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National Aeronautics
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Summary

The forward noise and overall aerodynamic performance are presented for a high-tip-speed, low-loading fan (identified as QF-13) having rotor blade airfoils designed to alter the conventional tip leading-edge bow shocks to weak, oblique shocks which are swallowed within the interblade channels. It was anticipated that these swallowed shocks, which have no wave propagating upstream, would greatly reduce the generation of multiple-pure-tone noise, which is a consequence of the upstream waves of the conventional bow shock. In the high-speed range, where tests of a larger model of a rotor having the same aerodynamic design had conclusively demonstrated swallowing of the shock, the measured multiple-pure-tone sound power reduction was only about 3 decibels, much less than had been anticipated. Among the several speculative possibilities advanced to explain this are the unknown shock structures on the part-span dampers and on the leading edge at radii well inboard of the tip.

The acoustic performance of this fan was compared with that of five modern fans designed with various low-noise features. On a constant-thrust basis, the present fan produced about the same multiple-pure-tone noise as did three of these fans at takeoff relative Mach numbers. However, it produced noticeably more such noise than the two other fans did, one of which had swept edges to reduce the normal Mach number while the other incorporated swallowed shocks similar to the present fan. In the high-speed range, the present fan produced less total noise than the reference shock-swallowing fan and one other fan and about the same total noise as the other three fans. At low speed, the present fan produced the least total noise of the six fans.

Tests with a honeycomb-screen inlet flow control device indicated that the multiple-pure-tone noise was reduced by about 5 decibels during part-speed operation where the rotor tip inlet relative Mach number was slightly supersonic and the tip rotative Mach number was sonic or less.

Introduction

Modern turbofan engines for aircraft use have successfully lowered the once dominant jet exhaust noise by employing high fan bypass ratios to lower the effective jet velocity. This has exposed the fan noise as a major source of the loudest and most objectionable components of the remaining engine overall noise. Consequently, much effort has been expended to study the processes by which this noise is generated and propagated and to devise and evaluate methods to reduce such generation and radiation.

The high-tip-speed fan, which has several quite important performance and engine-systems advantages over the low-tip-speed fan, has an acoustic disadvantage in that it produces an additional and powerful component of noise. This noise, multiple pure tones (or buzz-saw noise), arises usually as a consequence of the spatially nonuniform pattern of rotor-inlet shocks at supersonic relative inlet velocities. Because the conventional takeoff and landing (CTOL) commercial airplane engine cycle requires a relatively high fan pressure ratio, the high-tip-speed fan has been the subject of much research into ways to reduce its noise as heard by ground-based observers.

As part of the noise reduction program at the NASA Lewis Research Center, several high-speed fan design concepts which have the potential to noticeably reduce the generation or radiation of multiple-pure-tone noise (e.g., ref. 1) are being studied. One of these concepts is the use of rotor blading which has been designed aerodynamically to contain or swallow the leading-edge shocks within the interblade channels. This should prevent the shocks from propagating forward and coalescing into a pattern which produces the multiple-pure-tone noise. This concept is the subject of the present report.

Some previous experimental efforts to this end have been made with another fan of about the same tip speed but using somewhat more conventional blading (ref. 2). The final modification of this rotor did indeed have exceptionally low production of multiple pure tones (ref. 1), but they were accompanied by considerably increased blade-passing-tone noise.

The blading used in the present fan was designed originally under contract to Lewis Research Center by the AiResearch Manufacturing Company with comparatively low loading at high tip speed (ref. 3). Because the usual strong rotor leading-edge normal shocks will, even without air turning through the rotor, produce an appreciable pressure rise, this fan rotor required very careful design of the airfoil contours to contain and weaken the shocks in the interblade channels. The contractor built a 730-millimeter- (28.74-in.-) diameter model of this fan and tested it for aerodynamic performance; no acoustic evaluation was made. Its aerodynamic performance was very good, actually exceeding its design in some important respects (ref. 4). Holographic studies of the rotor shock system verified the swallowing of the shocks by the rotor at all speeds above about 94 percent of design (ref. 5). The AiResearch Manufacturing Company proposed, and was contracted to design and fabricate, a slightly modified model of the shock-containing fan for acoustic testing at the NASA Lewis Research Center.

The fan resulting from the cooperative design effort between the contractor and Lewis (designated QF-13) was constructed with a nominal tip diameter of 508 millimeters (20 in.). It was sized and configured for testing in both the acoustic and aerodynamic test facilities at Lewis. The present report details results of the experimental investigation into the forward noise signature of the shock-swallowing fan and compares its noise with that of other modern high-speed fans having various design criteria. Some information is also presented on the fan's overall aerodynamic performance. During testing the fan was operated over the speed range from 50 to 100 percent of design corrected speed, and on operating lines from choke to stall over most of this speed range. Tests were made using an inlet having simulated flight-type internal contours and a thicker lip required for static testing. Additional tests were made using a turbulence-reducing honeycomb-screen inflow control device (ref. 6) over the flight inlet in an attempt to reduce the excess blade-passage tone noise associated with inflow disturbances interacting with the rotor.

Fan Design

The fan (designated QF-13) designed and fabricated for this acoustic test program has a rotor which is a scale model of the one designed, built, and successfully tested aerodynamically in larger size by the contractor, AiResearch Manufacturing Company. The present rotor is 508 millimeters (20.0 in.) in diameter, while the original one was 730 millimeters (28.74 in.) in diameter. The scaling was performed to produce a fan which would dimensionally fit the Lewis acoustic and aerodynamic test facilities. Because of the exceptionally thin forward portion of the rotor airfoil sections and the very small radius on the leading edges, it was not feasible to exactly scale the nominal thickness and the thickness tolerance band. Instead, the nominal thickness of the larger fan blade was made the minimum thickness for the smaller blade; thus, a very slightly thicker nominal blade is provided for the rotor presently under consideration. This was not expected to measurably affect the aerodynamic performance of the scaled fan.

The rotor blade airfoil sections in the tip region where incoming relative velocities are supersonic were designed to eliminate the usual strong bow shock systems by substituting weak oblique shocks. The weak leading- and trailing-edge shocks are identified in figure 1 (from ref. 3), which shows airfoil sections of the rotor blades at the tip radius on a conical stream surface. This figure also depicts the very thin leading edges and the calculated airfoil boundary layer thicknesses. The strengths and positions of the shocks in the interblade channels were carefully controlled at the design point by shaping the blades and channels to restrict the static pressure rise across the shocks to values less than the separation criterion for turbulent boundary layers. Details of this design process may be found for the original, larger fan in reference 3, with a brief summary relative to the present, scaled fan in reference 7. Holographic tests of the full-sized rotor (ref. 5) confirmed the establish-

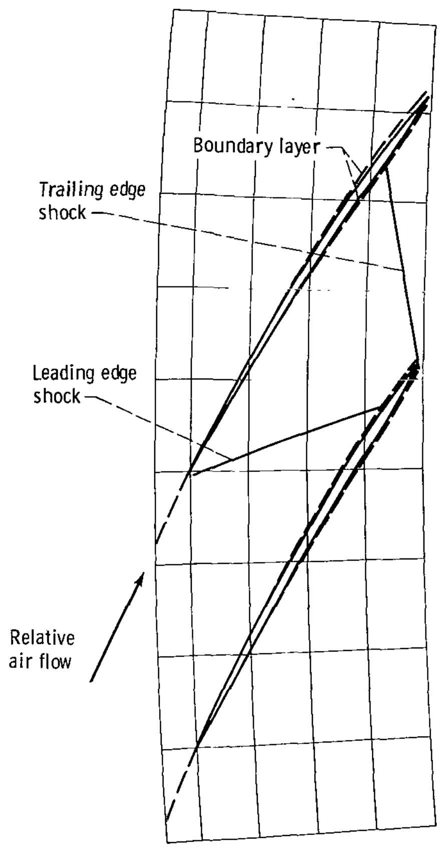

Figure 1. - Rotor blade tip section on conical surface showing leading and trailing edge shock waves and boundary layer thicknesses. (From ref. 3.)

ment of the desired shock systems at and near design aerodynamic conditions.

It was expected that, at design condition, no tip waves would extend upstream from the QF-13 rotor, while a conventional rotor at the same velocity levels would project forward a field of strong shock waves. Because the strength of the forward-propagating shock system determines the levels of multiple pure tones generated in the duct and radiated to the far field, the designers expected the QF-13 fan would produce considerably less multiple pure tone noise.

While the tests of the original fan stage indicated that rotor inflow design conditions had been met, the measured rotor outflow conditions deviated slightly from design values with the result that the stator was operating off its best aerodynamic conditions. Even though this defect was relatively small, the designers elected to provide a new stator for the scaled fan which would accept as inflow conditions the actual measured rotor outflow conditions from the tests of the original fan. In addition, minor changes were made to lower the stator diffusion factors and thus losses. These changes were expected to yield an increase in stage efficiency of 1 to 2 percentage points over that of the original fan.

The major items in the aerodynamic design of this fan of interest to the present acoustic investigation are summarized in table I. Photographs of the rotor and stator assemblies viewed from the front are shown in figures 2 and 3, respectively.

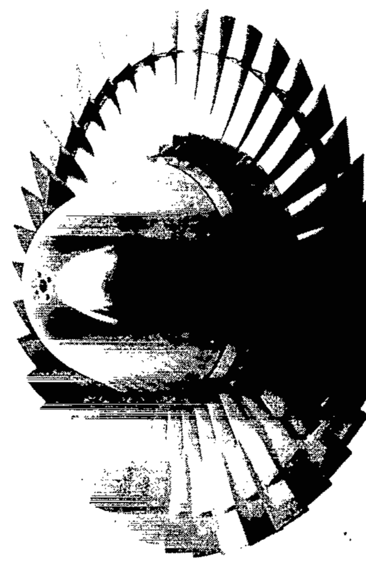

Figure 2. - QF-13 rotor viewed from upstream.

TABLE I. – QF-13 FAN DESIGN CHARACTERISTICS

Total pressure ratio	1.500
Rotor-tip diameter, m (in.)	0.508 (20.0)
Tip speed, m/sec (ft/sec)	487.7 (1600)
Hub-tip radius ratio	0.46
Stage adiabatic efficiency	0.88
Total flow, kg/sec (lb/sec)	32.5 (71.7)
Inlet specific flow, kg/sec/m^2 (lb/sec/ft^2)	205.1 (42.0)
Number of rotor blades	40
Number of stator vanes	45
Rotor-tip inlet relative Mach number	1.647
Shaft speed, rpm	18 366
Rotor blade passage frequency, Hz	12 244

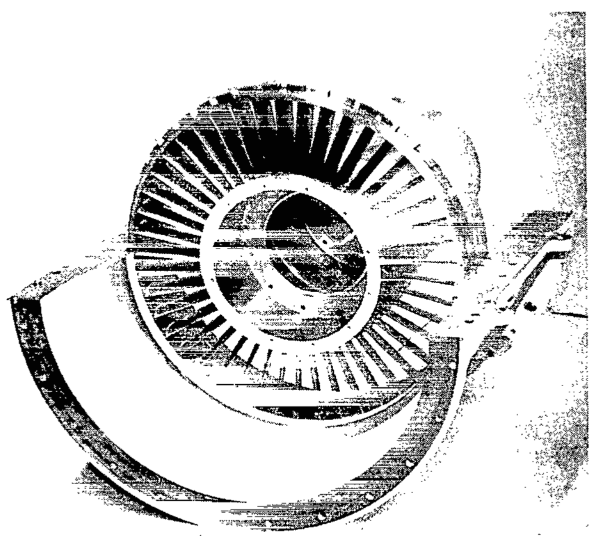

Figure 3. - QF-13 stator assembly viewed from upstream.

Apparatus and Procedure

Test Facility

The fan shown in figures 2 and 3 was installed for acoustic testing in the Lewis engine fan and jet noise facility that has been described in detail in reference 8. Figure 4 shows a fan with the modified flight-type inlet installed in the facility and also some of the microphones used for far-field noise measurements. Plan and elevation views of the facility are shown in


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Figure 4. - Fan in acoustic test facility.

figure 5. Calibration of the chamber indicated that it can be considered anechoic within 1 decibel at frequencies above 500 hertz (ref. 8). The chamber may be operated with inlet flow either through the silencer (shown in fig. 5) or through aspirating floor, ceiling, and walls. All noise data presented herein were obtained with inlet air flowing through the silencer. The fan is driven by a variable-speed electric motor and speed-increasing gearbox located in an acoustically isolated room. The fan discharges into a collector in the motor-drive room from which the air exhausts through two mufflers and flow-control valves to the atmosphere outside the building. The test facility has an array of fixed far-field microphones on a 7.6-meter- (25-ft-) radius centered at the fan inlet face. These are positioned at 10° spacings from 0° to 90° from the fan inlet axis. There is also a microphone mounted on the end of a 6.1-meter- (20-ft-) boom, which can be continuously traversed between the fan inlet axis and 90° from the axis.

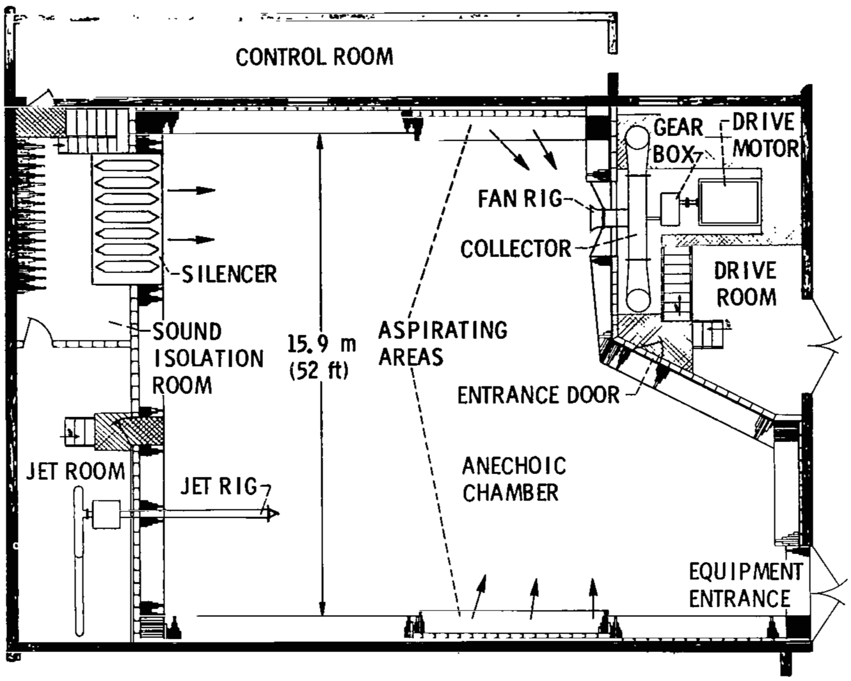
Test Hardware

Two different inlet assemblies were used with this fan for the tests reported herein. Most of the data were obtained with an inlet having flight-type internal contours and a thicker lip, which was in fact the identical unit used on tests reported in reference 8. Some tests are also reported using this same inlet with the addition of the turbulence-reducing, honeycomb-screen inlet flow control device reported in reference 6 and illustrated in figures 6 and 7.

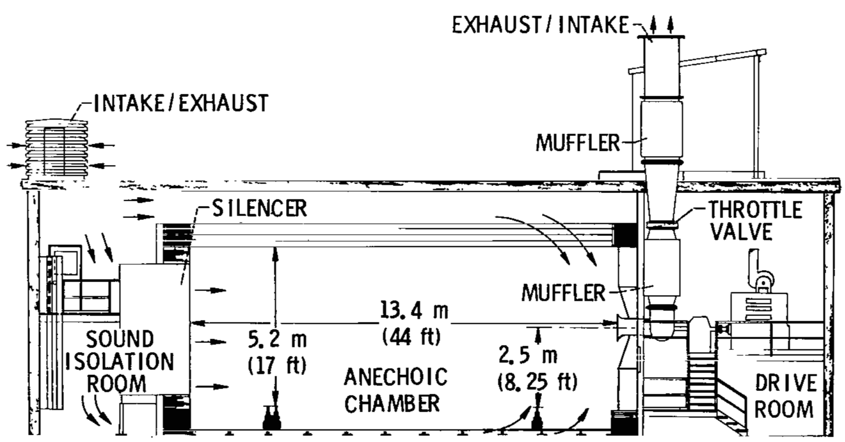
Although the testing of this fan was primarily for acoustic evaluation, sufficient aerodynamic instrumentation was provided to establish the overall operating point and to permit an approximate assessment of the fan's overall aerodynamic performance. The instrumentation included thermocouples and static pressure taps in the inlet assembly for inlet mass flow calculations, and four five-point radial rakes at the fan discharge measuring total temperature and pressure. These measurements were processed through a pressure multiplexer and computer system to calculate the aerodynamic performance parameters. All performance parameters were corrected to standard day conditions (288.2 K, 10.13 N/cm^2; 518.7° R, 14.70 lb/in^2).

Test Procedure

Inasmuch as the present fan design had previously been tested in larger scale, there was no reason for serious concern over the mechanical integrity of the hardware. Testing with most combinations of operating line and inlet hardware covered the speed range from 60 to 100 percent of design in 5- or 10-percent increments. For some test configurations the speed range from 90 to 100 percent of design was covered in 2-percent increments in an attempt to



(a) Noise facility floor plan.



(b) Noise facility elevation.

Figure 5. - Anechoic chamber.

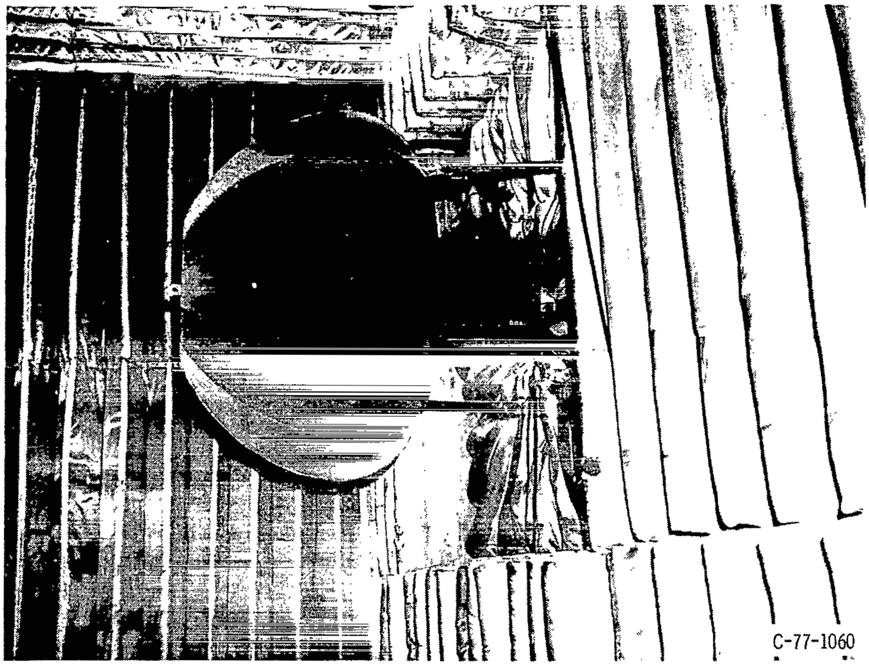


Figure 6. - Inlet flow control device installed on research fan in anechoic chamber.

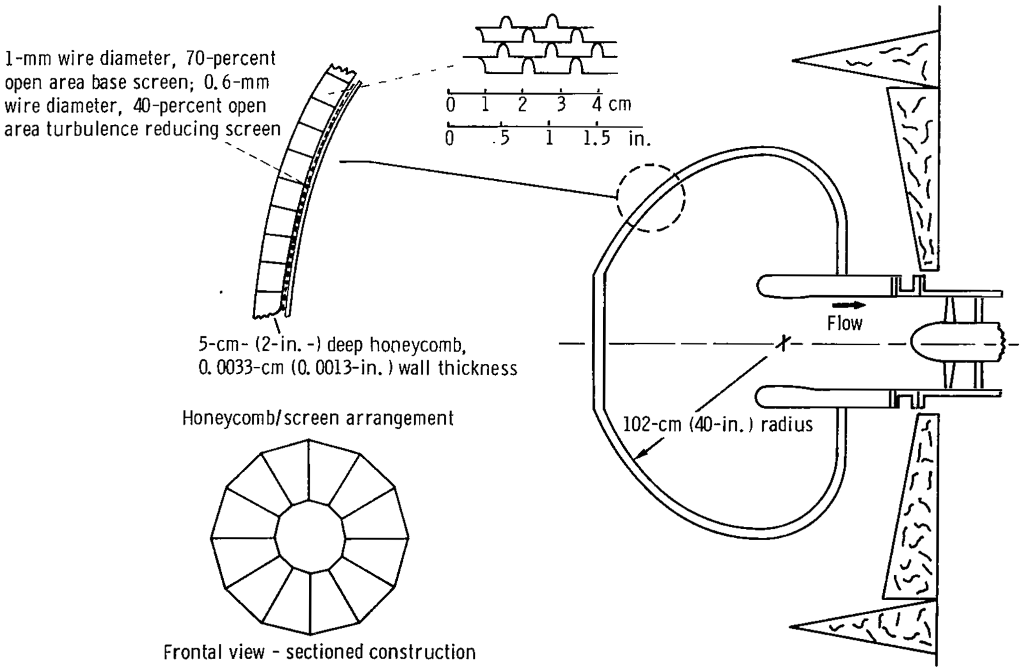


Figure 7. - Inlet flow control device.

identify the acoustic effects associated with starting of the design shock system.

Approximately six samples of all aerodynamic measurements were obtained at each operating point by an automatic digital data encoder. These samples were averaged, and from them the aerodynamic performance was computer processed online. A continuous trace of fan discharge pressure against inlet static pressure was displayed on an X-Y recorder for comparison with a predicted standard operating line plotted on the recorder chart.

Strain gages were placed on four of the rotor blades in locations appropriate for measuring the maximum predicted steady-state stress and the vibratory stresses for several predicted low-order modes. The steady-state and vibratory stresses were separately displayed on oscilloscopes and were continuously monitored visually.

Acoustic data were obtained concurrently with the aerodynamic data. Signals from all fixed microphones were processed online by a one-third-octave analyzer using a 4-second averaging time with the output recorded digitally on magnetic tape. The three data samples on tape were averaged and processed offline by computer using the analysis programs detailed in reference 9. Simultaneously with the online analysis, the microphone outputs were also recorded as analog signals on magnetic tape for offline analyses as desired.

Results and Discussion

Aerodynamic Performance

An analysis and assessment of the fan acoustic characteristics require some knowledge of the aerodynamic characteristics. It must be determined if the fan is performing aerodynamically as designed, and, if not, how any differences would be expected to affect the noise generation processes and relate to the measured noise output. The basic design of the present fan had been evaluated in the larger scale (0.73 m diam) fan test. However, a determination was required of any effects on aerodynamic performance due to the stator redesign and the slightly thicker rotor blade nominal airfoil sections.

Figure 8 presents the fan stage overall aerodynamic performance without the inflow control device as curves of total pressure ratio and adiabatic efficiency against percent of design corrected inlet flow for various speeds. The symbols and solid lines represent the data from the present fan, while the dashed lines represent data from the original 0.73-meter-diameter fan included for reference. Although the inflow control device would not be expected to affect the fan overall aerodynamic performance, the aerodynamic

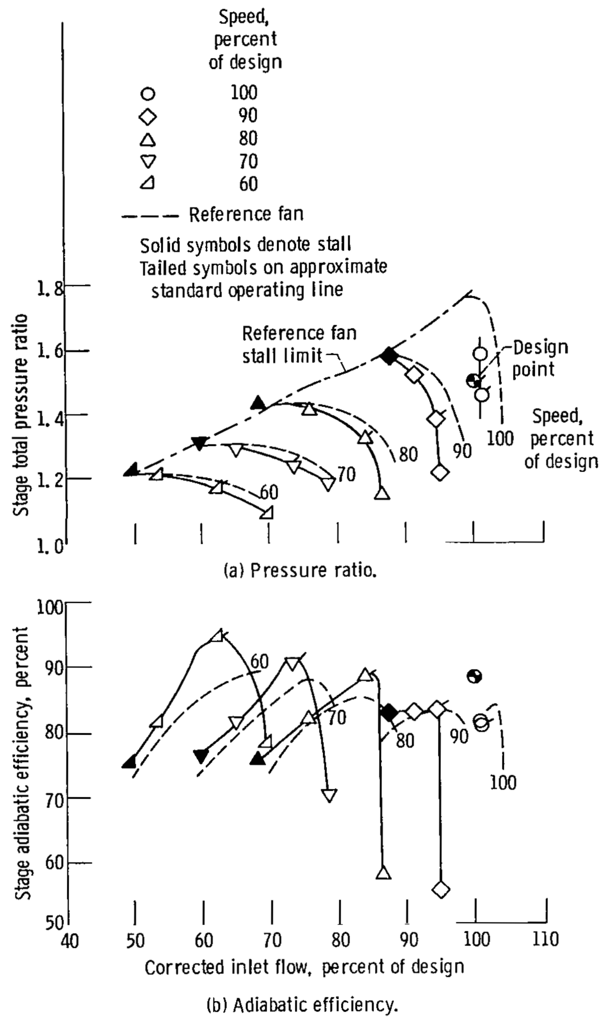


Figure 8. - Comparison of 0.73-meter- (28.74-in.-) diameter reference fan with QF-13 fan having simulated flight-type inlet without inflow control device.

data obtained while using this device are presented in figure 9 to lend weight to the repeatability and accuracy of the aerodynamic measurements to be discussed.

The minor changes made to the design of the scaled fan have resulted in several obvious differences in performance. The scaled fan compared to the reference fan has a somewhat lower flow range at each speed, particularly at the higher speeds where the range has been severely restricted. The stall line appears to have been improved slightly at speeds below about 90 percent of design with inflow control. No comment can be made on the stall line at design speed because a vibration problem in the drive shaft system, unrelated to the fan, made operation at that condition imprudent. Efficiency at high speeds was about the same as for the reference fan. However, at

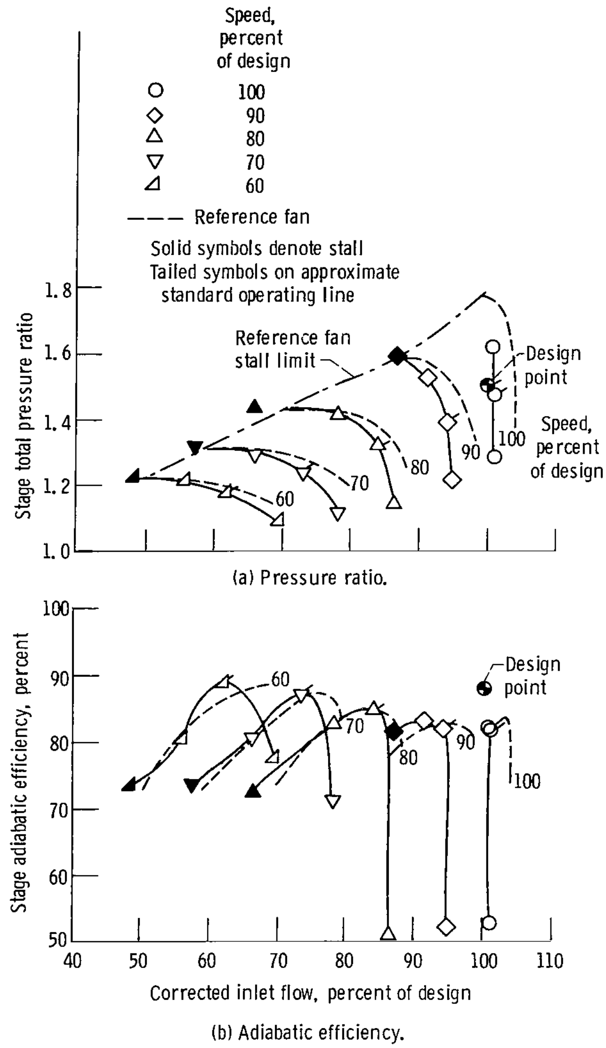


Figure 9. - Comparison of 0.73-meter- (28.74-in.-) diameter reference fan with QF-13 fan having simulated flight-type inlet with inflow control device.

lower speeds the two sets of data (figs. 8(b) and 9(b)) differ by some 3 to 5 points; this may simply be related to the difficulty in obtaining accurate efficiencies with low temperature rises and limited instrumentation.

The efficiencies of the scaled fan are essentially unchanged from those of the reference fan. By far the most interesting difference in the performance of the two fans from the standpoint of acoustic analysis is the lowering of the measured inlet flow of the scaled fan at design speed and pressure ratio from 104 to 101 percent of design. The original fan was designed for what was, at the time, a high specific inlet flow (see table I); quite surprisingly, it exceeded that by some 4 percent. The flow capacity of such a fan is controlled primarily by the details of the flow between rotor blades and the local channel flow area margins. It seems apparent that the present scaled fan has suffered by about 3 percent in flow capacity, probably because of the slightly thicker nominal rotor blade airfoil sections, but the flow capacity is still slightly better than design. There is no direct evidence from these aerodynamic test results to prove that the inlet shock has been swallowed in the present rotor. However, since the performance along the standard operating line is sufficiently close to that of the reference fan and to design, the assumption of swallowing at about the same speed as the reference fan is justified.

Acoustic Performance

Narrow-band spectral presentation. — The noise reduction concept implied by the aerodynamic design of the QF-13 fan was expected to reduce the amplitude of the multiple pure tones normally present at supersonic tip speeds. These tones occur at integral multiples of the shaft rotative frequency, predominantly in the forward-arc noise, and are most graphically displayed on narrow-band spectra. Figure 10 displays such narrow-band spectra for QF-13 at 70° from the inlet axis and at several speeds along the approximate standard operating line. It is obvious that multiple-pure-tone noise is present at all speeds at and above 60 percent of design, which is the speed range of the supersonic tip relative inlet Mach number. It was expected that multiple-pure-tone noise would exist at about the same level as with a conventional fan of the same tip speed at all supersonic speeds below that at which the strong bow shock system on the rotor leading edges is altered to the swallowed weak oblique shock system. This sudden transition occurred in the larger-scale fan just below 95 percent of design speed (ref. 4). If it is assumed that the present fan has the same transition speed, the 100-percent-speed spectrum of figure 10 would be expected to demonstrate the effect on multiple pure tones of the shock swallowing. Certainly the multiple-pure-tone content in the spectrum is strong, although it appears to be somewhat lower in amplitude with respect to the blade-passage tone level than that at 90-percent speed. Whether this is an effect of a decrease in multiple pure tones or an increase in blade-passage tone with shock swallowing, or both, must be determined by a study of component power levels. These will be obtained from the one-third-octave power spectra discussed in the next section. It is reasonable to conclude at this point, however, that the swallowed weak oblique shock system on the outer portion of the rotor blades did not greatly reduce the production of multiple-pure-tone noise.

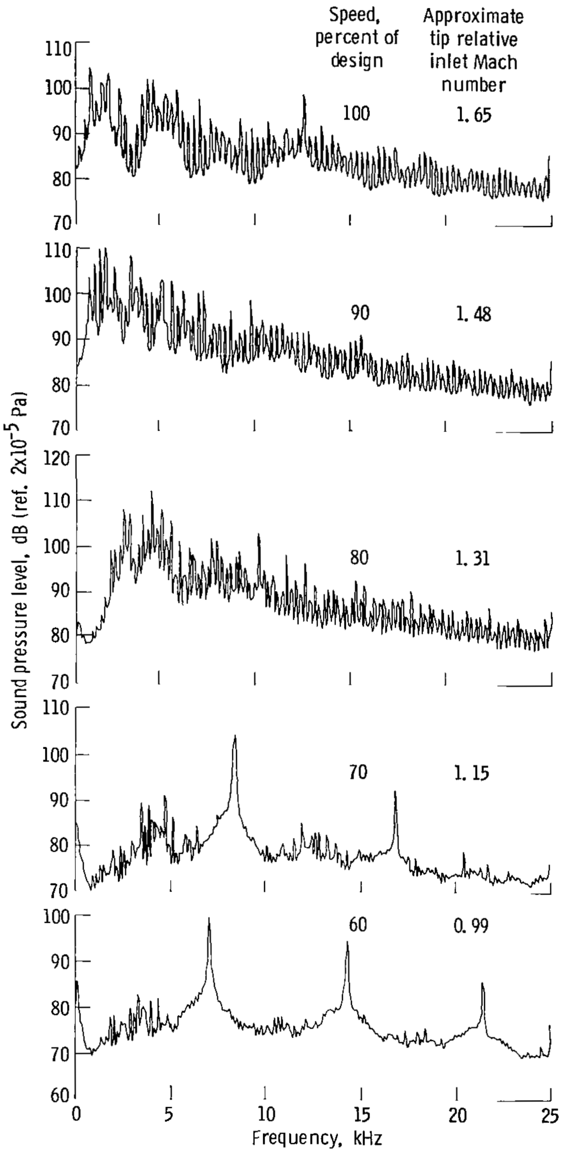


Figure 10. - QF-13 narrow-band spectra on standard operating line at 7.6-meter- (25-ft-) radius and at 70° angle from fan inlet axis without inflow control device.

One-third-octave presentation. – Figure 11 presents one-third-octave spectra of inlet sound power level along the approximate standard operating line at various speeds from 60 to 100 percent of design, both with and without the inflow control device. Multiple-pure-tone noise is present in the spectra at all speeds without inflow control; it appears first as only a small spike in the 2000-hertz band at 60-percent speed, then as a broader area centered at about 4000 hertz at 70-percent speed, and finally as an increasingly broader area with increasing speed. As indicated on the typical narrow-band sound pressure level spectra of figure 10, at 80- and 90-percent speeds the multiple-pure-tone sound power levels over a significant part of the spectra are dominant over the blade-passage frequency tones. At design speed the peak multiple-pure-tone sound power levels are below the level at blade-passage frequency and below the peak multiple-pure-tone values at 90-percent speed by about 2 or 3 decibels; this is an indication that the swallowed shock system may have a beneficial effect on the multiple-pure-tone noise.

From the one-third-octave sound power level spectra of figure 11 and similar spectra for other speeds, the approximate component power levels were extracted for both multiple pure tone and blade-passage tone with its harmonics. Identification of the bands in which the tones predominated was made from appropriate narrow-band sound pressure level spectra (e.g., fig. 10). These component power levels and the total values are shown in figure 12 for each speed along the approximate standard operating line. Also shown are similar values for the residual sound power levels including broad band obtained by subtraction of the tone components from the total power. This figure clearly shows that the QF-13 fan multiple-pure-tone noise behaves conventionally below the shock-swallowing speed, with a fast rise at low supersonic speeds and a leveling at higher speeds. As the speed rises to the point at which the design swallowed-shock system is started, just below 95 percent of design speed, the level of multiple-pure-tone noise drops about 3 decibels and remains at this lower level through design speed. The acoustic effect of the shock swallowing on shock noise from this fan is thus a beneficial one as expected, but it is definitely not a strong effect. At all speeds above about 75 percent of design the multiple-pure-tone noise is the most powerful component and controls the total noise level.

It would seem most likely that the 3-decibel lowering of the observed multiple-pure-tone noise results simply from the weaker-than-conventional shock system present at the rotor inlet rather than from the expected complete swallowing of the shock within the rotor inter-blade passages. Perhaps it was unreasonable to expect a considerable reduction in multiple-pure-tone noise from the actual swallowing of the inlet shocks, as differentiated from the effect of the relatively lower strength of the associated oblique shock. While the swallowed shock system by design does not have the forward-running component of the conventional bow wave, it is nevertheless standing in a subsonic absolute flow field, and any instability in its position or strength will radiate an acoustic signal forward. The blade to blade differences in these forward projected acoustic waves would then be expected to yield the once-per-

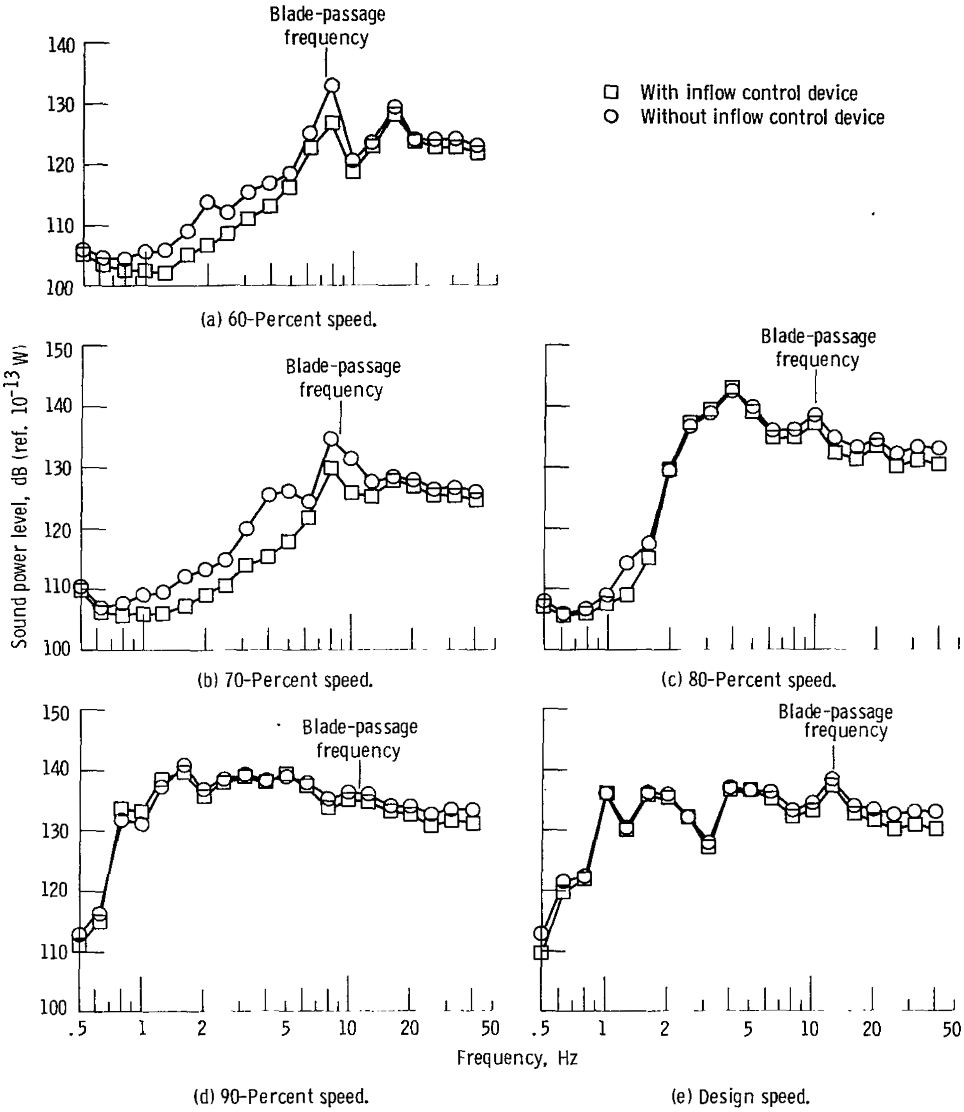


Figure 11. - QF-13 inlet sound power spectra on standard operating line with and without inflow control device.

revolution tone and its harmonics which characterize multiple-pure-tone noise production.

Figure 12 also indicates, though not as clearly as for the multiple-pure-tone noise, that the blade-passage-tone noise has been lowered slightly by the shock swallowing process. This would be expected because the type, location, and strength of the rotor inlet shock might have an effect on the flow conditions in the inter-blade channels and on rotor exit flow conditions and hence possibly on the blade-passage-tone noise. The one-third-octave band containing the blade-passage tone is wide enough to contain about nine of the multiple pure tones as well as the blade-passage tone. Because the multiple pure tones have been lowered in level, the blade-passage tone calculated this way could appear slightly low especially when the blade-passage tone is at about the same level as the multiple pure tones. The figure also indicates a slight increase in the residual noise, including broad band, after the shock is swallowed. Because the component including broad-band noise is found by subtracting the separate tone levels from the total, slightly too low values of blade-passage-tone noise would yield slightly too high values of apparent broad-band noise. Given this source for small errors and the small (1 to 1.5 dB) apparent effects of shock swallowing on broad-band noise and blade-passage-tone noise, it seems unwise to infer any signficant effect of shock swallowing on the generation of these two noise components.

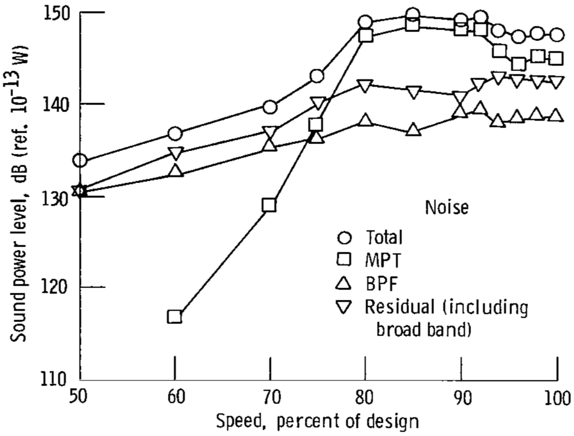


Figure 12. - Components of QF-13 noise on standard operating line.

Inflow control effects. – The inflow control device shown in figures 6 and 7 was used during a portion of the QF-13 fan test program to reduce the turbulence and any flow distortion in the inlet air. It was expected that at subsonic tip speeds the less turbulent inlet air would reduce the blade-passage-tone noise of the fan much the same as occurred when the same inflow control device was used with another fan in the tests reported in reference 6. By this method it is hoped that measured blade-passage-tone noise at low speeds will approach that generated by the fan in flight rather than the higher amount normally found in static testing as the result of a spurious propagating tone caused by interaction between the rotor and incoming turbulence and flow distortions. While such information is not a prime requirement in the noise rating of the present high-speed fan, it is nevertheless presented here as an indicator of the acoustic sensitivity of this fan at low speeds to inflow disturbances.

From figure 11 it can be seen that at the lowest speed, 60 percent of design or about a 0.86 tip rotative Mach number, the inflow control device lowers the blade-passage frequency tone about 6 decibels in sound power level. At 70 percent of design speed with a tip rotative Mach number of about 1.00, the reduction is about 5 decibels. At higher speeds, where no reduction is expected from such treatment of the inflow conditions, there is an indicated 1-decibel reduction which may simply represent the limit of experimental accuracy and repeatability.

It is interesting to note in figure 11 that at the low tip speeds (60 and 70 percent) the inflow control device not only lowered the blade-passage-frequency tone as expected but also significantly reduced the multiple-pure-tone content. This same effect is noted in reference 6, which gives the tests results of the same inflow control device with a different fan having a much lower tip speed. It would seem likely from this indication that the initiation of a noise-producing shock system at or near the leading edge is retarded by the lower turbulence in the fan inlet air after flowing through the inflow control device. This effect could cause some potential errors in assessing the multiple-pure-tone noise of a fan at relative inlet Mach numbers which are just slightly supersonic, but from figures 11(c) to (e) it is obvious that no serious error will be caused at higher Mach numbers.

Forward-arc directivity plots of blade-passage-frequency one-third-octave sound power level are presented in figure 13 at several speeds for the fan with and without the inflow control device. Generally, this fan does not exhibit strong directionality in its blade-passage-tone noise on a one-third-octave prsentation, which makes only the gross effects obvious. As noted with respect to figure 11, only at the two lowest speeds, 60 and 70 percent of design, is there a significant reduction in the tone noise by the inflow control device. This reduction of as much as 10 decibels tends to be greatest near the sideline rather than near the axis. This does change the apparent fan directivity at low speed from one which peaks, albeit rather mildly, near the sideline to one with a slight peak much nearer the axis. This apparent change in directivity would seem to be related to the process of noise generation within the fan rather than to a nonuniform transmission loss through the inflow control device, because the tests reported in reference 6 indicated a circumferentially uniform attenuation by the device within 1 decibel.

Figures 14 and 15 present the directivity effects at 60 and 100 percent of design speed, respectively, but in a different format than that used in figure 13. Here, the narrow-band (40-Hz) sound pressure level at blade-passage frequency is presented as a continuous function of angle from the fan inlet with the data obtained from the single traversing boom

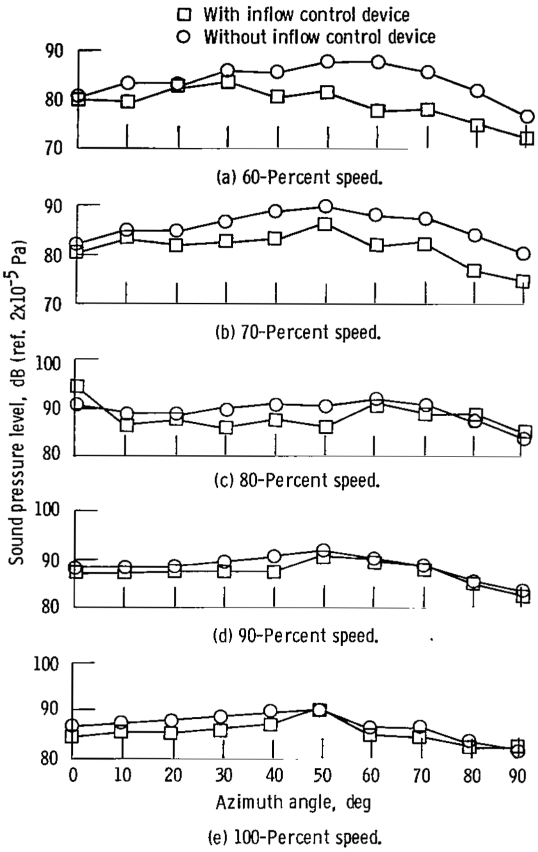


Figure 13. - QF-13 one-third-octave sound pressure level at blade passage frequency with and without inflow control device at 7.6-meter (25-ft) radius.

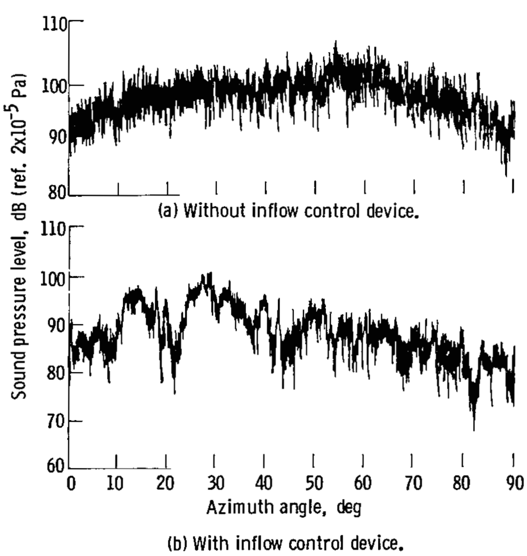


Figure 14. - QF-13 narrow-band (40-Hz) sound pressure level at blade passage frequency at 60 percent of design speed with and without the inflow control device at 6.1-meter (20-ft) radius.

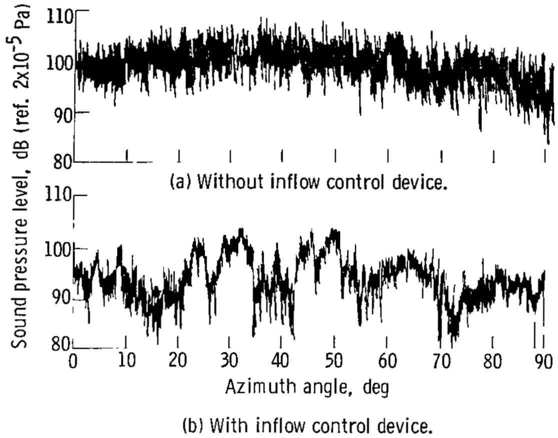


Figure 15. - QF-13 narrowband (40-Hz) sound pressure level at blade passage frequency at design speed with and without the inflow control device at 6.1-meter (20-ft) radius.

microphone. The closely spaced excursions in sound pressure level of some 10 decibels do not represent directivity effects; they are the result of fluctuations of the tone level with time, not azimuth angle, as the traversing microphone moves through the 90° forward arc in approximately 4 minutes. Overall, the same comparisons can be made at each speed between the data without inflow control and that with the inflow control device, although there does seem to be slightly more difference in the two cases at design speed than was observed in the one-third-octave comparisons of figure 13. The one-third-octave band at blade-passage frequency has sufficient width to include several multiple pure tones which tends to weaken comparisons on this basis. With the finer angular resolution displayed in figures 14 and 15 there is now a distinct lobular pattern present with the inflow control device. It appears that the inflow control device has decreased the circumferentially uniform components of the blade-passage-tone noise that were caused by interaction between the rotor and the turbulence and flow distortions in the incoming flow field.

Acoustic comparison with other high-speed fans. – An adequate assessment of the noise production characteristics of the QF-13 fan must certainly involve a comparison with other fans of similar overall aerodynamic performance characteristics. For this purpose, five fans have been selected which have approximately the same tip speed and thus should have about the same mix of noise generating mechanisms. These reference fans have slightly higher pressure ratios than the QF-13 fan; this is unavoidable since the QF-13 fan was originally designed as an effort to produce an efficient fan having low loading while operating at a high tip speed.

The disparity of pressure ratio among the six fans is, however, little enough that noise comparisons will be valid. All of these fans are of modern design and incorporate various design features which are intended to minimize one or more components of the noise. These features will be described, and a brief summary of pertinent aerodynamic design parameters for the six fans is presented in table II.

TABLE II. – DESIGN SUMMARY
HIGH-TIP-SPEED FANS

Fan	Tip speed, m/sec (ft/sec)	Tip diameter, m (in.)	Pressure ratio
QF-13	488 (1603)	0.508 (20.0)	1.5
QF-12	480 (1575)	.498 (19.6)	1.6
JT8D Refan	488 (1600)	.508 (20.0)	1.67
Fan C	472 (1550)	1.73 (68.0)	1.6
Fan C - Mod VIII	472 (1550)	.914 (36.0)	1.6
GE-ATT	503 (1650)	.904 (35.6)	1.8

The QF-12 fan was designed with a rotor blade leading edge sweep that yields a component of the incoming relative Mach number normal to the leading edge which is subsonic at all radii. The intent of this design was to minimize the generation of rotor leading-edge shock waves, thereby minimizing the consequent multiple-pure-tone noise. Leading-edge sweep was also incorporated on the stator vanes to minimize the rotor-stator interaction noise at blade-passage frequency. Reference 1 presents some results of forward-noise testing of this fan, while references 10 and 11 present the design in more detail.

The JT8D Refan is a scale model in 0.5-meter size of the full-scale Refan which was designed as a modernized, quieter replacement fan for the JT8D engine fan (ref. 8). The Refan has inlet guide vanes which were designed to lessen the radial gradient of inlet relative Mach number. The consequent lowering of the tip relative Mach number would slightly weaken the normally strong leading-edge shocks and, thus, would be expected to lessen somewhat the multiple-pure-tone noise generation. In addition, the presence of the guide vanes constitutes a flow area blockage which locally raises the already high axial Mach number and could therefore possibly inhibit somewhat the forward propagation of noise at high speeds. However, even though only this fan among the six has inlet guide vanes, it is a good fan for forward noise comparisons because it is a modern, well-developed fan which was tested in the same facility as the QF-12 and QF-13 fans. Some of the acoustic test data for this fan are presented in references 1 and 8.

Fan C, one of the candidate fans for the NASA Quiet Engine Program, is a conventional high-speed fan designed to be as quiet as possible within the framework of conventional aerodynamic design practice. Its rotor uses blade sections at other than the hub area which are "generally similar in appearance to the NASA multiple-circular-arc profiles" (ref. 12) rather than the special shapes of the QF-13 fan. The rotor of Fan C as originally tested produced a strong bow shock at design speed ahead of the leading edge. The blades were modified to weaken and swallow this shock at design speed which they successfully accomplished. This modified fan was built and tested in full engine size, and the noise data cited herein are reported in reference 13.

In Fan C - Mod VIII, a modification of Fan C, the rotor blade was very carefully reshaped to swallow the inlet shock at 90-percent speed (the takeoff speed) rather than at 100-percent speed as originally designed and still retain the original fan efficiency. This model was the result of several successive modifications to the airfoil shapes, and it finally included flow-path alteration. The basic intent was to reduce the multiple-pure-tone noise at takeoff speed with the altered shock structure. In this it was quite successful, although at the expense of noticeably increased blade-passage-tone noise. The noise characteristics of this fan, which was about half the size of Fan C, are reported in reference 2.

The General Electric GE-ATT fan had about the same tip speed as the other reference fans under consideration here, but it had a somewhat higher pressure ratio and design specific inflow. It was designed with as many quieting features as possible, including swallowed shocks at takeoff speed. This fan was again about half the size of Fan C, and the noise data are reported in reference 14.

The Fan C and GE-ATT inlet noise data were obtained with bellmouth fan inlets, while the other fans used modified flight-type inlets. Where data from all six fans are compared, these data are corrected in level and frequency to the design thrust level of Fan C. Where only QF-12, QF-13, and Refan are compared, the as-obtained data are used since these three fans have nearly identical thrust levels and were tested in the same facility with the same inlet.

Figure 16 compares one-third-octave spectra for QF-12, QF-13, and Refan at their design speeds without using the inflow control device. QF-13, with its inlet shocks swallowed at this speed, does not appear to be significantly different in any important respect from the other two fans. The equivalent spectra at 90 percent of design speed, now with the QF-13 inlet shocks not swallowed, are shown in figure 17. Here the levels in the range below blade-passage frequency, where multiple pure tones are expected to determine the levels, show that QF-13 is slightly the noisiest of the three fans. QF-12 is obviously the noisiest of the three fans at blade-passage frequency, but it is the quietest of the three in multiple-pure-tone noise at 90-percent speed. It is noted in reference 1

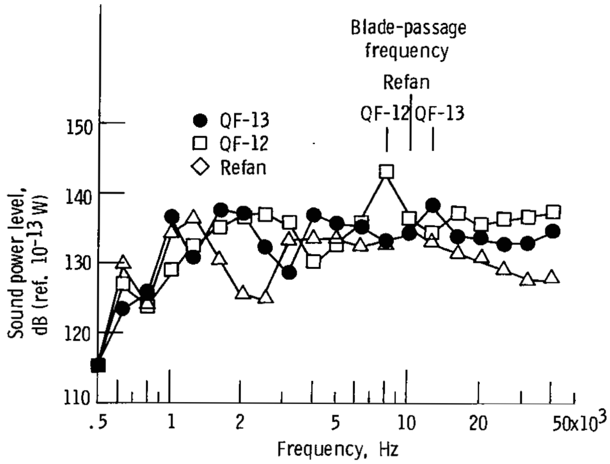


Figure 16. - Comparison of sound power spectra of three high-tip-speed fans at their design speeds.

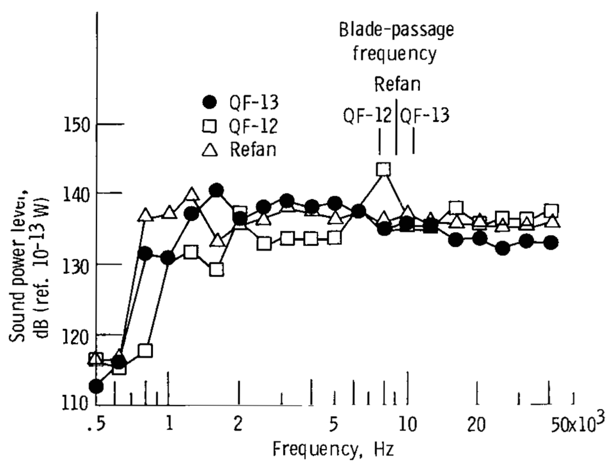


Figure 17. - Comparison of sound power spectra of three high-tip-speed fans at 90-percent of their design speeds.

that an apparent interchange of power occurred between blade-passage-tone noise and multiple-pure-tone noise for QF-12 at the higher speeds such that as one component was reduced the other tended to increase. However, as QF-13 is raised in speed from 90 to 100 percent of design and the multiple-pure-tone noise decreases with the alteration of the inlet shocks, the blade-passage-tone noise remains at approximately the same level. With the lowering of the rest of the spectrum at design speed, however, the peak at blade-passage frequency becomes more prominent relative to the adjacent one-third-octave bands.

The sound power level of the multiple-pure-tone content in the overall noise can be approximated with reasonable accuracy by identifying the one-third-octave bands below the blade-passage frequency in which such noise predominates and then

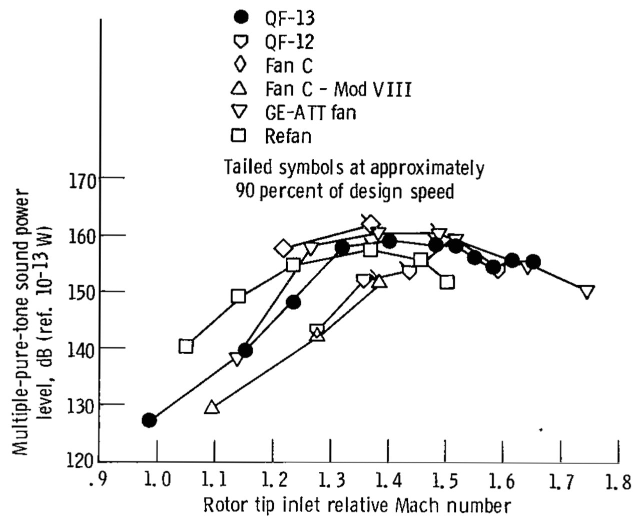


Figure 18. - Multiple-pure-tone sound power levels of QF-13 and five reference high-tip-speed fans scaled to Fan C thrust level. Obtained from one-third-octave power spectra.

logarithmically adding the levels in these bands. While the resulting numbers are not precisely the true multiple-pure-tone noise, they do represent a reasonable and consistent "figure of merit" for such noise. The results of this analysis are displayed in figure 18 as a function of the relative inlet Mach number at the tip of the rotor because multiple-pure-tone noise is presumably primarily a function of this Mach number (or its component normal to the edge if the leading edge is swept).

It is obvious from figure 18 that QF-12 and Fan C - Mod VIII are the lowest producers of multiple-pure-tone noise at speeds of 90 percent of design or less, which is the range over which such fans would be noise rated. The low noise production of QF-12 was related in reference 1 to the effect of rotor blade leading edge sweep. The other four fans including QF-13 all fall within a band some 6 to 20 decibels above the Fan C - Mod VIII levels. QF-13 is thus seen to be conventional in producing multiple-pure-tone noise at speeds below the shock-swallowing speed. The limited reference data available at the highest speeds make it difficult to assess any relative merits of the QF-13 swallowed shock, but it appears that any differences would be small.

If the QF-13 blading concept were to be used in an engine to reduce the multiple-pure-tone noise at takeoff speed, the highest of the noise rating speeds, the fan would require redesign to bring the shock-swallowing speed under about 90 percent of design. This is exactly the design process by which Fan C - Mod VIII was derived from Fan C, and for the same reason. The modifications to Fan C were a spectacular success in reducing the multiple-pure-tone noise some 10 to 20 decibels over the range of speeds for which data are available. It is unfortunate that no noise data are available at speeds higher than about 90 percent of design for the two versions of Fan C so that they could be compared with the available data for the other conventional fans. If multiple-pure-tone noise results only from the strength of the rotor leading edge shocks, it is difficult to understand why QF-13 and Fan C - Mod VIII are so different in multiple-pure-tone noise production at speeds below shock-swallowing. However, the QF-13 fan rotor blades have part-span dampers (fig. 2) whereas Fan C - Mod VIII does not, and it is possible that the shock system associated with these dampers (ref. 5) makes a contribution to the multiple-pure-tone noise. It seems unlikely that this mechanism by itself could result in the differences noted in noise level.

The six fans under consideration are compared in figure 19 on the basis of a current correlation of the sound power from modern, quiet, low-tip-speed fans (ref. 15). This correlation presents the thrust-corrected sound power level as a function of the total pressure rise ratio, and it correlated the noise of many low-speed fans within ±2.5 decibels. Note, however, that the correlation was developed for total fan sound power, and the high-speed fan data to be presented on this correlation are only from the fan inlet noise.

The fans for which sufficient low-speed noise data are available show trends which follow the slope of the correlation well, with QF-13 the best of the group by approximately 1 to 2 decibels. At the approximate speed for each fan where multiple-pure-tone noise becomes prominent, the data curves rise much more steeply than the correlation, generally to values above the correlation band. At high speeds, the fans for which such data are available (QF-12, QF-13, Refan, and GE-ATT) all show a marked dropoff in noise. A portion of this latter effect is probably an attenuation due to the high axial Mach numbers in the fan inlet. The GE-ATT fan shows the greatest dropoff because it is the only fan for which an overspeed point is shown (106 percent of design). The data for QF-13 are somewhat confusing in this respect at high speed. Beyond 96 percent of design speed the thrust-corrected noise does not continue to fall as it does for the others. It seems likely, however, that this speed region covers a brief period of adjustment between aerodynamic and acoustic performance, and that overspeeding the fan would cause an additional drop in the thrust-corrected noise.

Fan C and GE-ATT are seen in figure 19 to be the noisiest in the multiple-pure-tone range below the point where inlet Mach number attenuation becomes evident. The other four fans are noticeably better and are about equivalent on this thrust-corrected basis. QF-13 is by a small margin the quietest at low supersonic speeds.

The QF-13 data of figure 19 are replotted in figure 20 along with equivalent data obtained by using the inflow control device. The comparison is essentially the same as that of earlier figures. At supersonic tip speeds the differences between the two data sets are

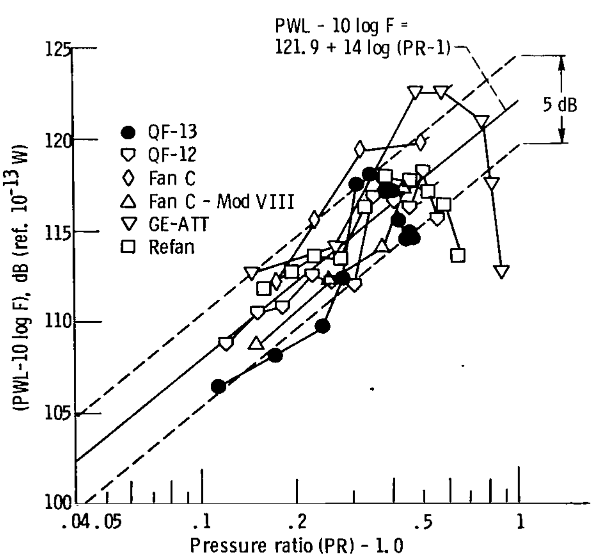


Figure 19. - Thrust-corrected (F, lb) inlet sound power levels (PWL) for QF-13 (without inflow control device) and other high-tip-speed fans on correlation of noise from low-tip-speed fans.

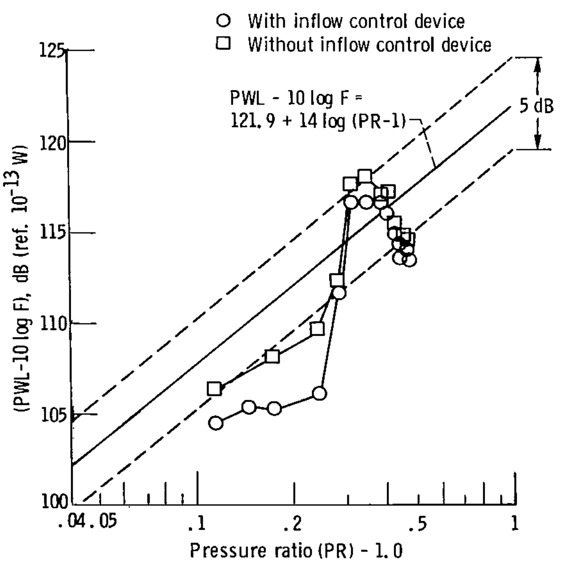


Figure 20. - QF-13 with and without inflow control device on correlation of noise from low-tip-speed fans. Sound power level, PWL; thrust, F (lb).

small, while at subsonic tip speeds with the less turbulent and distorted inflow there are indicated reductions of some 2 to 3 decibels in thrust-corrected forward noise, with actual values some 4 to 7 decibels below the correlation line. The correlation was developed with total noise data obtained from low-tip-speed fans in static test facilities, and there is a strong indication from the present tests, as well as from other recent tests such as those of reference 9, that the correlation is overpredicting the total noise of low-tip-speed fans in flight by perhaps 5 or more decibels.

Concluding Remarks

A series of experiments was conducted to assess the overall aerodynamic and inlet acoustic performance of an aircraft fan built with rotor airfoil sections which were designed to have a weak oblique shock that was swallowed within the interblade channels at speeds above about 94 percent of design. It was expected that the completely swallowed shock would greatly reduce the multiple-pure-tone noise which results primarily from such leading-edge shocks.

At fan speeds where the inlet relative Mach number at the rotor tip was supersonic, but below 94 percent of design speed, multiple pure tones were present in the noise spectra. This was expected because the rotor leading edge has a relatively strong bow shock system at these speeds. At speeds above about 94 percent, with the shock system presumably swallowed, the multiple-pure-tone noise was decreased only about 3 decibels, considerably less than had been expected. Although the point cannot be proven with the data taken, it would seem possible that the small noise reduction was simply the result of the existing rotor leading-edge shocks being weakened as they were swallowed. It probably cannot be argued that a shock system without the forward-running component of the conventional bow shock will "eliminate" multiple-pure-tone noise. The fact that a shock system exists, and is located in an airstream flowing at a subsonic absolute Mach number, apparently means that any instability or perturbation of the shock will be propagated forward as an acoustic wave. The blade to blade differences in these rotating, forward-propagating waves will cause a repetition pattern at a once per revolution frequency, which is the pattern required for generation of multiple-pure-tone noise.

There are several other sources of shaft-order aerodynamic disturbances which could conceivably result in acoustic signals. Reference 5 indicates that the part-span dampers on the QF-13 rotor blades have two shock systems at high speeds, both oblique with one rather strong. Possibly the blade to blade nonuniformities in these shocks, rotating at rotor speed, could result in forward multiple-pure-tone noise if the waves are perturbed. Reference 5 does not depict any details of the actual shock structure on the rotor blades inboard of the damper. The design of these blades (refs. 3 and 7) only incorporates the special shock-swallowing airfoils in the outer portion of the blade which passes about 35 percent of the total flow and where the outlet relative Mach numbers are supersonic. The inboard part of the blade, with subsonic inlet and outlet relative Mach numbers and about 20 percent of the total flow, is the result of using more conventional geometrical techniques to derive the airfoil shapes. The central portion of the blade is analytically blended between the inboard and outboard portions. The design edge and internal shock structures in the inboard and central portions of the blade are not defined in the references, and in the absence of any experimental information on these shocks, it is possible that an uncontained wave could exist in these regions and result in multiple-pure-tone noise.

Reference 5 also identifies and pictures a rather strong tip-clearance vortex at high speeds. With the QF-13 rotor shaft supported on the oil film in a journal bearing which has clearance, it is known that the rotor does not run with its axis coincident with that of the fan casing. The noncoincidence of the fan and casing axes can be 10 to 15 percent of the static rotor blade tip clearance and can approach 100 percent of the running tip clearance. This gross nonuniformity of running tip clearance will result in a strong once-per-revolution variation of the clearance vortices for all the blades. These vortices impose a blockage on the through flow at the tip which result in a cyclic variation of both relative Mach number and angle of incidence. These variations will cause a corresponding cyclic variation in the strength and position of the associated shock waves, and they could presumably cause a cyclic variation in the started-unstarted situation at the tip. If that should happen, it would certainly result in the production of multiple pure tones in the far field.

In comparison with other modern fans designed by various means to be quiet, QF-13 is seen to be spectrally quite similar. The overall noise of QF-13 is also quite similar to that of the comparison fans, and it is actually somewhat lower at the lower speeds. The multiple-pure-tone noise is about the same as for conventional fans at the same Mach numbers, but is noticeably higher than that of one fan designed with swept rotor blade leading edges and another designed with much the same shock-swallowing features as QF-13. This latter deficiency of QF-13 was especially surprising and disappointing in view of the experimentally proven success in attaining the carefully designed weak swallowed shock system in the largescale model. Perhaps the deficiency of QF-13 in this respect can be related to the previous discussion in that the QF-13 rotor blades had part-span dampers and the comparison shock-swallowing fan did not. This could presumably be the source of a measurable difference in multiple-pure-tone noise. In addition, it is possible that there were significant differences in the blade shock wave structures in the inboard regions of the two fans. Finally, the comparison fan was tested on a shaft that was supported on rolling element bearings which permitted essentially no circumferential variation of tip clearance. This again could have made a measurable difference in generated noise. This latter possibility does point up one of the inherent difficulties in making acoustic comparisons among fans tested in varying environments.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 28, 1979,
505-03.

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15. Supplementary Notes

16. Abstract

Forward noise and overall aerodynamic performance are presented for a high-tip-speed fan having rotor blade airfoils designed to alter the conventional leading-edge bow shocks to weak, oblique shocks which are swallowed within the interblade channels. It was anticipated that the swallowed shocks would minimize the generation of multiple-pure-tone noise. In the speed range where the shocks presumably were swallowed, the multiple-pure-tone noise was lowered only about 3 decibels. Comparison with several high-speed fans on a thrust-corrected basis indicated that the present fan was the quietest in total forward noise at low speeds but offered no advantage at high speeds.

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