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AN ANALYSIS OF FLOW AND SOUND FIELD OF A DUCTED AXIAL FAN

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ABSTRACT
The present work describes the prediction method for the unsteady flow field and the acoustic pressure field of a ducted axial fan. The prediction method is comprised of time-marching free-wake method, acoustic analogy, and the Kirchhoff-Helmholtz BEM. It assumed that the rotor rotates with a constant angular velocity and the flow field around the rotor is incompressible and inviscid. Then, a time-marching free-wake method is used to model the fan and to calculate the flow field. The force of each element on the blade is calculated using the unsteady Bernoulli equation. Acoustic analogy is used to predict the acoustic source. The newly developed Kirchhoff-Helmholtz BEM for a thin body is used to calculate the sound field of the ducted fan. The ducted fan with 6 blades is analyzed and the sound field around the duct is calculated.

1 - INTRODUCTION
Many researchers developed the numerical method to predict the radiated sound field of an axial fan [1]. The acoustic analogy method is prominent among them. But, the acoustic analogy can be applied only to the rotor in the free field in general. In a ducted axial fan, the duct modifies the generated sound source. In order to consider the duct effect, hybrid method is developed [2]. But even in that method, the acoustic source is assumed simple source, such as monopole, dipole and normal surface vibration. The real rotating rotor source cannot be considered. So, the new Kirchhoff-Helmholtz BEM is developed and applied to the ducted fan. The source is modeled by Kirchhoff surface, which surrounds the rotor. This method is applied to the centrifugal fan and shows good results [3], [4].
In this paper, the developed method is applied to a ducted axial fan. The scattering effect of the duct modify the radiation pattern as shown in results.

2 - NUMERICAL METHOD
In order to calculate the aeroacoustic source of a rotating rotor in a duct, the flow field should be analyzed. We assume that the rotor rotates with a constant angular velocity and the flow field around the rotor is incompressible and inviscid. The free-wake time-marching method is used to model the rotor and duct. With this method the flow field of a ducted fan is analyzed. The Bernoulli equation is used to calculate the unsteady force of a rotor blade [4].
Neise shows that the dipole, especially the unsteady force fluctuation is the dominant source of the fan noise [5]. Therefore, we assume the unsteady force fluctuations of the rotor blades is the dominant source of the axial fan [3]. So, the acoustic analogy about the dipole source can be applied in the prediction method at the free field. The acoustic analogy derived by Lowson is used to calculate the acoustic pressure at the free. A general formula for the sound field of a point force in arbitrary motion, derived by Lowson in 1965, is as below.

$$P - P_o = \left[\frac{x_i - y_i}{4\pi a_o r^2 \left(1 - M_r\right)^2} \left\{ \frac{\partial F_i}{\partial t} + \frac{F_i}{1 - M_r} \frac{\partial M_r}{\partial t} \right\} \right] \tag{1}$$

Here,

$$M_r = \frac{M_i r_i}{r} \tag{2}$$

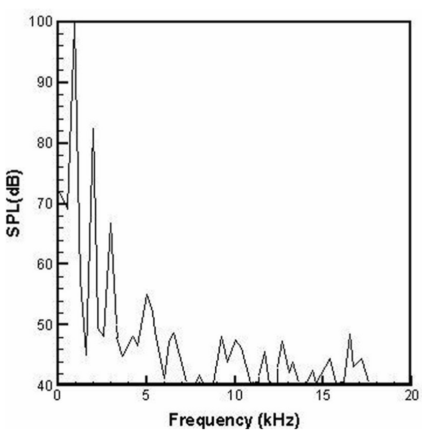
F_i is the calculated force of the rotor blade and a_o is the speed of sound. x_i and y_i are the source position and observer position and r is the distance between them.
In the case for the ducted axial fan, the acoustic characteristics such as reflection, scattering and diffraction of the duct are included in the radiated sound field. But there is no method to consider this steering effect with rotating rotor source. So we derive a Kirchhoff-Helmholtz BEM to calculates the scattering effect of the duct with a known rotating rotor source. This method − Kirchhoff-Helmholtz BEM − could be derived by considering some source mesh in a computational domain. This mesh surrounds the source region. The acoustic value of this Kirchhoff source mesh can be calculated by Lowson's equation, and this value is considered as a source. The equation (3) is the Kirchhoff-Helmholtz BEM;

$$\begin{aligned} C(P)\phi(P) = & \int_s \left[\phi(Q) \frac{\partial G}{\partial n}(P,Q) - \frac{\partial \phi}{\partial n} G(P,Q) \right] dS(Q) \\ & + \int_{Kirchhoff} \left[\phi(K) \frac{\partial G}{\partial n}(P,K) - \frac{\partial \phi}{\partial n} G(P,K) \right] ds(K) \end{aligned} \tag{3}$$

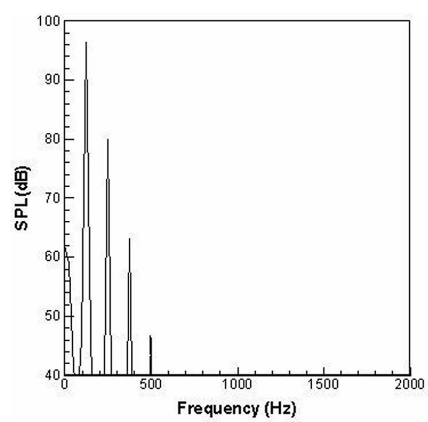
Here, the index K means the value on the Kirchhoff mesh. The value of this Kirchhoff source term is calculated from equation (1) at the Kirchhoff surface points.

3 - NUMERICAL RESULTS

In order to validate the proposed method, the axial fan in the free field was introduced. This axial fan was used in Lohmann's research [1]. The calculated and measured free field acoustic pressures are compared. Fig. 1 shows good agreement with experiments data. In the numerical calculation, the shroud effect does not considered.



(a): Measured by Lohmann.



(b): Present calculation.

Figure 1: Measured and calculated acoustic pressure.

A ducted fan is calculated in this paper. This is shown in Fig. 2. The number of blade is 6 and the diameter of rotor is 0.25 m. It rotates with 2000 rpm. In the figure, the rotor and the shed wake is shown. The diameter and length of the duct are 0.27 m and 0.5 m. The blade is modeled with 54 vortex panels and the duct is modeled by 300 panels. 36 time steps are employed for one revolution of the rotor.

Fig. 3 shows the force variation at one mesh point of the blade. In the figure, x and y forces are highly periodic due to the rotation of rotor inside the duct, but the thrust force (Fz) is almost constant. This periodic rotating force makes the acoustic pressure.
The predicted acoustic pressure with the assumption of the free field at 1 m apart from the inlet of the duct is shown in Fig. 4. In the figure BPF and its higher harmonic peaks are shown. The level is low

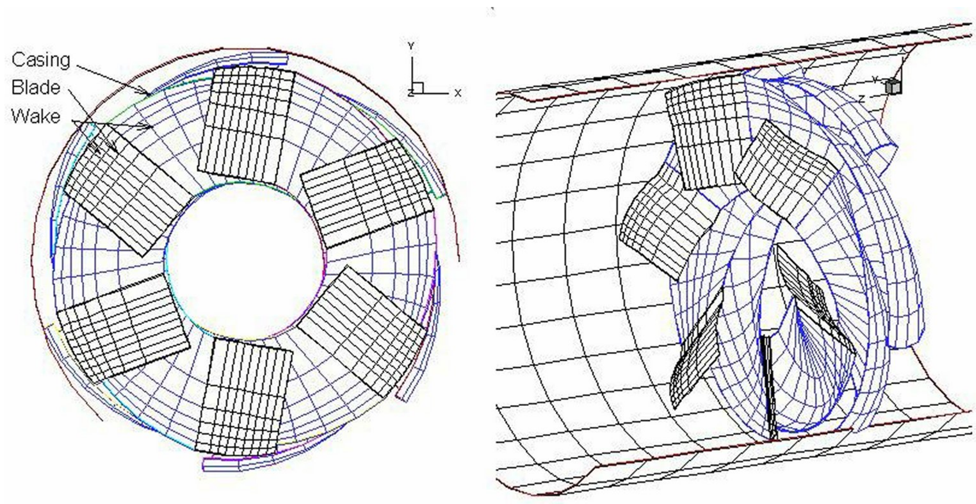


Figure 2: Ducted axial fan.

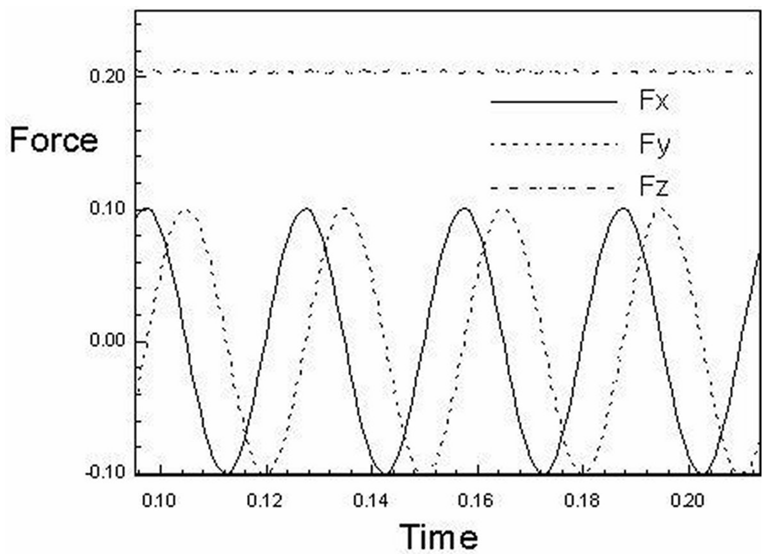


Figure 3: Calculated unsteady force.

because of the free field assumption for acoustic analogy. The source of Kirchhoff surface is introduced and the source value at this Kirchhoff surface is calculated. This surface is used in the source of BEM calculation.

The results are shown in Fig. 5. In the figure, the radiated sound fields of 200 (BPF) and 400 Hz are shown. In each frequency, the radiated sound fields are stronger than the free filed calculation and the scattering effect of duct is clearly shown.

4 - CONCLUSION

A numerical prediction method for the unsteady flow field and the acoustic pressure field of a ducted axial fan is developed. The prediction method is comprised of time-marching free-wake method, acoustic analogy, and the Kirchhoff-Helmholtz BEM. The predicted sound signal of a rotor is similar to the experiment one. The newly developed Kirchhoff-Helmholtz BEM for a thin body is used to calculate the sound field of the ducted fan. The ducted fan with 6 blades is analyzed and the sound field around the duct is calculated.

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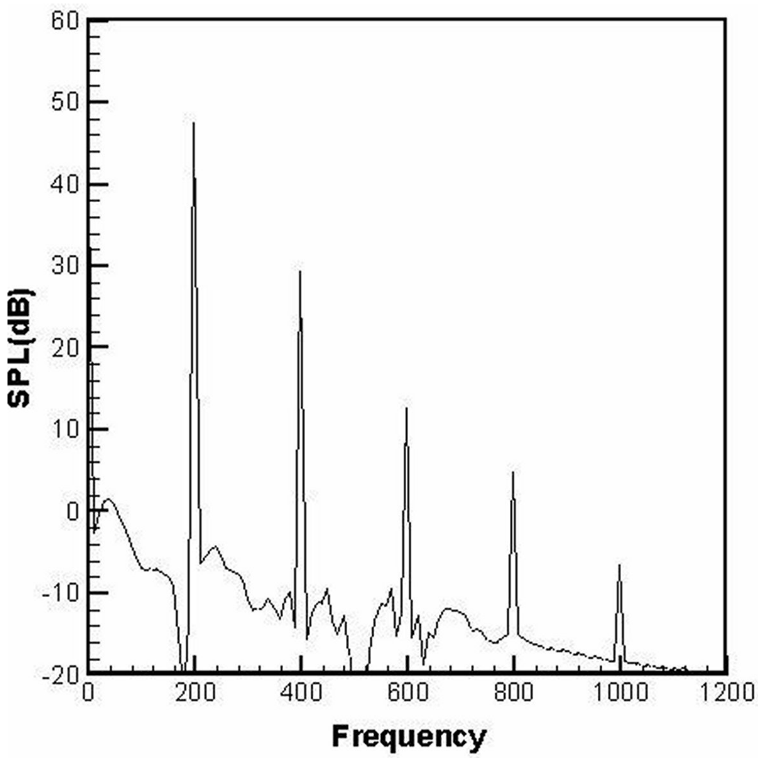

Figure 4: Predicted acoustic pressure.

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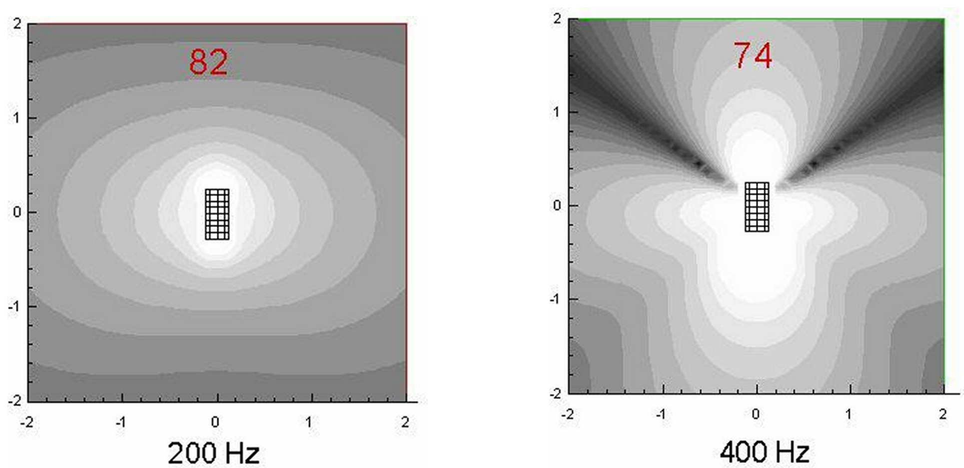

(a): f=200 Hz. **(b):** f=400 Hz.

Figure 5: Sound field of ducted fan.