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T. F. BROOKS AND T. H. HODGSON

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Langley Research Center
Hampton, Virginia 23665

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T. F. Brooks
NASA, Langley
Research Center
Hampton, VA

T. H. Hodgson
Center for Acoustical Studies
North Carolina State University
Raleigh, NC

Summary

A comprehensive experimental investigation of airfoil trailing-edge noise up to a Reynolds number based on chord of 2.96×10^6 is described. Comparisons are made with current theory, particularly with regard to the nature of the pressure field in the vicinity of the trailing-edge and its influence on the radiated noise.

Introduction

The enhancement of aerodynamic sound by large sharp-edged surfaces has received the attention of both theoretical and experimental investigators in recent years in view of its importance in airframe noise and possible application to rotor noise. The simplest experimental case pertinent here is that of two-dimensional flow at low Mach number over an airfoil of chord dimension large relative to the wavelength. The Reynolds number of the flow is such that turbulent boundary layer flow exists over most of both surfaces of the airfoil.

Comprehensive reviews of the theoretical treatments which principally model the airfoil trailing-edge problem by a semi-infinite rigid plate with an idealized turbulent eddy have been given by Ffowcs Williams [1] and Howe [2]. Howe divided these theories into three groups, namely those based on the Lighthill analogy, linearized hydroacoustic methods and ad hoc approaches. He showed that, when suitably viewed, all relevant theoretical models lead to the dependence of the radiated sound on the fifth power of a characteristic flow velocity V. An extension of the usual assumption of uniform flow velocity U_∞ to incorporate a sheared flow has since been given by Goldstein [3] with a result that reduced to a V^5 dependence at low Mach numbers. Since the theories cannot easily account for the structure of the turbulence and the effects of viscosity at the trailing-edge, then as was described in Ref. 1, the prediction of edge enhancement effects by potential flow theories could be highly dependent on the manner in which the unsteady Kutta condition is

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applied at the trailing-edge. Howe's unified theory [2] represents the most recent attempt to evaluate the effect of an unsteady Kutta condition on the level of sound radiated. Howe's result for the no-Kutta condition case can be written in the following form for the mean-squared sound pressure $\langle p^2 \rangle$ per unit span at right angles to the airfoil chord ($\theta = 90^o$),

$$\langle p^2 \rangle \simeq K\ (\rho_0^2/a_0)(v/u^*)^2(u^*/U_\infty)^2(U_\infty/V)^2(\ell/r^2)\ V^n \qquad (1)$$

where K is of order unity, ρ_0, is the fluid density, a_0 is the speed of sound, v is the fluctuating velocity, u* is the friction velocity, ℓ is a spanwise turbulence scale, r is the observer radial location and the exponent n=5. But when the Kutta condition is applied, Howe predicted that the sound pressure level should decrease by a factor $(1-W/V)^2$, where W is the convection velocity in the wake. This decrease might then establish a lower bound on estimates of trailing-edge noise from two-dimensional flow.

There obviously was a need for a carefully designed and controlled experiment in order to help resolve these issues raised by theory. The present investigation was therefore planned towards 1) establishing the mechanism and sound pressure level for two-dimensional rigid airfoil trailing-edge noise with turbulent boundary layer flow and 2) determining the nature of the trailing-edge condition and its possible effect on the noise estimate of Equation 1.

Experimental Description

An aluminum NACA 0012 airfoil of 0.61m chord and 0.46m span, supported by two reinforced sideplates, was immersed in the potential core of a 0.3m x 0.46m free jet in the recently improved anechoic quiet-flow facility at NASA-Langley, see Fig. 1. As shown, porous material was attached to the sideplates in order to reduce extraneous edge noise. Mean flow and hot-wire traverses, together with tuft studies and spanwise boundary layer and skin friction measurements, were used to confirm the uniformity of the two-dimensional flow. Most of the tests were run with the turbulent boundary layer (TBL) tripped over the entire span with roughness strips of 2cm width placed at 6% chord from the leading edge on both surfaces. The highest free-stream velocity of the tests was U_∞=73.4m/s for a Reynolds number of 2.96×10^6 based on chord. This corresponded to a value of 1.9×10^4 based on the boundary layer displacement thickness δ^* at the trailing-edge (TE). Several TE geometries were tested including a 1.27cm extension for the sharp case and with degrees of bluntness achieved by contoured wooden strips at the TE, see Fig. 2. The angle of incidence α was set at either 0^o, 5^o or 10^o, but only the $\alpha=0^o$ case will be discussed since this parameter had negligible effect on the results.

The airfoil surface was instrumented with 32 specially developed Kulite pressure sensors, each with a sensing area of 0.36mm dia. and with excellent amplitude and phase response up to a frequency of 20 kHz. The sensors were flush-mounted in symmetrical pairs on opposing surfaces, chordwise along the midspan and spanwise at 0.42% chord from the blunt TE, see Fig. 1. Eight 1.27cm dia. condenser microphones were used to measure the radiated noise arranged as shown.

Experimental Results

Narrow-band sound spectra at r=1.22m and $\theta=90^o$ for different mean velocities and TE geometries are shown in Fig. 2 with the overall levels plotted in Fig. 3. The noise spectra were determined using the cross-spectra between the geometrically opposite microphones 1 and 2. Signals from these microphones were 180^o out-of-phase over the entire frequency ranges of the spectra of Fig. 2. Cross-spectral phase measurements between pairs of all microphones verified that the noise is emitted from the TE region to a resolution of 5mm (with shear layer refraction due to the free jet taken into account) and that the noise field is dipole-like in nature. Initial measurements have revealed a dipole-like directivity pattern. The cross-spectral technique provided excellent resolution in that the background noise from extraneous causes was 20dB below the measured level in any frequency band. The noise spectra show Strouhal dependence and it is clear that the spectral humps shown here for U_∞=69.5m/s case due to the separated flow from the blunt TE (which is itself Strouhal dependent) is an additive effect. The localized dipole characteristics of the sound generated by the coherent separated flow field is illustrated by taking a cross-spectrum between opposing microphone signals and the differential pressure signals close to the TE for the blunt case, see

Fig. 4. For sensors immediately upstream the spectral hump decays in amplitude. Note that although the degree of bluntness is only a fraction of the TBL δ^*, the separated flow can produce a significant contribution to the sound field, of the order of 2dB above the overall level for the sharp case, see Fig. 3.

Fig. 5 shows the coherence γ^2 between surface pressures at close separations in both the chordwise and spanwise directions for the sharp TE case. Comparison with the noise spectra of Fig. 2 shows that the frequency of maximum coherence of the near field pressure does correspond to the peak of the noise spectrum. In support of the theory, the dominant frequencies of interest corresponded to wavelengths of order the airfoil chord or smaller, but greater than the scale of turbulence. These coherence results are in close agreement with TBL pressure field data quoted by Heller and Dobryznski [5] in which the spanwise integral scale $\ell = 0.26 U_\infty / f \simeq 3\delta^*$ in the present case.

From Fig. 2, the measured sound pressure for this experimental case for the sharp TE is given by (in S.I. units)

$$\langle p^2 \rangle = 3.0 \times 10^{-12}\, U_\infty^{5.07} \tag{2}$$

If expressed in the form of Equation 1, the small change in u* over the Reynolds number range of the experiment would increase the exponent n by 0.23 while the small change in measured convection velocity V would reduce n by 0.33 for a measured dependence on convection speed of $\langle p^2 \rangle \sim V^{4.97}$ close to the theoretical result. The measured value of the factor K using $\ell = 3\delta^*$ and typical turbulence levels is determined to be $K = 1.9 \times 10^{-3}$ compared to the no-Kutta value of unity. Thus it would appear that the TE conditions present in the real case are such that the measured levels are well below the prediction for the no-Kutta condition case of Equation 1. The value of average wake convection speed W measured between a pressure sensor and x-wire just downstream of the sharp TE was found to be of order V which would also support Howe's contention that the presence of a Kutta condition would tend to reduce the edge noise. If the overall levels of Fig. 3 are compared with full-size data reduction by Fink [4] the present data is some 15dB below conventional aircraft.

Figs. 6, 7 and 8 show the most important findings of this investigation and constitute the first measurements of the scattered pressure field close to the TE. Fig. 6 shows cross-spectra G_{xy} and phase ϕ_{xy} between an upstream sensor A and a downstream sensor B and also with sensors C and D on the opposite surface. The fact that the spectrum level $G_{BA}<G_{AA}$ demonstrates the decaying nature of the TBL pressure field, convected at velocity V given by the slope of ϕ_{BA}. Note that communication to the opposite surface from sensor A is in the same phase sense and at sonic velocity upstream to sensors C and D, since ϕ_{DA} is very close to ϕ_{CA} (i.e., almost simultaneous perception from C to D). This represents one component of the scattered pressure field. From data not presented here, a second component of equal amplitude but opposite sign was detected which propagates upstream from B to A. In addition, the TBL pressure field on the opposing side produces a statistically similar but independent scattered field to that just described. It can be shown from a model incorporating the convected TBL fields and the scattered fields that the net effect of these components of the nearfield is to produce statistically in-phase and 180° out-of-phase regions for the phase difference between opposing sensors upstream of the TE. It has been found that the 180° out-of-phase region should occur when $\lambda_c/4<\xi<3\lambda_c/4$ where λ_c is the convected hydrodynamic wavelength. However, when the opposing sensors are in the nearfield of the blunt TE, the 180° out-of-phase region due to the coherent shedding can dominate over the scattered field phenomena, see as an example Fig. 7 for the 2.5mm blunt TE where the pressures are 180° out-of-phase over the frequency range of the "hump" in the corresponding noise spectrum of Fig. 2.

Fig. 8 represents a summary of all the phase-region data taken at various distances ξ from the TE plotted vs the parameter frequency x distance $f\xi$. It can be deduced from Fig. 8 that as the distance $\xi \to 0$, that is as the pressure sensors approach the TE, the in-phase region would extend over all finite frequencies (except for the case of strongly coherent separated flow shedding). In addition, as $\xi \to 0$ the two pressure fields become coherent with equal amplitude. This can be demonstrated from properties of Fig. 6 where the cross-spectra G_{CA} and G_{BA} would ultimately approach equal values with $\phi_{BA}=\phi_{CA}$.

This then suggests that $\Delta p \to 0$ at sharp TE. This result, measured over a wide frequency range, supplies support for potential flow modeling which embody the unsteady Kutta condition, see McCroskey [6]. Further data analysis and development of the pressure field model is in progress.

Conclusions

The noise spectra and source location for the two-dimensional flow case of airfoil edge noise have been determined. The overall level closely follows a V^5 dependence for the sharp TE case and when scaled is well below measured full-scale results. It would seem that for the TBL case the conditions prevailing at the TE are such to reduce the noise level to a much lower value than predicted by no-Kutta condition theory. For the sharp TE case it appears that the unsteady pressure differential tends to zero there. The convected TBL, scattered and separated flow fields were successfully measured in the TE vicinity.

Acknowledgments

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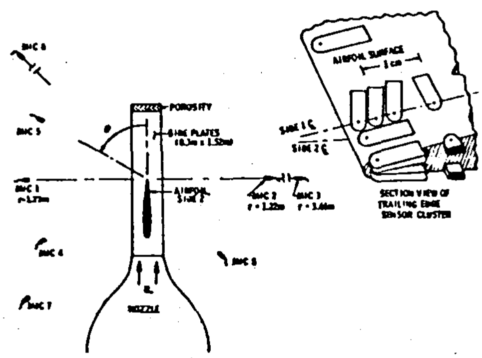

Fig. 1 Schematic drawing of test set-up and instrumented airfoil

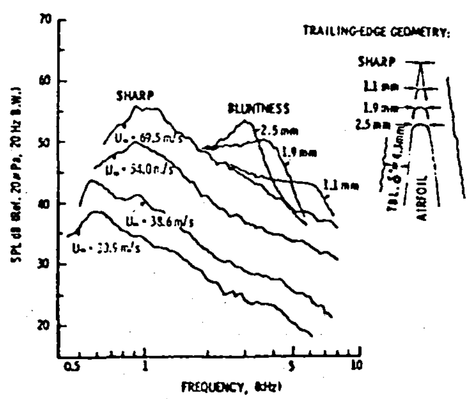

Fig. 2 Narrow-band noise spectra at r=1.22m and θ=90°

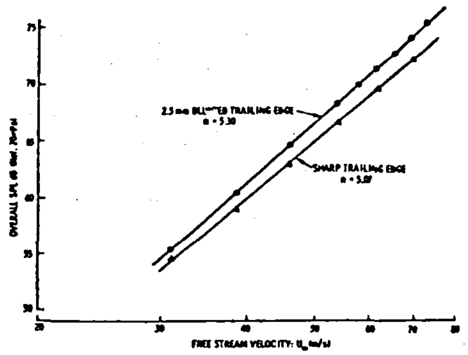

Fig. 3 Overall SPL vs freestream velocity at r=1.22m and θ=90°

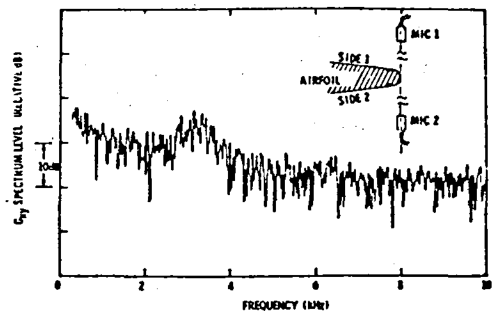

Fig. 4 Cross spectrum between microphone difference signals (r=1.22m) and TE pressure differential, blunt case, U_∞=69.5m/s

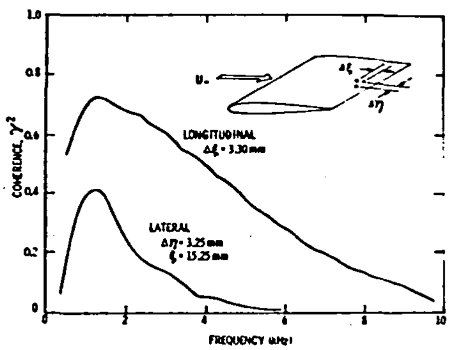

Fig. 5 Chordwise and spanwise variations of surface pressure coherence, U_∞=69.5m/s

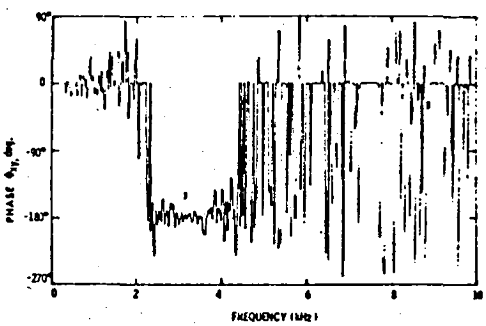

Fig. 7 Phase difference between opposing TE surface pressures, blunt case, U_∞=69.5m/s

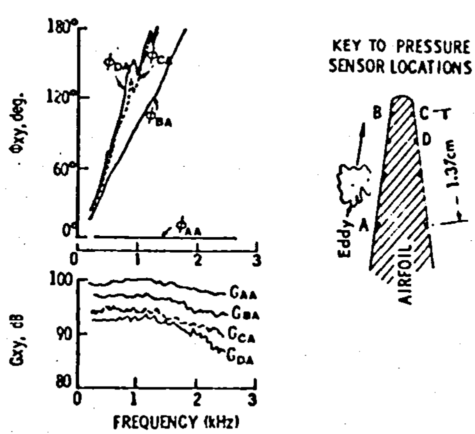

Fig. 6 Cross spectra and phase between surface pressures on same and opposing sides of airfoil, U_∞= 69.5m/s

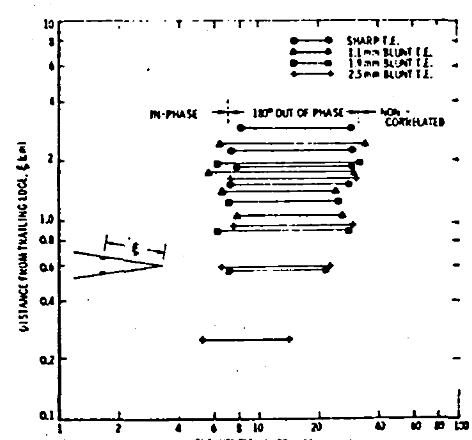

Fig. 8 Regions of phase difference opposing side surface pressures at distance ξ from TE, U_∞= 69.5m/s

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15. Supplementary Notes

16. Abstract

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