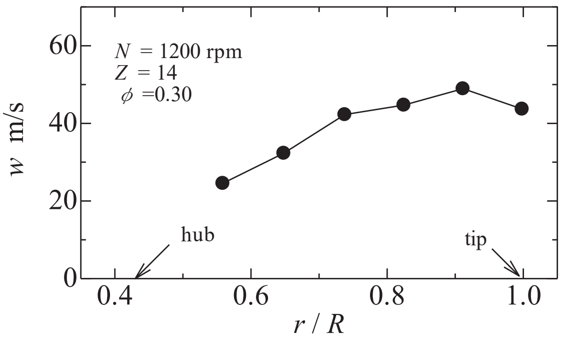
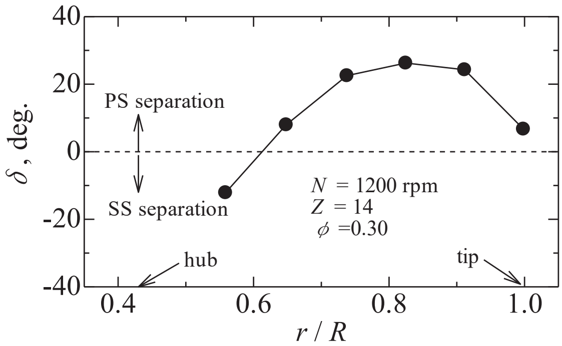


Fig. 8 Velocity distribution in the wake

The flow regime of the impeller in the wake measured by the hot-wire anemometer is presented in Fig. 9. The operating point is the maximum efficiency point. In Fig. 9(a), the relative velocity in the vicinity of the blade tip becomes the high velocity. In Fig. 9(b), the distribution of the deviation angle indicates that the relative flow is separated to the way of the pressure surface side over the wide span range of the impeller. The deviation angle is the equivalent scale to the angle of attack in the wind tunnel test. The angle in the domain of the high relative velocity is about 20 °.



(a) relative velocity



(b) deviation angle

Fig. 9 Flow regime in the wake of the impeller

In Fig. 10, the characteristics of the sound pressure level of the flat blade is presented. The horizontal axis is the angle of attack; the vertical axis is the sound pressure level. The negative angle is the situation that the noise is measured from the suction side, whereas, the positive angle is measured from the positive pressure side. The spectral distribution of the sound pressure level of the flat blade is shown in Fig. 11. The angle of attack is 20 °. The thin solid line in the figure is the spectral distribution of the background noise of the wind tunnel. The thin solid line is the background noise of the wind tunnel. In the case of the flat plate with the chord length of 40 mm, the thickness of the shear layer is approximately 28 mm (D = 40 sin α + 2). At this time, if Karman vortex street is formed in the wake, the vortex shedding frequency becomes approximately 214 Hz ($f = S_t\, U / D$) according to the Strouhal number relation. The noise of the flat plate increases in the frequency domain of 100 Hz to 400 Hz.

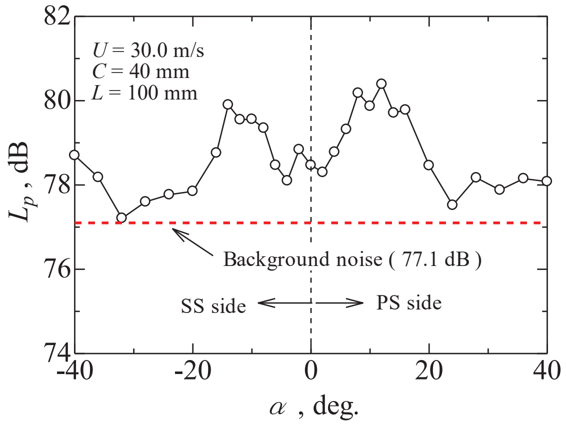


Fig. 10 SPL characteristics of the flat plate

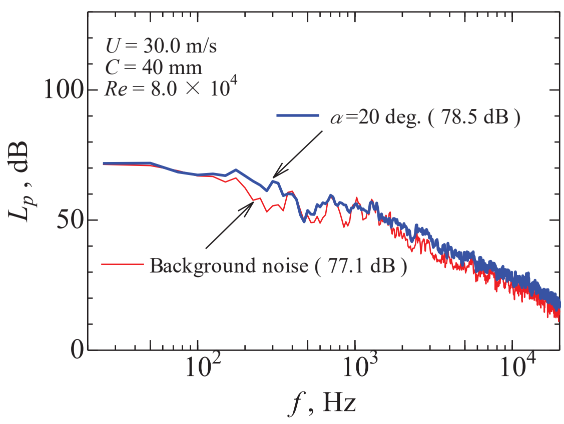


Fig. 11 Spectra of SPL of the flat plate

In Fig. 12, The measured broadband noise of the fan is compared with the predicted one. The predicted broadband noise level was more than 10 dB higher than the measured value; this result indicates that the impeller itself becomes an acoustic impedance. The predicted broadband noise could represent the tendency of the measured value. From the results in Fig. 11, it is recognized that the reduction of the broadband noise in the low frequency domain in the operation point of the cooling fan is the effect of the reduction of the wake vortex noise made by the pressure side separation.

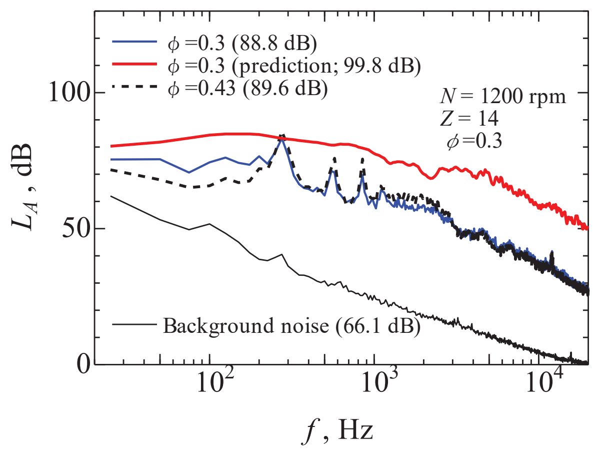


Fig. 12 Comparison on the measured SPL spectra with the prediction

4. SUMMARY

The sound pressure level of the operation point of the cooling fan became decrease than that of the maximum efficiency point in the domain of the low frequency. The relative flow is separated to the way of the pressure surface side over the wide span range of the impeller in the maximum efficiency point. The prediction methodology on broadband noise of the fan could represent the tendency of the measured value. The prediction by the suggested methodology could explain the reduction of the broadband noise in the low frequency domain in the operation point of the cooling fan is the effect of the reduction of the wake vortex noise made by the pressure side separation.

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