bulent) and a turbulent PBC calculation. These allow an assessment of the relative importance of viscous effects and wall effects for the two flows. For the attached flow (Fig. 2), viscous effects exert little influence on shock position and trailing-edge pressure recovery, the main viscous effect being a smoothing of the overcompression at the foot of the shock. Also, there is a slight (2% chord) forward positioning of the shock due to the viscous effects. Once the flow separates, however, viscous effects on the surface pressures are significant, as seen in Fig. 3. A comparison of the two free-air calculations shows the shock position for the turbulent solution to be about 9% chord upstream of the inviscid position. Trailing-edge pressure recovery is also significantly reduced in the turbulent solution.

On the upper surface of the airfoil none of the free-air solutions are close to the experimental data at either test condition. Imposition of the measured pressures on the upper and lower computational boundaries dramatically improves this situation. For the attached flow (Fig. 2), the turbulent PBC solution shows excellent agreement with the data, the main effect of the PBC being a forward positioning of the shock to the experimental location. For a flow with a separation bubble (see Fig. 3), the PBC moves the shock forward, but still downstream of the measured position. It appears that deficiencies in the turbulence model for describing separated flows are responsible for the lack of agreement, although mesh resolution may still be a factor.

Conclusion

For attached flows, the pressure boundary condition has been demonstrated to be effective in accounting for wind tunnel wall-interference effects in numerical calculations. Surface-pressure results also agree well with experiment for this situation. For separated flows, however, turbulent PBC calculations show an improvement over free-air solutions even though inadequacies in the turbulence modeling are still important limitations. Evaluation of turbulence models for separated airfoil flows could benefit from using the Reynolds-averaged Navier-Stokes code with the pressure boundary condition and appropriate experimental data.

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Effect of Blunt Trailing Edge on Rotor Broadband Noise

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TURBULENT vortex shedding from blunt trailing edges is a source of rotor high-frequency broadband noise.[1] Brooks and Hodgson[2] were the first to demonstrate the importance of this self-noise mechanism for stationary airfoils. In their experiment with an isolated airfoil, they found that the radiated noise increased significantly for airfoils with thickened trailing edges. This Note studies the parametric dependence of this noise mechanism and develops a method to predict rotor broadband noise associated with turbulent vortex shedding from blunt trailing edges.

Blunt trailing-edge noise radiation is a result of higher surface presssure fluctuations near the airfoil's trailing edge due to turbulent vortex shedding. To predict this noise mechanism, our first task is to scale the fluctuating surface pressures. Using dimensional analysis or physical reasoning, the following relationships for the parametric dependence for S_{pp} and f were found

$$S_{pp} \sim q^2 t^3 / U, \qquad f \sim U/t$$

where S_{pp} is the power spectral density of surface pressure fluctuation, f the frequency, q the dymanic pressure $(\rho U^2/2)$, t the trailing-edge thickness, and U the freestream velocity. By using the above relationships, the surface pressure spectrum S_{pp} is assumed to have the following form

$$S_{pp}(f) = q^2 t^3 S_0(\tilde{\omega}) / U$$

where $\tilde{\omega} = 2\pi f t / U$. The normalized spectrum $S_0(\tilde{\omega})$ can be found empirically from experimental data. Due to the lack of measurements for surface pressure fluctuation near blunt trailing edges, such data were obtained by inverting the acoustic data measured by Brooks and Hodgson[2] using their stationary airfoil analysis. Using the above scaling relation, the data representing a wide range of freestream velocities and trailing-edge thickness are collapsed reasonably well to a single curve. By using curve-fitting techniques, the empirical expression for the normalized spectrum S_0 is found in terms of $\sigma = \log_{10}\tilde{\omega}$ as follows:

$$\log_{10} S_0(\tilde{\omega}) = 17.394 - 106.57\sigma - 158.12\sigma^2 + 99.27\sigma^3 - 33.249\sigma^4 + 16.721\sigma^5$$

for $0.2 < \sigma < 2$, otherwise

$$S_0(\tilde{\omega}) = 0$$

Figure 1 shows the fitted curve along with the experimental data.

To predict the additional broadband noise radiation from a rotor due to its blunt trailing edge, several assumptions have to be made. First the source is modeled as rotating radiating dipoles, and the rotor/observer relative position is

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assumed to be fixed. Then we follow the similar analysis of Kim and George for boundary-layer/trailing-edge noise.[3] The result for far-field radiated sound pressure level can be expressed as follows:

$$\langle S_1(x,f)\rangle = \frac{Bf^2b^2U_c^2\sin^2\phi}{2\pi\rho c_0^3 r^2}\sum_{n=-\infty}^{n=\infty}$$
$$\times\frac{F_g(|f-n\Omega|)S_{pp}(|f-n\Omega|)}{\{1+[b/1_2(|f-n\Omega|)]\}(f-n\Omega)^2}J_n^2\left(M_0\frac{f}{\Omega}\cos\phi\right)$$

where

B	= number of blades
f	= acoustic frequency in Hertz
b	= rotor blade span
U_c	= turbulence convection velocity
ϕ	= elevation angle of observer from the rotor plane
ρ	= density of the acoustic medium
c_0	= undisturbed sound speed
r	= distance from rotor hub to observer
Ω	= rotor frequency in Hertz
M_0	= effective dipole Mach number
F_g	$=F^2+G^2$
F	$=\left(\frac{\mu+M\mu+K_1}{\mu+M\mu}\right)^{1/2}[(c_1+s_1)\cos 2K_1 + (c_1-s_1)\sin 2K_1)]+1-(c_2+s_2)$
G	$=\left(\frac{\mu+M\mu+K_1}{\mu+M\mu}\right)^{1/2}[(c_1-s_1)\cos 2K_1 - (c_1+s_1)\sin 2K_1)]-(c_2-s_2)$
c_1-is_1	$=E^*[2\mu(1+M)]$
c_2-is_2	$=E^*[2(\mu+\mu M+K_1)]$
K_1	$=\omega c/2U_c$
μ	$=Mk/\beta^2$
$1_2(\|f-n\Omega\|)$	$\simeq 2.1(U_c/2\pi\|f-n\Omega\|)$

Due to the dipole assumption, the present analysis cannot predict the exact sound radiation pattern, neither does it allow the inclusion of the effect of forward flight. However,

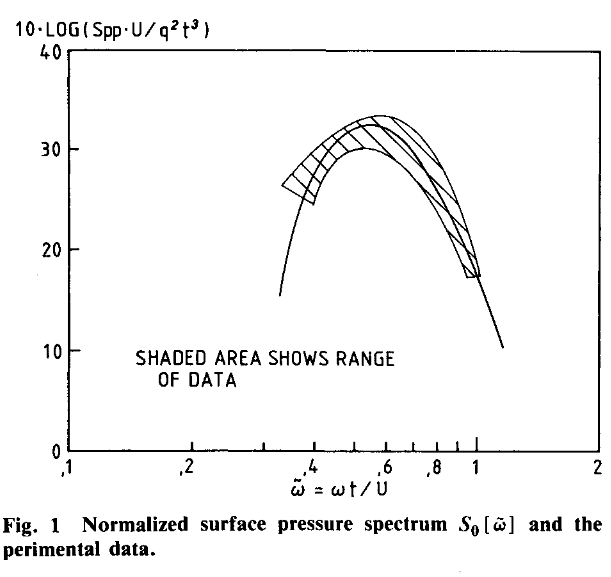

Fig. 1 Normalized surface pressure spectrum $S_0[\tilde\omega]$ and the experimental data.

a previous study[4] has shown that these are not very serious restrictions for rotors with advance ratios less than about 0.4 and for observers not within about 15 deg of the rotor plane.

The present analysis is evaluated by comparison with existing experiments. Figure 2 compares the results calculated for the MOD-2 wind turbine to the experiment of Hubbard et al.[5] The results shown used a calculated trailing-edge thickness, which is based on the standard NACA 23XXX series airfoil sections as in the MOD-2 blade application. The results compare favorably with the acoustic data obtained from the experiment; the present analysis successfully explains the spectrum hump at about 1000 Hz that cannot be explained from previous studies.[4] Note that turbulent vortex shedding noise is significant only within certain frequency range; thus, to predict the overall noise spectrum, one should also include

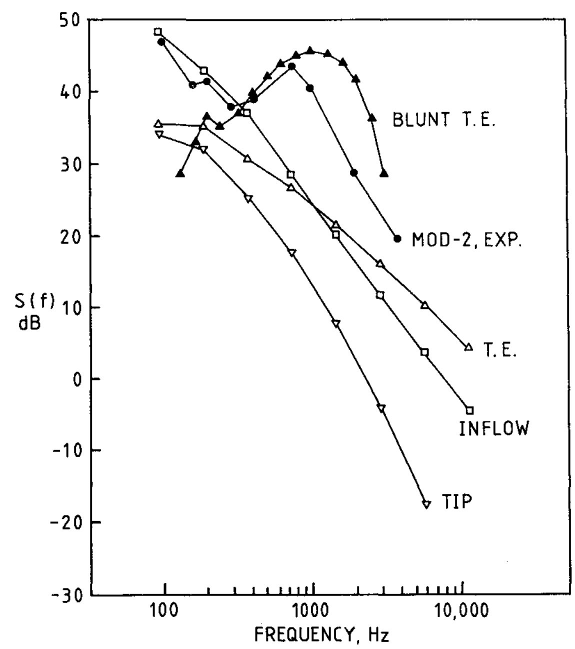

Fig. 2 Comparison of predictions for the MOD-2 wind turbine, experiment of Hubbard et al.[5]

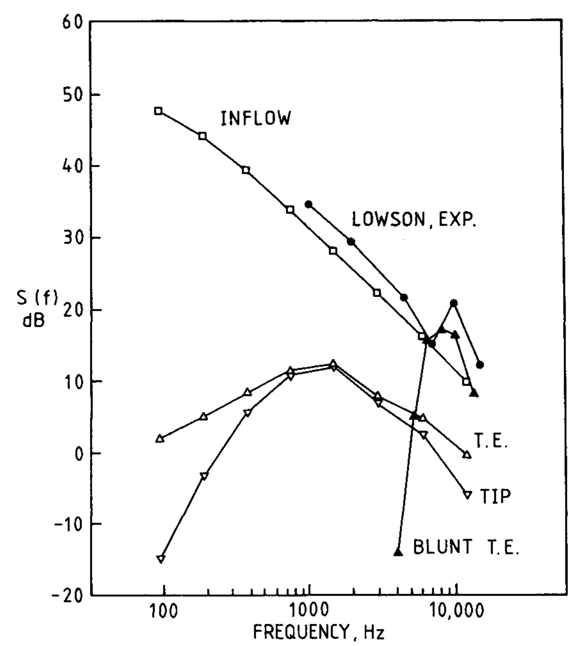

Fig. 3 Comparison of predictions for model low-speed fan, experiment of Lowson et al.[6]

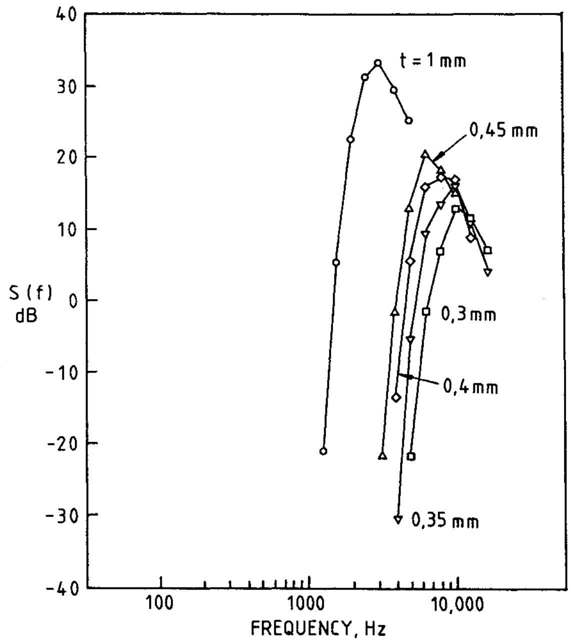

Fig. 4 Effect of trailing-edge thickness on rotor broadband noise.

other sources like in-flow turbulence noise, trailing edge noise, and tip vortex formation noise.

Figure 3 shows the comparison of the analysis to the low-speed fan noise experiment of Lowson et al.[6] Again, all possible broadband noise sources are included. The results show excellent agreement with the experiment.

Figure 4 shows the effect of trailing-edge thickness on rotor broadband noise. Calculations were made based on the low-speed fan as used in Lowson's experiments. It is clear that trailing-edge thickness is a very important parameter for the rotor noise problem. Generally speaking, the noise spectra due to turbulent vortex shedding from blunt trailing edges are peaks occurring at various frequency ranges. The peak frequency depends on the trailing-edge thickness; a small trailing-edge thickness will generate a high-frequency peak, and a thick trailing edge will result in a peak of lower frequencies. The level of the spectrum peak also depends on the thickness of the trailing edge; the peak level increases roughly according to the third power of trailing-edge thickness.

In conclusion, turbulent vortex shedding noise from blunt trailing edges is a very important broadband noise source for rotors. A slightly blunted rotor trailing edge can contribute significantly to the overall noise spectrum. Present analysis provides reasonable predictions for such mechanisms. More accurate prediction could be achieved with better empirical expression for $S_0(\tilde{\omega})$, the normalized spectrum. Clearly, more measurements of surface pressure fluctuations near blunt trailing edges are needed.

Acknowledgment

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Turbulent Boundary-Layer Modification by Surface Riblets

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Introduction

In the past several years, significant efforts have been made to develop passive techniques that result in a net reduction in surface shear stress due to boundary-layer turbulence. One technique that demonstrated net surface drag reduction and has the potential for practical aerodynamic and hydrodynamic applications is the use of streamwise triangular V-grooves or riblet surface modifications. Extensive wind tunnel investigations at NASA Langley[1-3] have shown that when these riblets are reduced in size to less than 30 viscous lengths in height and span, surface drag reductions of up to 8% can be achieved.[2] However, despite this apparent success of the riblets in reducing surface drag, it is still unclear how this type of surface affects the fluid interaction with the surface.

The present Note reports on the results of a flow visualization study that examined the most promising drag-reducing riblet surface configuration and attempts to determine changes in the turbulent flow structure precipitated by the riblet surface relative to a conventional flat-plate flow.

Experimental Facility

The experiments were conducted using the Lehigh University free-surface, visualization water channel and high-speed video viewing system described in Ref. 4. Streamwise, triangular riblets were machined on a removable 0.15×1.21 m Plexiglass insert, which began 0.91 m from the leading edge of the test plate shown in Fig. 1. The riblets were triangular in cross section, 1.6 mm deep by 1.6 mm wide, providing optimal nondimensional riblet height and spacing of $h^+ = s^+ = 15$ for 0.21 m/s freestream velocity (see Refs. 5 and 6 for further construction details). The insert was inset such that the peaks of the riblets are flush with the test plate. The side-by-side arrangement of the unmodified and riblet surfaces allowed comparative studies to be performed without realignment of the test plate or readjustment of the channel velocity. A three-dimensional flow trip, designed

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