Conclusions

Conclusions reached in the current study are:

1) Thin-element riblets are as effective in reducing drag as symmetric V-grooves, but exhibit a larger range of allowable spacings.

2) The thin-element geometry shows qualitatively predictable influence of independent variation of riblet height and spacing.

3) Evidence of more than one drag reduction mechanism for thin-element riblets is inconclusive.

References

[1]Walsh, M.J. and Lindemann, A.M., "Optimization and Application of Riblets for Turbulent Drag Reduction," AIAA Paper 84-0347, Jan. 1984.

[2]Wilkinson, S.P. and Lazos, B.S., "Direct Drag and Hot-Wire Measurements on Thin-Element Riblet Arrays," Paper presented at IUTAM Symposium on Turbulence Management and Relaminarization, Bangalore, India, Jan. 1987.

[3]Walsh, M.J., "Drag Characteristics of V-Groove and Transverse Curvature Riblets," *Progress in Astronautics and Aeronautics: Viscous Flow Drag Reduction*, Vol. 72, edited by G.R. Hough, AIAA, New York, 1980, pp. 168–184.

[4]Bechert, D.W., Bartenwerfer, M., and Hoppe, G., "Drag Reduction Mechanisms Derived from Shark Skin," Paper 86-1.8.3 presented at 15th Congress of the International Council of the Aeronautical Sciences, London, Sept. 1986.

Aerodynamic Interaction Tones of a Model Counter-Rotating Propeller

R. T. Nagel* and H. V. L. Patrick†
North Carolina State University, Raleigh, North Carolina

Introduction

It has been well established that counter-rotating propellers (CRP's) are more efficient and exhibit significantly different radiated noise characteristics than single-rotation propellers (SRP's).[1] The difference in noise characteristics is primarily associated with interaction between the forward and aft propellers. The mechanism causing this aerodynamic interaction noise is not well understood, and numerous studies investigating this phenomenon have been initiated.

A series of radiated noise measurements using a Fairey Gannet AEW3 aircraft with CRP's have been reported[2] where the forward propeller rotated at a different rotational speed than the aft propeller. The investigation showed that the interaction noise could be identified in the noise frequency spectrum as discrete tones associated with the sums and differences of the forward and aft propeller blade-passing frequencies (BPF). These interaction tones were clearly different than the tones associated with single-rotation propellers and are similar to blade-vane interaction noise in ducted rotating machinery.

Presented as Paper 86-4.6.1 at the 15th ICAS Conference, London, England, Sept. 7-12, 1986; received July 20, 1987; revision received Sept. 22, 1987.

*Associate Professor, Department of Mechanical and Aerospace Engineering. Member AIAA.

†Visiting Instructor, Department of Mechanical and Aerospace Engineering. Senior Member AIAA.

A theory predicting interaction noise has been developed by Hanson[3] which requires the calculation of the unsteady forces for all radial positions of the blade. Unfortunately, the information required for this model is presently not available and would be very difficult to obtain.

From a fundamental point of view, the radiated noise generated by propellers is directly related to the flow through the blade disk. The flow over the blades generates forces (lift and drag) that in turn generates sound in the surrounding fluid medium. The flow between the forward and aft propellers of CRP contains both the response information of the upstream blades and the input information to the downstream blades. One may, therefore, hypothesize that the flowfield between the propellers would be directly related to the radiated aerodynamic interaction noise. It is likely that simple coherence, based on the flow fluctuations and interaction noise, will exist at any location where the flow signal contains information from both the forward and aft rotors.

By measuring the velocity field between the propellers and the radiated noise and then performing coherence analysis between the two different physical phenomena, correlation would be established if the given hypothesis is valid. Coherence $\gamma(f)$ is related to the autospectrum $G_v(f)$ of the fluctuating velocity in the flowfield, the autospectrum $G_p(f)$ of the radiated noise, and the cross-spectrum $G_{vp}(f)$ by the relationship

$$\gamma(f) = G_{vp}(f)/G_v(f)G_p(f) \tag{1}$$

where f is the frequency.

If $0<\gamma(f)<1$, one or more of the following possible explanations exists:[4] 1) random noise is present in the experiment, 2) the relationship between sound and velocity is not linear, and 3) at least one of the measured signals is, in part, due to other sources. If $\gamma(f)=1$, the two signals are clearly defined and linearly related at frequency f. When $\gamma(f)=0$, the signals are completely unrelated. This Note shows that such information can be used to tentatively establish that interaction tones based on sum frequencies are more closely related to circumferential velocity components between the propellers whereas tones at difference frequencies are more closely related to axial flow fluctuations.

Discussion

Experiments were performed with counter-rotating hobby aircraft propellers. The two-bladed propellers had a tip diameter of 0.28 m, the pitch was 0.18 m, and were axially separated by $0.1r_t$, where r_t was the tip radius. The right- and left-hand counter-rotation propellers were powered with small electrical motors at speeds of near 20 rps. A single-sensor hot-film anemometer was placed at an axial location halfway between the propellers at a radial location of $0.5r_t$. The microphone was located $0.6r_t$ in front of the leading edge of the forward propeller and at a radial position of $0.82r_t$. The tests were performed inside an anechoic chamber where the propellers were operated at zero advance ratio, i.e., the propellers were fixed in a static fluid environment. Figures 1 and 2 represent typical results from this configuration; however, 36 sets of data were obtained at various transducer spatial locations and two rotor spacings.

Acoustic tests were also performed in the anechoic chamber without the propellers rotating. It was determined that the background noise associated with the experiment was not negligible at all frequencies but was a minimum of 15 dB below the measured CRP noise for all frequencies of concern. Background noise is comparable to test data at frequencies below 20 Hz. Tones that occurred in the background noise level did not correspond in frequency to interaction tones, and coherence between background noise and the background anemometer signal produced significant values only at frequencies that were multiples of 60 Hz.

To determine the microphonic characteristics of the hot-film anemometer, a speaker excited with one-octave-band

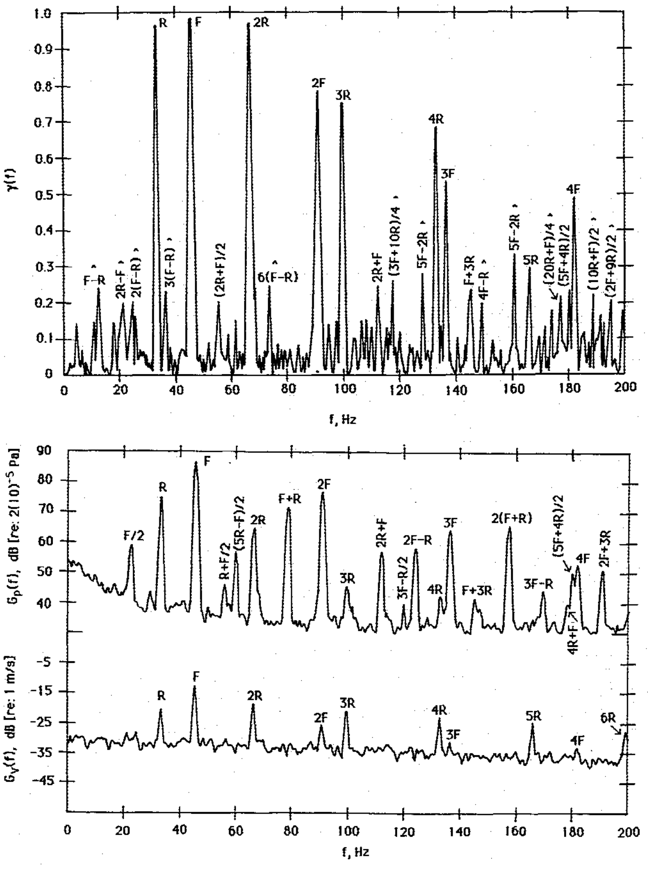

Fig. 1 Coherence [$\gamma(f)$], radiated noise spectrum [$G_p(f)$], and fluctuating velocity spectrum [$G_v(f)$] with vertical anemometer sensor.

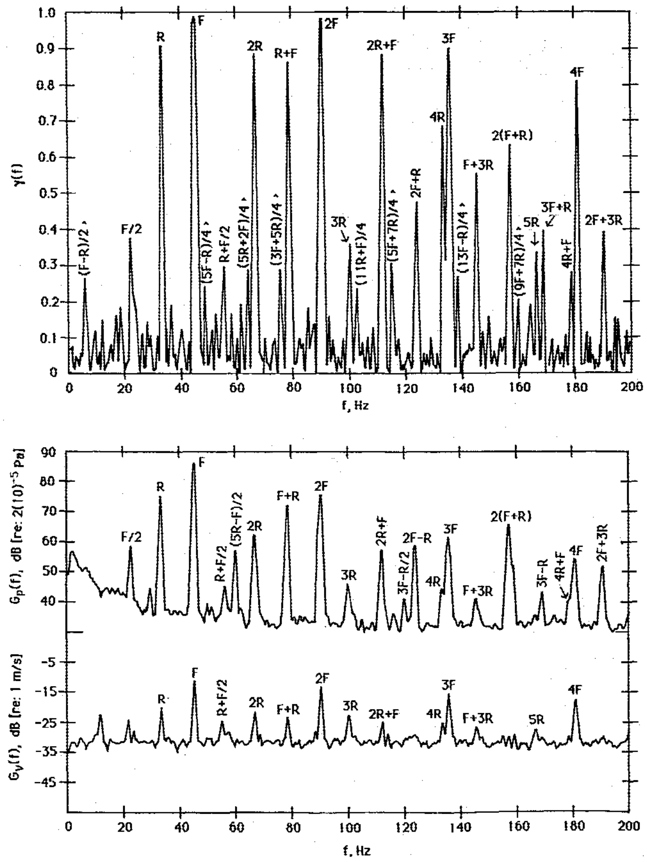

Fig. 2 Coherence [$\gamma(f)$], radiated noise spectrum [$G_p(f)$], and fluctuating velocity spectrum [$G_v(f)$] with horizontal anemometer sensor.

white noise was placed an equal distance from the anemometer and the microphone (placed 1.3 cm apart). The SPL measured by the microphone was 80 dB re $2(10)^{-5}$ Pa in a 0.5-Hz bandwidth at one-octave bands centered at frequencies of 31.5, 63.5, and 125 Hz, and no measurable signal was produced by the anemometer. In addition, the microphone and anemometer sensors were placed on opposite sides of the rotor system at $1.05r_t$ (outside the flow) near the blade tips. At this location the microphone measured 85 dB peak SPL (88 dB OASPL), whereas the anemometer signal was not measureable. It was clear that the microphonic response of the anemometer was not contributing to the measured flow signal.

Shown in Fig. 1 is the spectrum $G_v(f)$ of the fluctuating components of the velocity measured by a vertically oriented hot-film sensor, acoustic spectrum $G_p(f)$, measured by the microphone, and the coherence $\gamma(f)$ between these two parameters in a 0.5-Hz bandwidth over a frequency range of 0–200 Hz. It had been established that very little information of interest existed at frequencies greater than 200 Hz by analyzing data up to 5 kHz. Figure 2 shows similar results but with the anemometer sensor placed in a horizontal position. The vertical hot-film sensor measured primarily axial components of velocity while the horizontal orientation was sensitive primarily to circumferential components. Both vertical and horizontal orientations were sensitive to radial components of velocity. Although these single-channel measurements are not a clean measurement of a particular flow component, they do represent significantly different velocity components at the same spatial location.

Peak values for all curves in Figs. 1 and 2 are labeled. For both figures, the BPF of the forward blades was labeled F, which was 44.5 Hz, and BPF for the aft (rear) propeller was denoted as R, which was 33.5 Hz. Harmonics of the fundamental BPF's were simply denoted as multiples of F and R, which were the tones, but not necessarily the magnitudes, that would exist if either the forward or aft propellers were acting independently from one another. The interaction tones were identified as multiples of the sums and differences of F and R as indicated by the relationship

$$f_c = a(bF \pm cR) \tag{2}$$

where f_c denotes the center frequency of the tone and a, b, and c denote integers. The labels of the interaction tones may not be the only possible interpretations, but they do provide a reasonable explanation of the source of the many peaks in the coherence plots.

After examining all of the data, it was decided that significant coherence could be defined when $\gamma(f) \geq 0.2$. In both Figs. 1 and 2 there are significant coherence peaks at 16 different frequencies that may be attributed to interaction noise. The coherence plots, however, are not identical, with differences in both frequency and amplitude of many of the interaction tones. The direct rotor fields, at frequencies R, F, $2R$, etc., generally produce coherence near 1.0. This fact implies the existence of a linear transfer function with little random noise and no independent sources.[4] This concept is reinforced by noting that discrete tones at these frequencies occur in both the acoustic and flow spectra.

It is worthwhile to note that the rotation frequency, labeled as $F/2$ in Figs. 1 and 2, was due to nonindentical blades of the forward propeller. Because no peaks existed in the SPL at $R/2$, it was concluded that the simple hobby-shop propeller used for the front rotor was not as well balanced as the rear rotor.

Coherence peaks associated with interaction tones and labeled with a caret denote a situation where significant coherence exists, but no noticeable tonal peaks exist in the SPL or velocity spectra. This fact clearly indicates that significant coherence can exist when tonal characteristics are buried in the background noise of the sound pressure and velocity spectra, i.e., nonzero coherence at a given frequency is independent of spectral magnitude and dependent upon the ratio given in Eq. 1.

When comparing Figs. 1 and 2, it was noted that the SPL's are essentially identical but that the $G_v(f)$ in Fig. 2 exhibited more tonal characteristics. Because the $G_v(f)$ in Fig. 2 was measured with a horizontal hot-film sensor and Fig. 1 data was based on a vertical hot-film, it can be stated that circumferential components of velocity exhibit more tonal characteristics than axial velocity components. This comparison also showed that, in general, the circumferential flow was more coherent with the radiated noise than the axial flow.

The most interesting information was obtained by examining the coherence of interaction tones in Fig. 1 and 2. Coherence at frequencies of $F+R$ and $2(F+R)$ was significant in Fig. 2 but absent in Fig. 1. Since the high coherence of the direct rotor fields at F, R, $2F$, and $2R$ suggests a linear transfer function, one may assume that a linear relation applies to the interaction tones as well. Thus, the circumferential flow components are closely related to interaction tones based upon sum frequencies, whereas the axial flow fluctuations are nearly independent of those same tones.

A similar comparison can be made with interaction tones associated with difference frequencies $(F-R)$. Although the level of coherence is less, there are a number of significant coherence peaks based upon $(F-R)$ and its harmonics in Fig. 1, but there are no such significant peaks in Fig. 2. This fact indicates acoustic frequencies at $(F-R)$, and its harmonics are more related to the axial flow fluctuations than circumferential fluctuations.

Interaction tones are directional, and results obtained from acoustic measurements in the forward quadrant do not assure similar coherence with sideline acoustic signals or with measurements obtained in the downstream quadrant. Although these results are from one microphone location and one hot-film sensor location, they suggest it may be possible to use this technique to help identify sources of CRP interaction noise. The method is not limited to interaction tones, since it was also observed that coherence peaks at $F/2$ and $(R+F/2)$ existed in the case of circumferential flow but not in that of axial flow. These observations indicate that there is a relationship between the radiated sound and the directional velocity components of the flowfield measured between the rotors of counterrotating propellers. Clearly, particular interaction tones are more coherent with some velocity components than with others.

Concluding Remarks

It has been shown that coherence analysis performed between the radiated sound of counter-rotating propellers and the fluctuating components of velocity between the rotors can be used to identify the existence of noise-flow relationships in aerodynamic interaction. The association of flow components with interaction noise can be identified through peaks of coherence associated with the sums and differences of the blade-passing frequencies of the forward and aft propellers. It was also found that the magnitude of the tones in the sound or flow velocity spectra were not important in establishing significant coherence.

References

[1]Magliozzi, B., "Advanced Turboprop Noise: A Historical Review," AIAA Paper 84-2261, Oct. 1984.

[2]Bradley, A. J., "A Study of the Rotor/Rotor Interaction Tones from a Contra-rotating Propeller Driven Aircraft," AIAA Paper 86-1894, July 1986.

[3]Hanson, D. B., "Noise of Counter-rotating Propellers," *Journal of Aircraft*, Vol. 22, July 1985, pp. 609–617.

[4]Bendat, J. S. and Piersol, A. G., *Random Data: Analysis and Measurement Procedures*, 2nd ed., Wiley, New York, 1986, pp. 172–176.

On Cone Frustum Pressure Gradient Effects on Transition

Kenneth F. Stetson*
U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio

Nomenclature

p = pressure, kPa (lb/in.^{2})
R = radius, cm (in.)
Re = Reynolds number
Re_{x_T} = transition Reynolds number based on conditions at the edge of the boundary layer and the surface distance from the stagnation point to the location of transition
X,S = surface distance, cm (in.)
T = temperature, K (°R)
X_{SW} = entropy-layer-swallowing distance, cm (in.)
X_T = surface distance from the stagnation point to the onset of transition, cm (in.)

Subscripts

B = base
N = nose
o = reservoir
st = model stagnation point
w = wall
∞ = freestream

Introduction

THERE is a characteristic pattern for the pressure distribution on the frustum of a sphere cone in hypersonic flow. The high-pressure gas generated by the nose-tip bow shock has a limiting expansion that is possible as it proceeds around the nose tip. The expansion continues on the frustum and is often characterized with a blast wave analogy. This region of expanding flow produces a favorable pressure gradient. Continuing down the frustum, the flow overexpands (below the equivalent sharp cone pressure) and requires a recompression (an adverse pressure gradient) to arrive at the "proper" pressure at some downstream location on the frustum. Thus, the frustum of a sphere cone in hypersonic flow has both a favorable and an adverse pressure gradient. The magnitude of these pressure gradients and the extent of the regions (in terms of S/R_N) are primarily functions of freestream Mach number and cone angle. Guidance from both stability theory and experiments suggests that a favorable pressure gradient would delay boundary-layer transition and an adverse pressure gradient would promote early transition (as compared with zero pressure gradient transition). The significance of these pressure gradients on sphere-cone transition was unknown, and this author did not know of any experiments that addressed these effects. Nose-tip bluntness experiments[1-3] provided some surprising results for the favorable pressure gradient region and some interesting possible effects of the adverse pressure gradient. As transition moved closer to the nose tip, the favorable pressure gradient became increasingly stronger, yet the transition Reynolds numbers became smaller; in some cases, they were of the same order as nose tip transition Reynolds numbers. It appeared that some other effect, stronger than the effect of the favorable pressure gradient, had taken over as the dominant parameter. Further investiga-

Received Oct. 20, 1987. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

*Aerospace Engineer, High Speed Aero Performance Branch, Aeromechanics Division, Flight Dynamics Laboratory. Associate Fellow AIAA.