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PREDICTION OF SPECTRAL DISTRIBUTION OF BROADBAND NOISE GENERATED FROM AN AXIAL FLOW FAN

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ABSTRACT
We have experimentally studied on the relation between the periodic velocity fluctuation in the near wake of a rotating blade and the generated broad band noise. Typical periodic velocity fluctuation was clearly caused by Karman vortex shedding and produced a discrete frequency noise. The frequency of the velocity fluctuation increased toward the blade tip. Then the spectrum of noise generated from the whole span of the blade becomes broadband. In addition we have proposed a theory to predict the spectrum of the broadband noise.

1 - INTRODUCTION
It is known that the controlling noise source generated from a low pressure axial flow fan is turbulent noise due to vortex shedding when the fan is operated near the design point [1], [2]. In order to make clear its noise generation mechanism the present authors investigated noise generated from a flat plate blade immersed in a uniform two-dimensional flow field, and theoretically introduced a formula to predict its sound pressure level [3].
We also investigated the relation between the noise generation from a rotating flat plate blade and the characteristics of the velocity field around the blade measured by hot-wire sensors which rotated with the same speed of the rotating blade. As a result it was made clear that even in the rotating flow field typical periodic velocity fluctuation was generated due to Karman vortex shedding. Its center frequency was constant at a fixed radius but it increased with the increase in the radius. Therefore the spectrum of noise due to this Karman vortex shedding became broadband [4]. In addition the theoretical formula introduced to predict the sound pressure level in the uniform flow field [3] was verified to be useful if some modifications were done so that it fitted the conditions of the rotating flow field [5].
In the present paper a similar examination has been applied to a NACA 65 blade.

2 - EXPERIMENTAL APPARATUS AND PROCEDURE
The velocity fluctuation in the near wake of the rotating blade was measured from a relative frame of reference fixed to the rotating blade by using an I-type hot-wire sensor shown in Fig. 1. The hot-wire sensor was automatically traversed and fixed at pre-determined location while turning. The other hot-wire prove (Probe (2) in Fig. 1) was installed when the cross-correlation of velocity fluctuations at two deferent radial locations was measured. The outputs from these sensors were automatically sampled and the statistical values were calculated.
One of the blades of a rotor with the outer radius of 285 mm, which are designed under the conditions of the flow rate of 130 m^3/min, the static pressure rise of 11 mm Aq. and the number of blade of 8, was used as the tested blade which has the cross section of a NACA 65 blade as shown in Fig. 2. The thickness at the trailing edge of the blade, D_t, was 1.8 mm over the whole span of the blade. The rotational speed of the blade, N, was normally 1000 rpm.

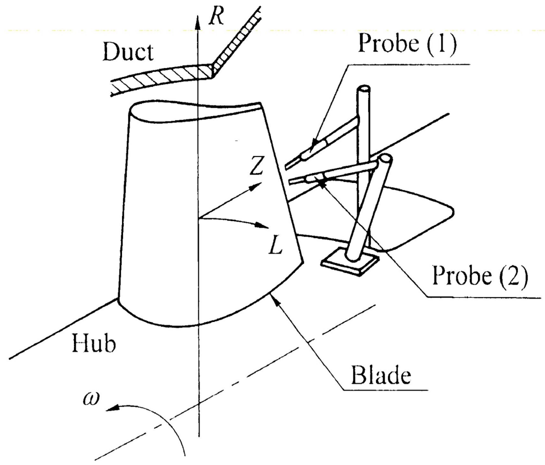


Figure 1: Schematic view of the test section.

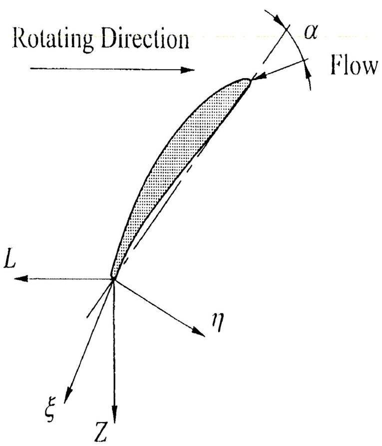


Figure 2: Tested blade and the coordinate.

The velocity distributions of the mean flow relative to the blade, its intensity and the spectrum of velocity fluctuation were measured on the L-Z plane at different radius and also on the R- η plane at the points 1.5 D_t downstream of the trailing edge of the blade. A microphone was set at the point on the axis of rotation and 1 m upstream of the rotating plane of the blade. The sound pressure level of the test blade only was evaluated by subtracting the sound energy generated from the rotating system without the test blade from that with the blade.

3 - RESULTS AND DISCUSSION

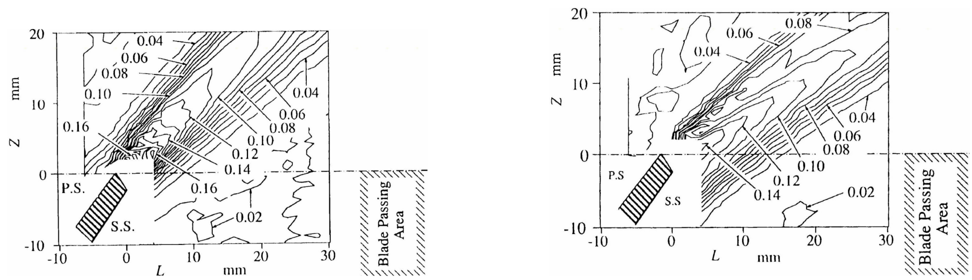
3.1 - The effect of attack angle on the flow field in the mid-span region

The effects of attack angle on the intensity of velocity fluctuation u' are shown in Figs. 3a and 3b as contour maps of u'/U_0, for the tip attack angle $\alpha_t = 4.4°$ and $-8.0°$, respectively. And Fig. 4 shows the comparison of spectrums (changing with α_t) of the velocity fluctuations measured at the points where the value of u'/U_0 became maximum. The notations P.S. and S.S. in Fig. 3 mean respectively the pressure and the suction sides of the blade.

As shown in Fig. 3b in case of $\alpha_t = -8.0°$ the intense velocity fluctuation regions are observed on both the S.S. and the P.S. sides of the blade. The distribution of u'/U_0 is symmetrical and the free shear layer is much stronger than that in the case of α_t= 4.4°.

The spectrum in this case shows a discrete peak at about 738 Hz as shown in Fig. 4.

The cross-correlation of the velocity fluctuations between two points on the pressure and the suction sides of the blade takes the maximum of the absolute value at the time lag τ>0 and the negative sign. This means that the periodic velocity fluctuations are out of phase with each other. And accordingly it is concluded that the periodic velocity fluctuation is caused by the Karman vortex shedding although the blade used is a streamlined body.



(a): R=212 mm, α_t = 4.4°. **(b):** R=212 mm, α_t = −8.0°.
Figure 3: Contour map of the coefficient of velocity variation, u'/U_0.

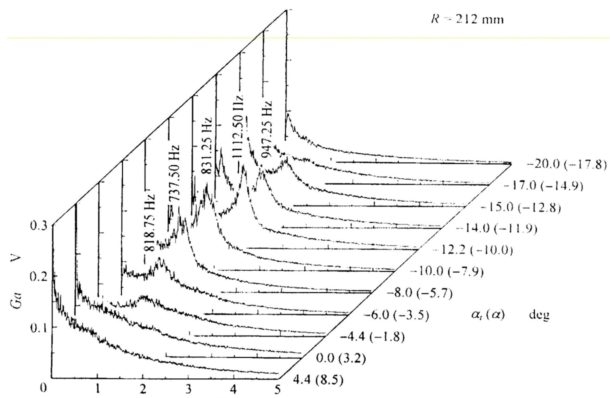


Figure 4: Effect of angle of attack on the spectrum of velocity fluctuation.

3.2 - Effect of the angle of attack on Strouhal number S_T

The Strouhal number is an important parameter in the estimation of the sound pressure level caused by the Karman vortex shedding as will be discussed later. Fig. 5 shows an example of S_t defined by the displacement thickness. It is shown that the S_t takes about 0.15 if the Karman vortex shedding is stable and increases as the stability becomes weak [7].

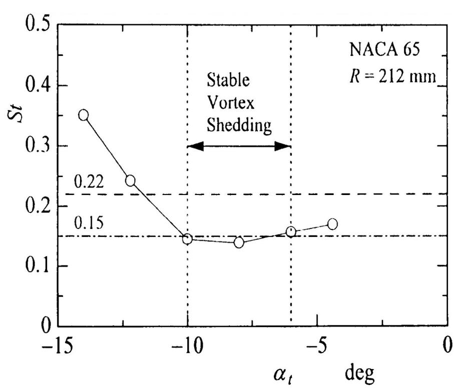


Figure 5: Strouhal number.

3.3 - Periodic component of velocity fluctuation in the near wake of the rotating blade

In this section the velocity fluctuation phenomena at the most intense points of *u'* in the near wake along whole span of the blade will be discussed. Fig. 6 shows the spectrum of the velocity fluctuations in the cases of α_t= 6.0° (partial load), 4.4° (design point), − 4.0°, − 6.0° and − 8.0° (over load). At the design point the periodic phenomenon is not clear while in the other condition single discrete peak generates at each radial point, signifying that the periodic vortex shedding clearly occurs in those regions. The spanwise region where the periodic phenomenon is remarkable, however, strongly depends on the attack angle. It is clearly seen that the vortex shedding frequency increases with the radius due to that the circumferential velocity, i.e., the approaching velocity to the blade increases with the radius.

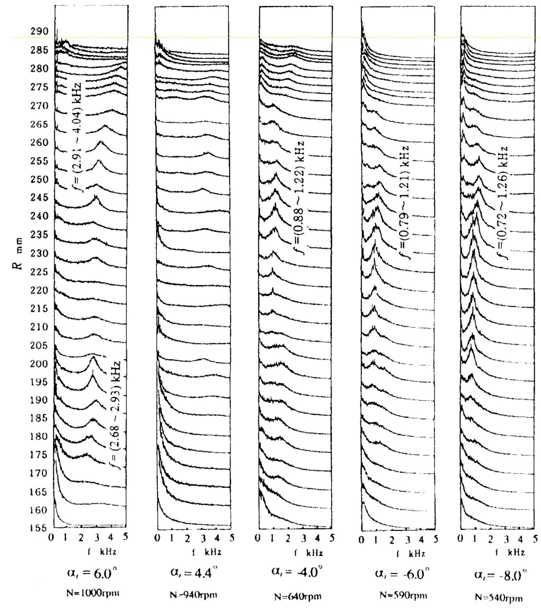


Figure 6: Effect of angle of attack on the spectrum of the velocity fluctuation.

3.4 - The effect of attack angle on the generated sound

Fig. 7 shows the spectral distributions of noise in the cases of $\alpha_t = 6.0°, 4.4°, -4.0°, -6.0°$ and $-8.0°$ which correspond to the cases shown in Fig. 6. It is noticed that the sound pressure level swells in the same frequency range (about $0.7 - 1.2$ kHz in the cases of $\alpha_t = -4.0°, -6.0°$ and $-8.0°$) as that in which the discrete peak forms in the spectrum of the velocity fluctuation as discussed in Fig. 6. Then it is concluded that although the generated noise has the same discrete frequency as the vortex shedding frequency that peak frequency increases with the increase in the radius of the blade. And accordingly the over all spectrum of noise from whole span of the blade becomes, so to speak, broadband. This is exactly the same as that in the case of the rotating flat plate blade [5].

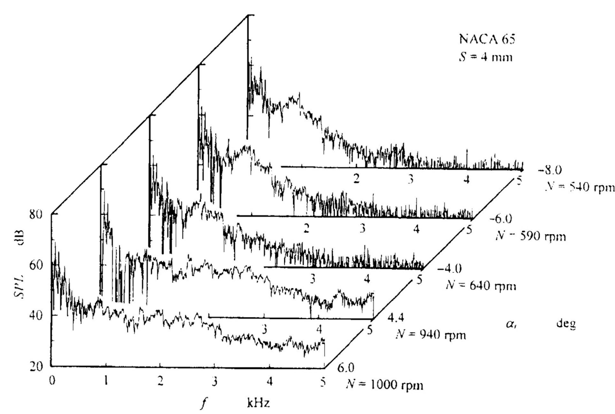


Figure 7: Effect of the attack angle on the spectrum of the noise.

4 - PREDICTION OF THE NOISE SPECTRUM

4.1 - Sound pressure level due to vortex shedding with a fixed frequency

We theoretically introduced a fundamental equation to predict the sound pressure level generated by the periodic vortex shedding from rotating flat plate blades with and without beveling near the trailing edge [5]. It is applied to the present NACA65 blade case.

The sound pressure level due to a vortex shedding with a frequency of f is expressed as,

$$(SPL)_f = 10\log_{10}\left(\frac{\rho_0}{p_0 a_0 r}\right) U_0^6 St^2 \left(\frac{u'_{vortex}}{U_0}\right)^2 \left(\frac{l_s}{C}\right)^2 l_p^2 B \tag{1}$$

where ρ_0 is the density of air, p_0 the reference pressure, a_0 the sound velocity, r the distance from the noise source to the observer, U_0 the main flow velocity, St the Strouhal number, u'_{vortex}/U_0 the coefficient of velocity variation due to vortex shedding, l_s and l_p the chord- and the span-wise correlation length, respectively. C is the chord length.
One of the Karman vortices has a coherent structure. The span-wise structure is referred to as the cell in the followings. The sound pressure level generated from a cell with a frequency of f is determined by substituting the measured values of St, u'_{vortex} and l_p into Eq. (1).

4.2 - Spectrum of noise

The spectrum of noise due to the Karman vortex shedding from the blade is obtained by applying Eq. (1) to each cell along the whole span of the blade. By assuming that the sound power generated from the different cells is independent with each other the values of sound power are plotted against the frequency which gives the spectrum of noise generated from the whole span of the blade [5].

4.3 - Determination of the correlation lengths

As an important parameter determining the sound pressure level by using Eq. (1) the spanwise correlation length l_p is determined by the measurement of the cross-correlation between two velocity fluctuations. For example the spanwise correlation length l_p is about 24 mm, 26 mm and 30 mm, respectively for the cases of $\alpha_t = -4.0°$, $-6.0°$ and $-8°$. The experimental determination of the chordwise correlation length l_s is much more difficult than l_p. And in the present paper it is estimated by the following formulae introduced for the flat plate blade in a uniform flow [3].

$$l_s = \begin{cases} \lambda/4 & C < \lambda/4 \\ C^2/(\lambda/4) & C > \lambda/4 \end{cases} \tag{2}$$

where λ is the wave length of the discrete noise and C the chord length of the blade.

4.4 - Magnitude of velocity fluctuation and Strouhal number

In order to estimate accurately the sound pressure level the values of u'_{vortex} must be carefully determined. In the present paper it is determined by using the peak value in the spectrum of the measured velocity fluctuation which is shown in Fig. 6 [5].
The Strouhal number which is defined by a displacement thickness as the characteristic length seems to take a smaller value in the case of a streamlined body, like a NACA blade, than 0.2 which is usually hold in the case of a blunt body. The Strouhal numbers in the region where the peak level in the spectrum of the velocity fluctuation shown in Fig. 6 became high were experimentally determined as $St = 0.22$, 0.17 and 0.15, respectively in the cases of $\alpha_t = -4.0° - 6.0°$ and $-8.0°$.

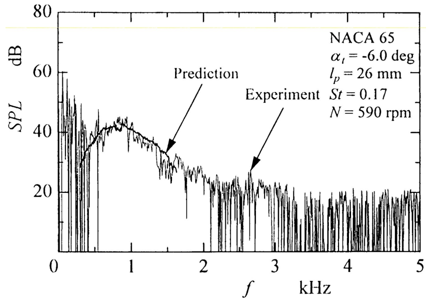
5 - COMPARISON OF THE ESTIMATED SPECTRUM WITH THE EXPERIMENT AND DISCUSSION

Figs. 8(a) and 8(b) show examples of the comparisons of the spectrum calculated by Eq. (1) with the experiment for the cases of α_t = -6.0° and -8.0°. The agreement of the distributions between the two is quantitatively quite well in the frequency range in which the sound pressure level remarkably swells, i.e., the periodic velocity fluctuation is remarkable. This good agreement shows that Eq. (1) to estimate the sound pressure level and the method of estimation of the spectrum, are useful in the case of streamlined blades such as used in the present experiment.
It is pointed out that the measured sound pressure level is higher than the calculated in the frequency ranges where the vortex shedding from blade is not remarkable as clearly seen in Figs. 8. This means that noise sources, which are different from the vortex shedding, control the noise level in those frequency ranges.

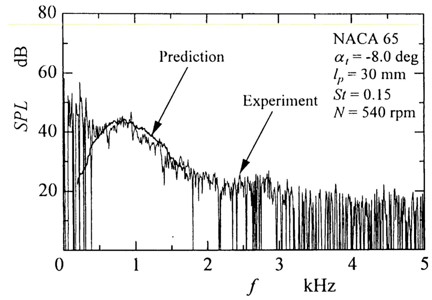
6 - CONCLUSIONS

The relation is examined between the broadband noise generated from a NACA 65 blade and the periodic velocity fluctuations in the near wake of the blade. The method to theoretically estimate the spectral distribution of noise is also developed. As a result the following conclusions are obtained.

- The periodic velocity fluctuation caused by Karman vortex shedding is remarkably observed in the near wake of the blade especially in the flow rate range above the design point, i.e., in the cases of negative attack angle even in a streamlined body.



(a): α_t = -6.0°, N=590 rpm.



(b): α_t = -8.0°, N=540 rpm.

Figure 8: Comparison of the spectrum of noise between the experiment and the calculated.

- The Strouhal number defined by the displacement thickness takes 0.15∼0.2 for a streamlined blade, which is smaller than that in the case of a blunt body.
- The frequency of the Karman vortex shedding increases with the velocity of the main flow oncoming to the blade, i.e., the larger the radius, the larger the shedding frequency. On the other hand each vortex shedding with different frequency produces its own discrete frequency noise. And accordingly the over-all spectrum of noise generated from a blade becomes broadband.
- By using the proposed method for calculating the sound pressure level due to the Karman vortex shedding the quantitative estimation of the broad band spectrum of the generated noise is possible with satisfactory accuracy when the Karman vortex shedding remarkably occurs.

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