[7] Squire, H. B. and Winter, K. G., "The Secondary Flow in a Cascade of Airfoils in a Nonuniform Stream," *Journal of the Aeronautical Sciences*, Vol. 18, No. 4, 1951, p. 271.

[8] Hawthorne, W. R., "Some Aerodynamic Problems of Aircraft Engines," *Journal of the Aeronautical Sciences*, Vol. 24, No. 10, 1957, pp. 713–731.

[9] Rao, G. V. R., "Use of Leaning Vanes for Fan Noise Reduction," AIAA Paper 72-126, San Diego, Calif., 1972.

[10] Clauser, Francis, "The Turbulent Boundary Layer," *Advances in Applied Mechanics*, Vol. 4, Academic Press, 1956, pp. 1–51.

[11] Kroeger, R. A., Gruschka, H. D., Helvey, T. C. et al., "Low Speed Aerodynamics for Ultra-Quiet Flight," TR AFFDL-TR-71-75, 1972, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio.

[12] Hersh, A. S. and Hayden, R. E., "Aerodynamic Sound Radiation from Lifting Surfaces with and without Leading-Edge Serrations," NASA CR 114370, 1971.

[13] Soderman, P. T., "Effects of Leading-Edge Serrations on a Two-Dimensional Airfoil in the Ames 7- by 10-foot Wind Tunnel," TN, NASA (to be published).

OCTOBER 1972 J. AIRCRAFT VOL. 9, NO. 10

Lifting Fan Noise Studies with Superimposed Cross Flows

G. Krishnappa*
National Research Council of Canada, Ottawa, Ontario, Canada

Experimental studies on noise radiation from a single-stage lifting fan operating at subsonic tip speeds are described. The effects on noise radiation of inlet flow distortion as a result of superimposed cross flow are presented. Under zero cross-flow conditions, narrow band analysis of the results shows the presence of discrete "shaft order tones," in addition to high-level tones at blade-passing frequencies at a subsonic tip speed of 628 fps. Propagating modes of these tones are identified with some reasonable success based on observed directivity patterns, using Tyler and Sofrin's radiation formula. Only the shaft orders at multiples of stator blade numbers giving a plane wave radiation are in evidence at lower fan speeds. Under cross-flow conditions, there is an increase of up to 10 db in the level of broadband noise. The shaft order tones become less conspicuous because of this rise in broadband noise. The radiation patterns of blade-passing tones show strong dependence on the cross flow. An unexpected reduction in peak blade-passing tone levels at some conditions of cross flow suggests the two interaction mechanisms, inflow distortion with rotor and rotor with stator, are interdependent.

Introduction

A LIFTING fan in the form of the fan-in-wing configuration is one of the potential lift-producing systems for the takeoff and landing operations for VTOL aircraft. The fan noise problem in this type of installation is aggravated by three special factors. 1) The fan assembly is housed compactly inside the wing to yield good cruise performance. Consequently, there is a close spacing of the rotor and stator blade rows which increases the rotor-stator interaction noise. 2) Because of the shallow depth, there is a decided limit to the extent of attenuation that may be achieved by way of introduction of acoustic absorption material. 3) During the transition maneuvers from vertical to horizontal flight and vice versa, the forward velocity of the aircraft is superposed on the vertical downward flow into the fan. Previous experiments and theory have indicated substantial radial and circumferential flow variations in velocity during cross flow conditions at the entrance to a fan rotor installed in a shallow inlet. While these variations affect the aerodynamic performance of the fan,[5] they are also likely to alter noise levels and radiating patterns by interacting with the rotor blades in a way similar to rotor-stator interaction.

The generally held concept of fan and compressor noise at subsonic speeds was that its spectrum was composed of discrete tones at blade-passing frequency and its harmonics, superimposed on broadband noise extending over a wide frequency range. This concept was based on the experimental studies done at filter bandwidths higher than 6%. The discrete tones were produced as a result of rotor-stator interaction, and the broadband noise was generated by the turbulence in the entering stream. The recent works of Mather, Savidge and Fisher[1] and a few others have shown that the spectrum at narrow bandwidths reveals that what might have been regarded as broadband noise is comprised of several tones at integral shaft orders. The interaction of rotor blades which are slightly dissimilar as a result of geometrical blade-to-blade variations (spacing, incidence, twist, thickness, etc.) with the stator blades suggests acoustic pressure fields which repeat once per rotor revolution.

The distorted flow entering the inlet may interact with the rotor field in a similar way as the interaction of rotor blades with stators generating propagating modes. These modes radiate energy in a characteristic pattern which may be identified by using Tyler and Sofrin's[2] analysis.

This paper presents some experimental work on the noise characteristics of a model-sized lifting fan, with and without cross flow over the wing. The experimental results at zero cross flow and cross-flow conditions are described in Secs. 4 and 5, with associated theoretical considerations in Sec. 2. The experimental results are discussed by identifying various propagating modes resulting from rotor-stator interactions and inlet flow-rotor interactions.

Theoretical Considerations

Tyler and Sofrin[2] have shown the possibility of propagating pressure fields even at subsonic tip Mach numbers resulting

Presented as Paper 72-128 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted February 7, 1972; revision received June 23, 1972.

Index category: VTOL Propulsion.

* Research Officer, Engine Laboratory, Mechanical Engineering Division.

from rotor-stator interactions. The stator vanes upstream or downstream of the rotating blades may be regarded as disturbances which produce a pressure field which is distinct from the pressure field generated by the rotor alone. The pressure field at harmonic n of the blade-passing frequency containing an m-lobed rotating mode is given by

$$P_{mn} = Va_{mn} \cos(m\theta - nB\Omega t + \phi_{mn}) \quad (1)$$

where $m = nB + kV$ and V is the number of stator blades, a_{mn} is the amplitude factor of the wave, B is the number of the rotor blades, θ is the angular location, $k = \ldots -1,0,+1 \ldots$, Ω is the angular velocity of the rotor, t is the time, and ϕ_{mn} is the phase factor.

The pressure field resulting from the interaction process at a particular harmonic n of the blade-passing frequency is a superposition of an infinite number of rotating patterns. Each m-lobed pattern rotates at $nB\Omega/m$ rad/sec, generating n times blade-passing frequency. Only the specific m-lobe spinning pattern given by the relation $m = nB + kV$ where $k = \ldots -1,0,+1 \ldots$ is produced. Each mode propagates when its speed of rotation is greater than a critical angular speed given by the relation

$$nB\Omega/m > \Omega_c.$$

The interaction of slightly dissimilar rotors resulting from blade-to-blade geometrical variations (spacing, incidence, twist, thickness, etc) will produce tones at shaft harmonic orders, and the expression in Eq. (1) becomes[1]

$$P_{mn} = Va_{mn} \cos(m\theta - n\Omega t + \phi_{mn}) \quad (2)$$

where

$$m = n + kV \quad (3)$$

and the rotational speeds of the modes are given by $n\Omega/m$.

Maldistribution of intake velocities produces flow disturbances which repeat in the rotating frame of reference once every revolution. This effect is similar to the presence of a single stator, since a single stator produces flow disturbances in an otherwise uniform flow which repeat in the rotating frame of reference once every revolution. Thus the condition (3) indicates that a given shaft order contains modes from $-\infty$ to $+\infty$ and each tone contains an $m = 0$ mode, which is a plane wave. This plane wave propagates at all rotor speeds, giving peak radiation on the fan axis. On the other hand, the rotor-stator interaction gives an $m = 0$ mode only at shaft orders which are multiples of the number of stator blades. The ranges of propagating harmonics for subsonic tip-speed fans are established in Ref. 1, and are given by the equation

$$1 - (\Omega/\Omega_c) \leq (|k| V/n) \leq 1 + (\Omega/\Omega_c) \quad (4)$$

where Ω_c is the critical angular velocity.

Experimental Arrangement and Details

Figure 1 shows the experimental arrangement. The acoustic tests were carried out outside the NRC 10 ft × 20 ft propulsion wind tunnel. The efflux from the wind tunnel provided the cross flow over the fan. The fan-in-wing model was placed 25 ft above the ground level, supported by two platforms, and 10 ft downstream of the tunnel exit. The fan was driven by a turbine located at one end of the 10-ft wing. The air supply to the turbine was provided by a remote compressor plant.

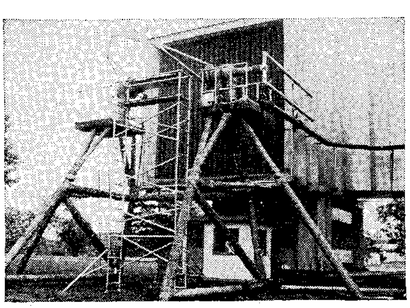

Fig. 1a Experimental set up. The view shows the tunnel exit and the fan-in-wing set up.

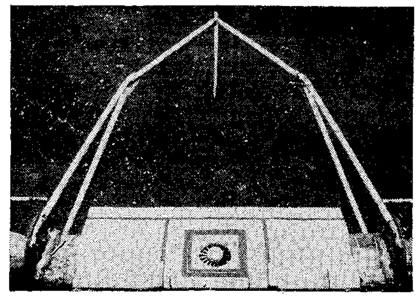

Fig. 1b Experimental set up. A top view showing the inlet side of the fan.

The fan was 12 in. in diam with a hub tip ratio of 0.5. It consisted of 18 rotor blades and 11 stator blades, with no inlet guide vanes. The rotor blades were of C7 profile with a chord length of 1.5 in., and the stator blades were of double-circular arc section with a chord length of 1.65 in. The rotor and stator blades had a very short spacing of 0.25 in. between them. The fan had a trumpet inlet with a duct length of 2.5 in. The main aerodynamic specifications of the fan are described in Ref. 3.

A far-field noise survey was made by a rotating microphone boom anchored at the wing, with ½-in. microphones at 6 ft and 10 ft from the center of the fan. The signal from the microphone was passed through a B and K analyser and tape recorded in FM mode. A "B" filter network was used on the analyser during the recordings to attenuate the frequencies below 1000 Hz in an attempt to increase the signal-to-noise ratio.

A one-minute sample of the signal was recorded for fan speeds of 6000, 9000, and 12,000 rpm under the conditions of 0, 45, 65, 105 and 150 fps cross-flow velocities. The angular intervals of the microphone boom settings were varied in 5° increments at the inlet and exhaust side of the fan on the downstream side of the wing. The recordings were analysed by using constant percentage and narrow bandwidth analysers.

Spectra at Zero Cross-Flow Condition

Figure 2 shows 50-Hz bandwidth spectrograms at zero cross-flow conditions at angles of 0°, 5°, 40°, and 90° to the fan axis at the inlet side of the fan for 12,000 rpm (corresponding to a tip speed of 628 fps). These spectra show a high level of tones at blade-passing frequencies, surrounded by tones at shaft harmonic orders. Comparisons indicate that these tones are directional. Several shaft orders which emerged at angles close to the axis had disappeared completely in the plane of the fan. Some of the shaft orders around the blade-passing frequency were more prominent than others.

The presence of these shaft orders at subsonic tip speeds has been reported in the work of Mather, Savidge and Fisher[1] and Goldstein, Glaser and Coats.[4] An explanation for these tones can be found if one accepts that the signatures from the rotor blades are not all identical. This is mainly attributed to the initial discrepancies in the rotor blade signatures caused by the blade-to-blade geometrical variations such as spacing, incidence, camber, twist, thickness, etc; such variations from blade-to-blade signatures at the rotor face are reported in

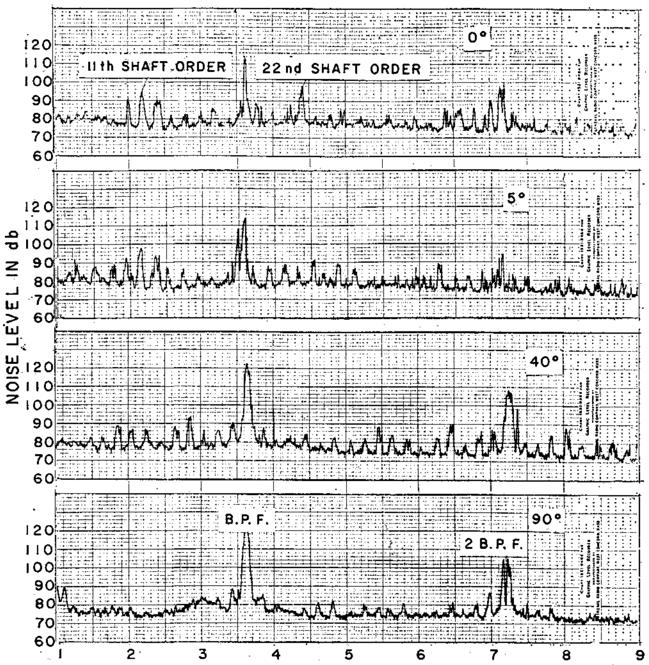

Fig. 2 Spectra at 12,000 fan rpm, zero cross flow.

Ref. 4. Following the theory of Tyler and Sofrin,[2] the pressure field can propagate at subsonic tip speeds only if it is produced by the interaction process as discussed in Ref. 2.

High attenuation of shaft order tones produced by the rotor alone operating at subsonic tip speeds has been indicated in Ref. 4. The research lift fan had a short spacing between the rotor and stator blades, and therefore the interaction between them produced a strong pressure field. Propagating shaft order tones are likely to occur as relatively lower-order lobes rotate at supersonic speeds.

The present tests were carried out in the outside environment with the wind speed varying up to 10 mph under zero cross-flow conditions. The relatively short inlet region cannot adequately guide the entering flow and, as a result maldistribution in the inlet velocities is present even at this zero cross-flow condition.

Figure 3 illustrates the associated contours of inlet velocity magnitude and inlet swirl angle distributions at a cross-flow velocity of 15 fps. This illustration is taken from Ref. 5 and is representative of some conditions at zero cross-flow velocity. Because of a change in the distribution of inlet swirl angle, all the rotor blades will not be operating under identical conditions. This point is discussed later.

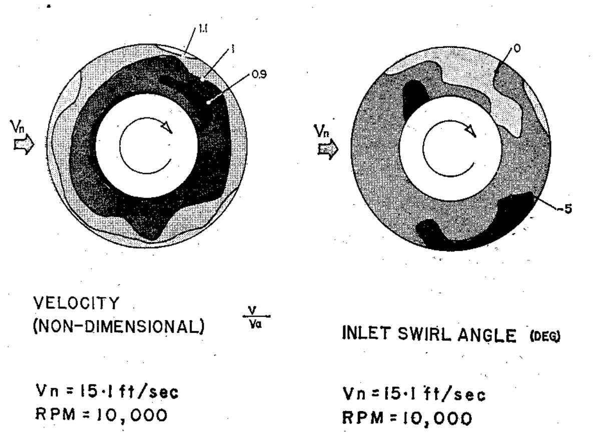

Fig. 3 Inlet velocity distribution at 15 fps cross-flow velocity.

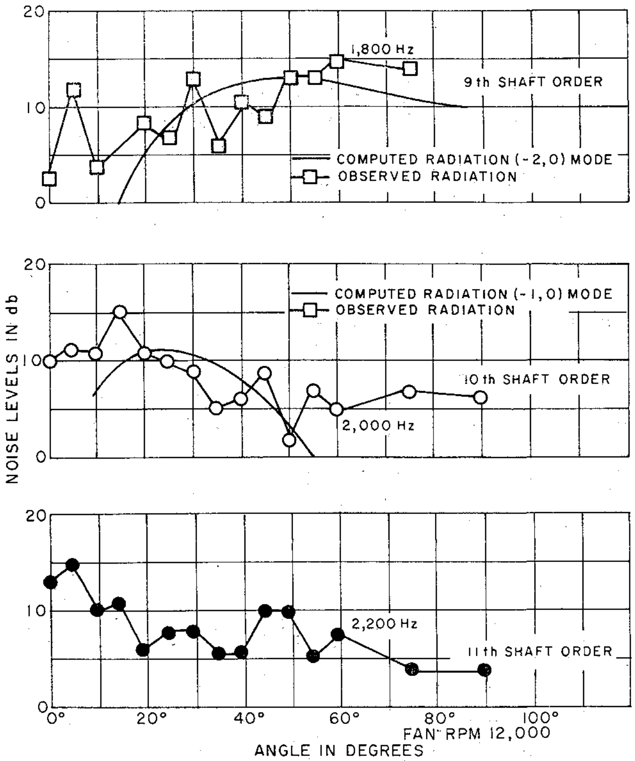

Fig. 4 Radiation pattern of the shaft orders.

These inlet flow variations at low wind speeds appear not to cause serious changes in the aerodynamic performance of the fan. However, their effect in producing acoustic pressure fields of significant levels by interacting with the rotor is less certain.

Figure 2 shows that the shaft orders $n = 11$ and $n = 22$ are particularly strong near the axis of the fan (0°). Consideration of the theory in Sec. 2 gives the modes produced because of interaction process at a given shaft harmonic. Rotor-stator interaction modes are given by the formula

$$m = n + kV$$

With the number of stator blades $V = 11$, the shaft orders $n = 11$ and $n = 22$ have an $m = 0$ mode with $k = -1$ and -2, respectively. This is a plane wave which propagates at all rotor speeds, giving a peak on the axis of the fan. The presence of these $m = 0$ modes may be further confirmed by the total absence of these tones in the plane of the fan (90°). The radiation from the $m = 0$ mode for a fan stage with the stator blade at $\frac{1}{2}$ chord distance has been shown in Ref. 1.

Since these shaft order tones are directional, observed directional patterns of some of these tones are shown in Fig. 4. Directivity of propagating modes of the tones is computed using Tyler and Sofrin's expression (2) for a cylindrical duct. Using these results, an attempt is made to identify the dominant circumferential modes and the radial order of each circumferential mode.

The lower-order tones shown in Fig. 4, shaft orders 9 and 10, have propagating modes $m = -2$ and $m = -1$, respectively, because of the interaction of the rotor with the stator. The speed of rotation of the modes is given by $n\Omega/m$. Therefore, the 10th order tone rotates faster than the 9th, and hence has a peak closer to the axis than the 9th. This is indicated by the observed results in Fig. 4. Theoretical calculations for the modes $m = -2$ and -1 show approximately the experimental trends at radial order $\mu = 0$ for the 9th and 10th shaft order tones, respectively. The highly lobular radiation patterns suggested by the calculations are not evident in the experimental results. Mani[6] has pointed out that these lobular

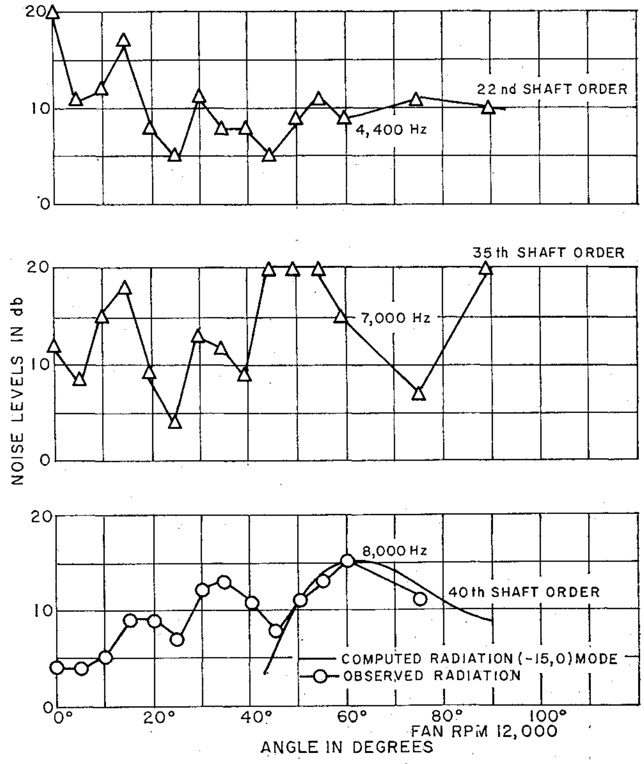

Fig. 5 Radiation patterns of the shaft orders.

patterns diffuse because of the scattering by inhomogeneities of the propagating medium.

The harmonics at the 11th and 22nd shaft orders, shown in Figs. 4 and 5, are the results of plane wave radiations as discussed in the earlier paragraphs, showing a peak on the axis, with decreasing tone levels at angles away from the axis.

The tones at higher harmonics have 3–4 propagating modes because of blade interactions. It is rather difficult to identify any particular mode as being dominant. The observed pattern of the 35th order appears to be a combination of (−2,0),† (−9,3), and (−9,1) modes. However, the shape of the 40th order can be described by (−15,0) mode at angles greater than 40°.

However, either these modes or modes at other radial orders do not seem to explain the finite tone levels at, or around, the fan axis—say, 0°–10°. This discrepancy can be explained if one accepts that a maldistribution in the inlet flow, however small, can produce an acoustic field resulting from the interaction between the inlet flow and the rotor. Calculations from the theory in Sec. 2 show that there are many more propagating modes including an $m = 0$ mode caused by this interaction. Radiation from either the $m = 0$ mode or a lower-order mode will explain the observed tone levels at angles closer to the fan axis.

The directivity of the tones at the blade-passing frequency and its second harmonic are shown in Fig. 6. The tone at the blade-passing frequency has two propagating circumferential modes: −4 and 7. The observed directivity may be identified with the mode (7,3) which has many lobes with increasing maximum levels with angle. The tone at the second harmonic of the blade-passing frequency has many more propagating modes, and the radiation pattern seems to be a combination of several of these modes.

Figures 7 and 8 show the spectra recorded at lower fan speeds of 6000 and 9000 rpm, respectively. At these speeds, again, the tones at blade-passing frequencies are prominent.

† Numbers in parentheses indicate circumferential and radial orders of the modes.

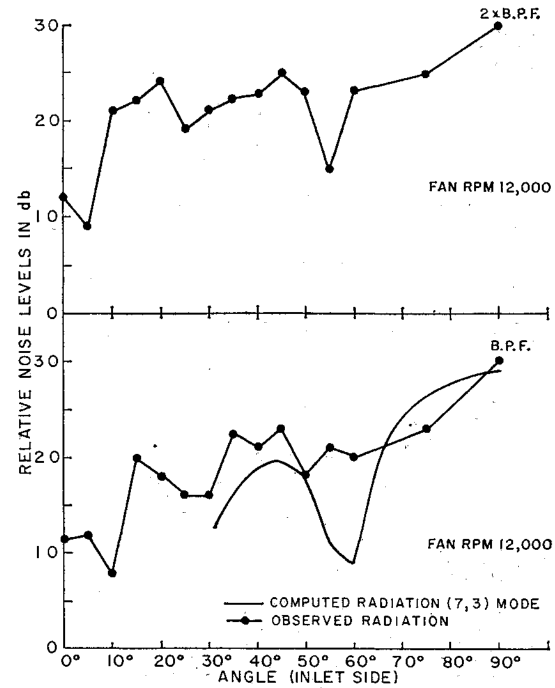

Fig. 6 Radiation patterns of B.P.F.

Although the calculations at 6000 rpm indicate the presence of propagating modes at harmonic orders $n > 8$, there is less evidence of these tones in the experimental results. A possible explanation could be that the fan operates at lower efficiencies at speeds away from the design point, and it may be that the broadband noise produced swamps the tones. These tones show up in low levels at 9000 rpm. The shaft orders present at $n = 22$, and $n = 33$ on the axis at both the speeds indicate plane wave radiation caused by rotor-stator interactions.

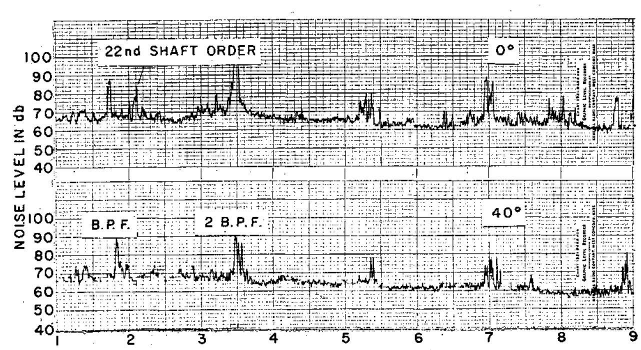

Fig. 7 Spectra at 6000 rpm, zero cross flow.

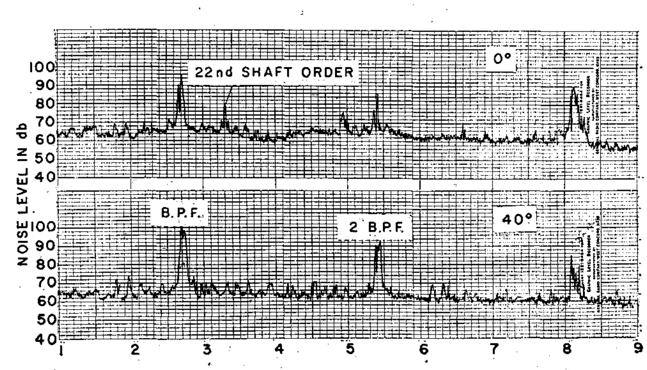

Fig. 8 Spectra at 9000 rpm, zero cross flow.

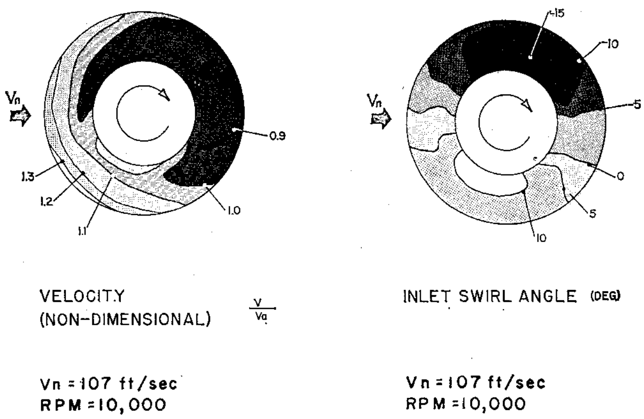

Fig. 9 Inlet velocity distribution at 107 fps cross-flow velocity.

Spectra at Cross-Flow Conditions

The fan under cross-flow conditions operates under substantial variations of swirl and axial components of velocity in the inlet flow. Figure 9 taken from Ref. 5 illustrates the associated contours of velocity magnitude and inlet swirl angle distributions for the fan operating at 10,000 rpm under a cross-flow condition of 107 fps. This shows a large increase of velocity over the forward portion of the intake, and a decrease over the aft portion. The positive and negative (anticlockwise and clockwise) swirl angle distributions cause advancing and retreating blade motions with respect to the oncoming air. This results in circumferential variations in angle-of-attack producing higher axial velocities and pressure rise on the advancing side, and lower axial velocities and pressure rise on the retreating side. This provides a forcing mechanism for noise generation resulting from the maldistribution of the inlet flow velocities.

Figure 10 shows the spectra for the conditions of cross flow 0, 45, 70, 110 and 150 fps at 30° to the inlet axis for the fan operating at 12,000 rpm. There appears to be a gradual increase in the level of the broadband noise with the application of cross flow. This increase is of the order of 8–10 db from 0 fps to 150 fps. Consequently, the multiple tones at shaft order harmonics are less conspicuous, and at the conditions of highest cross flow, these tones are almost swamped by the broadband noise.

It is particularly interesting to observe that there is no systematic variation of tone levels at cross-flow conditions. For

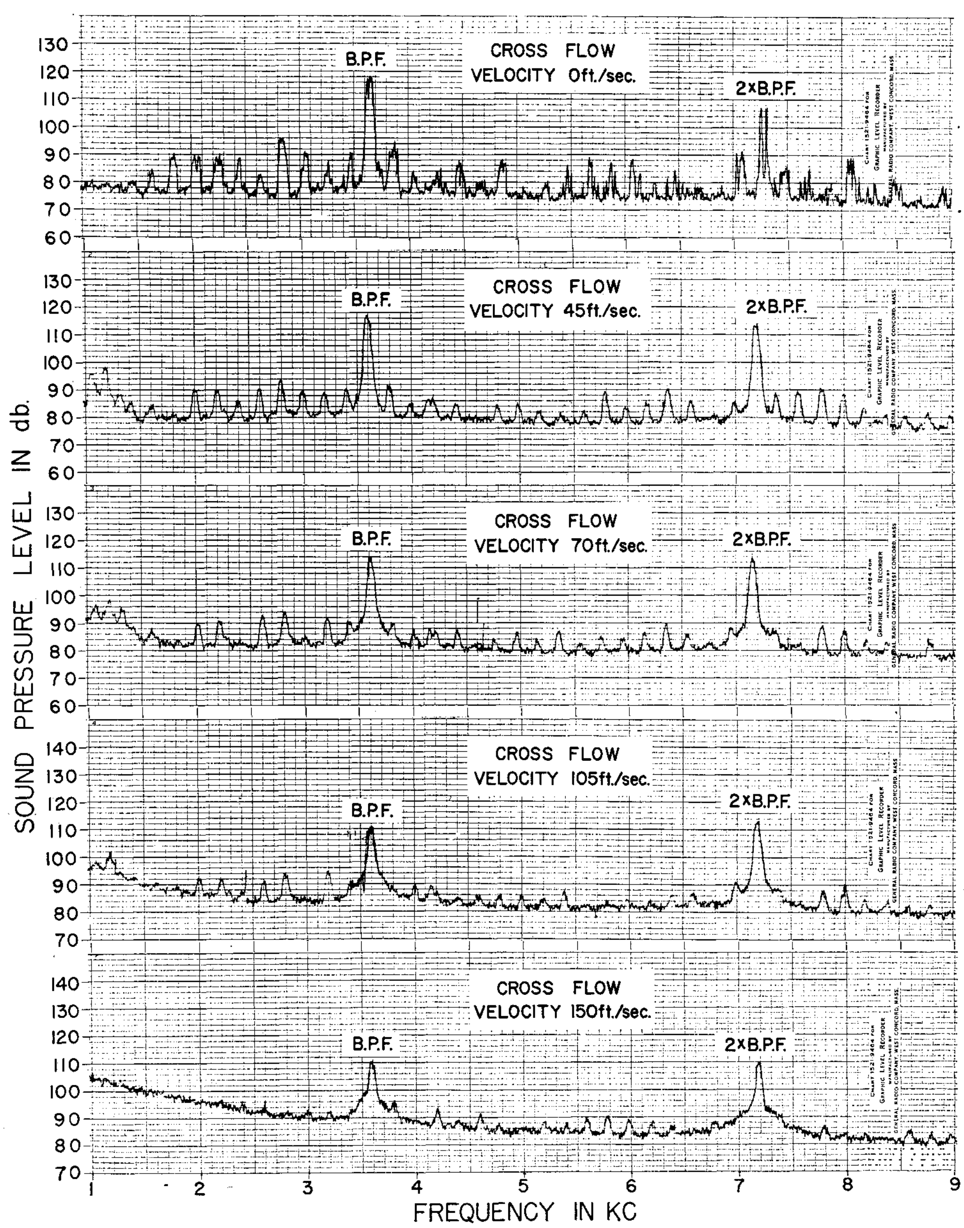

Fig. 10 Spectra at various cross-flow conditions, 12,000 rpm, inlet angle 30°.

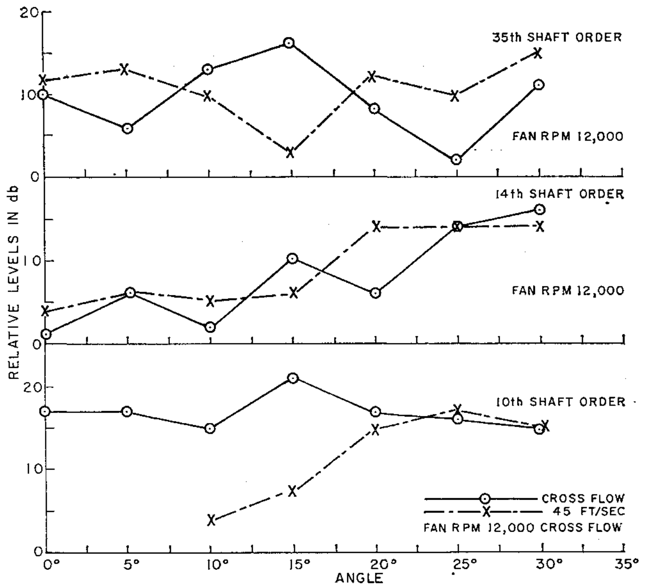

Fig. 11 Effect of 45 fps cross flow on noise radiation pattern.

example, the blade-passing tone shows a decrease of 8 db from 0 fps to 150 fps velocity, whereas at the second harmonic, there is an increase of 6 db from 0–110 fps. Figure 10 shows the emergence of some lower-order tones around 1000 Hz at lower cross flows. This may be caused by the effect of inlet flow-rotor interactions, as the theory in Sec. 2 indicates propagating modes even at lower-order tones.

The behavior of shaft order tones due to maldistribution in the inlet flow is illustrated in Fig. 11. The directivity shown in the figure represents a limited analysis of the recordings near the fan inlet axis for the conditions of 0- and 45-fps cross-flow velocity. The level of the 10th shaft order has decreased substantially near the axis at cross-flow condition, whereas the 14th order tone does not show a marked variation. A different pattern altogether is indicated by the tone at the 35th order. Certain results are rather intriguing as, contrary to expectations, we observe reduced tone levels at some locations with the cross-flow.

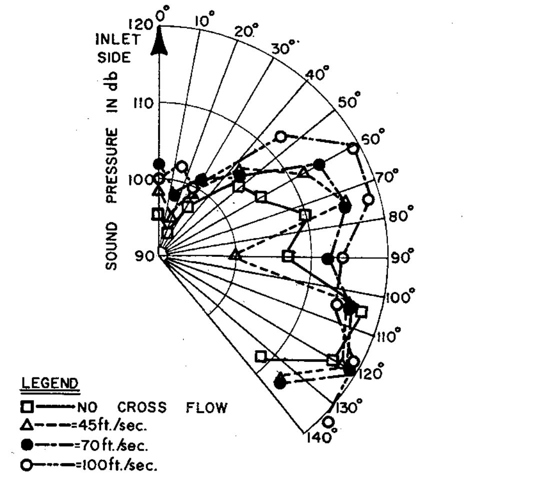

Fig. 13 Radiation pattern of the fundamental tone at blade-passing frequency. rpm 9000.

The changes in the radiation pattern with cross-flow velocity of tones at blade-passing frequency are shown in Figs. 12, 13, and 14 for 6000, 9000, and 12,000 fan rpm, respectively. They represent the results on a 6% bandwidth analyser of some earlier runs using 15° angular intervals. The angular intervals are rather too wide to elucidate in detail the effects of flow distortion. The task of identifying the modes would be considerably easier and more accurate with small angular intervals. However, these results are intended to demonstrate only some gross effects on the noise field.

The results indicate that the far-field radiating patterns of the tones are altered with the introduction of cross flow over the fan, and the differences appear to depend strongly on the speed of the fan and the inflow distortion. Figure 12 shows, at 6000 rpm, a general increase in tone levels at most of the angular positions at cross-flow conditions, the change being approximately proportional to the cross-flow velocity. At 120°, the tone level has risen approximately 22 db from the condition of zero cross flow to 100 fps. The position of the peak tone level shifted to the efflux side from the inlet side when the cross flow was introduced. The above evidence

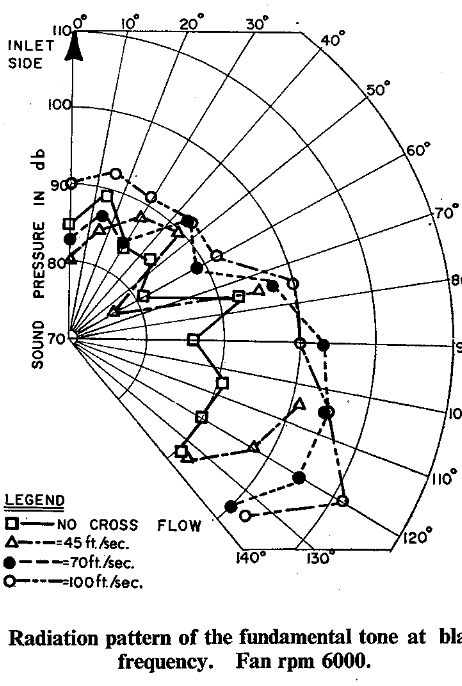

Fig. 12 Radiation pattern of the fundamental tone at blade-passing frequency. Fan rpm 6000.

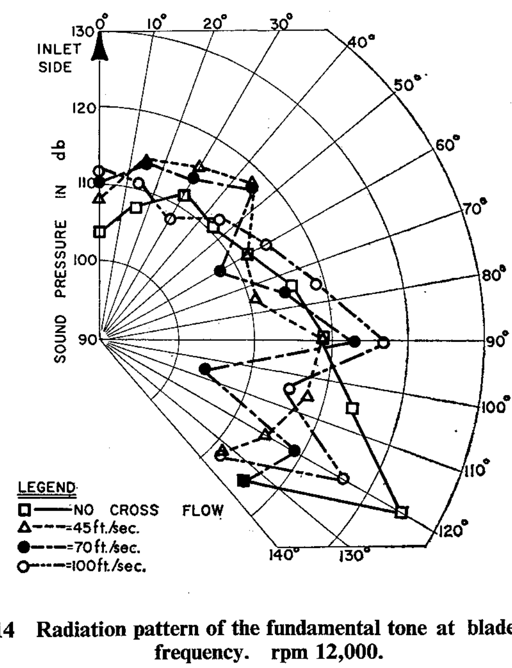

Fig. 14 Radiation pattern of the fundamental tone at blade-passing frequency. rpm 12,000.

seems to suggest that the new propagating modes generated at low fan speeds may perhaps dominate over the rotor-stator interaction modes generated at zero cross-flow conditions.

Figure 13 indicates at 9000 rpm that the cross-flow effects are well confined to the region 45°–90°, showing an increase in tone levels with the cross-flow velocity. Unlike the trend at 6000 rpm, there seems to be no apparent change at the efflux side of the fan. Significant changes in the tone levels occur in the plane of the fan (90°). The level of the tone decreased from the condition of zero cross flow when 45 fps velocity was introduced, showing again an increase well above the level at zero cross-flow condition with the application of higher cross flows. Normally, one would have expected an increase in tone levels with the introduction of distortion to the inlet flow resulting from the additional propagating modes generated by the interaction of the maldistribution in the inlet flow with the rotor.

The changes occurring at 12,000 rpm are shown in Fig. 14. The radiation patterns seem to differ markedly at each cross-flow condition. While the variations are within 10 db at the inlet side for the four operating conditions, particularly significant changes are in evidence at the efflux side of the fan. The high peak tone level occurring at 120° is reduced by 20 db when a cross flow of 45 fps velocity is passed over the fan. A similar reduction in tone level at 105° is produced by 105 fps velocity. Contrary to expectations, a general rise in tone levels under cross-flow conditions is not evident at this fan speed; instead, we observe reduced tone levels at many locations.

The foregoing analysis reveals that the inflow distortions notably alter the noise field generated by rotor-stator interaction modes under zero cross-flow conditions. Notwithstanding the coarseness of the data points, one may attempt with reasonable success to identify the propagating modes generated by rotor-stator interaction under zero cross-flow conditions, as the theory outlined in Sec. 2 indicates comparatively few modes that propagate. There are many more propagating modes resulting from the interaction of the inflow distortions with the rotor. Consequently, in the absence of information on the amplitude of the propagating pressure wave, the identification of the dominating modes becomes difficult. Fourier analysis of the velocity field, axial and swirl components indicates that only the first few coefficients are important. By using this result, it may be possible to isolate a few radiating modes in future analysis.

The increased peak tone levels at cross-flow velocities at 6000 and 9000 rpm may lead to the conclusion that the inflow distortions produce stronger fields with the rotor, the tone level depending upon the magnitude of the distortions. Aerodynamically, the fan operated with the inflow distortion as if there existed a set of loss-free inlet guide vanes providing different degrees of preswirl.[5] The application of cross flows at 12,000 rpm has reduced a strong peak generated by rotor-stator interaction indicating a noticeable change in the far-field radiation pattern. This complex situation may perhaps suggest that the two interactions are not independent of each other, and probably the distortions are carried further ahead of the rotor, altering the pressure field patterns generated under zero cross-flow conditions. However, the aerodynamic measurements reported in Ref. 5 show that despite severe maldistribution in the inlet of the fan, substantial redistribution took place within the fan stage and almost completely attenuated the inlet distortion. The fan also seems to have imparted an almost uniform swirl to the efflux.

In view of the complexities of the nature of the phenomenon involved, further work is in progress to elucidate in a general way the flow distortion effects on noise radiation, in the light of the measured inlet aerodynamics and fan performance results.

Conclusions

1) Narrow band analysis of spectra from a research lift fan operating at a subsonic tip speed of 628 fps indicates the presence of shaft order tones, in addition to high-level tones at blade-passing frequencies. 2) These shaft order tones are shown by Tyler and Sofrin analysis to propagate, and by examining the radiation pattern, propagating modes were identified with some success. 3) At lower rotational speeds, only the shaft orders at multiples of stator blade numbers giving plane wave radiation are in evidence. 4) The broadband noise level increases with the velocity of cross flow over the fan. At a cross-flow velocity of 150 fps and the fan operating at 12,000 rpm, there is an increase of up to 10 db from the zero cross-flow condition. 5) At higher cross-flow velocities, the shaft order tones are submerged as a result of the rise in broadband noise levels. 6) Experimental results with the fan operating under cross-flow conditions show that the tones generated depend on the inflow distortion. The radiation pattern of the tones varies at each cross-flow condition. The substantial reduction in blade-passing tone levels after introducing cross flow suggests that the two interacting mechanisms—the inflow distortion with rotor and the rotor with the stator—are interdependent.

References

[1] Mather, J. S. B., Savidge, J., and Fisher, M. J., "New Observation on Tone Generation in Fans," *Journal of Sound and Vibration*, Vol. 16, No. 3, June 1971, pp. 407–418.

[2] Tyler, J. M. and Sofrin, T. G., "Axial Flow Compressor Noise Studies," *Transactions of the SAE*, Vol. 70, 1962, pp. 309–332.

[3] Schaub, U. W. and Bassett, R. W., "Analysis of the Performance of Highly Loaded 12-Inch VTOL Z Axis Fan-in-Wing Model at Zero Forward Speed," DME Aero Rept. LR-439, Sept. 1965, National Research Council, Ottawa, Ontario, Canada.

[4] Goldstein, A. W., Glaser, F. W., and Coats, J. W., "Acoustic Properties of a Supersonic Fan," AIAA Paper 71-72, New York, 1971.

[5] Schaub, U. W. and Bassett, R. W., "Flow Distortion and Performance Measurements on a 12″ Fan-in-Wing Model for a Range of Forward Speeds and Angle of Attack Settings," 38th Meeting of the AGARD Propulsion and Energetics Panel, Sept. 1971.

[6] Mani, R., "Diffusion of Random Patterns due to Scattering by Random Inhomogeneities," *Journal of Sound and Vibration*, Vol. 17, No. 1, 1971, pp. 95–104.