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Scientific and Technical Information Branch

Summary

The forward noise and aerodynamic performance are presented for a high-tip-speed fan (identified as QF-14) having an exceptionally high average axial Mach number at the rotor inlet face and associated swallowed shocks. It was anticipated that the high Mach number would have the same noise-reduction effect as if it existed in the inlet throat. It was proposed to operate this fan during takeoff at design speed to obtain the expected noise reduction during that noise rating period. It was also expected that noise reduction could be attained during approach to landing by operating the fan at design speed, and thus design axial Mach number, but with the exhaust nozzle and stators opened to lower the fan pressure ratio and, thus, thrust. Testing of the fan was performed in an anechoic facility, but the test program was inadvertently shortened by a drive system mechanical failure.

The aerodynamic performance of the fan was reasonably close to the design, although the design-speed flow was low by about 3 percent. Overall noise above 70 percent speed is controlled by the multiple pure tones. From 90 to 100 percent speed on the standard operating line, the levels of all noise components in the far field decrease, indicating that the high incoming axial Mach number at the rotor face may be attenuating the takeoff forward noise as expected by the designers. This conclusion is supported by measurements made in the inlet and discharge ducts with dynamic pressure sensors, which indicated that, as all the forward noise components decreased, all of the rear noise components increased. The QF-14 fan is shown to produce some 5.5- to 11-decibels less forward noise at the design takeoff operating point than several reference quiet fans of modern, high-tip-speed design.

The abbreviated test program did not include a test of the actual approach-point noise. However, the data from the test condition closest to approach indicated that the design-speed approach operation of this fan is 3 decibels quieter than the conventional operation. This result is considered tentative until an assessment can be made of the correct approach point.

Introduction

The development and utilization of the high-bypass-ratio turbofan engine for application to conventional commercial transport aircraft yielded the advantage of greatly reduced exhaust-jet noise. It was this noise of the aircraft powered by turbojet and low-bypass-ratio turbofan engines that had caused the bulk of the noise complaints by airport neighbors and led to the search for quieter engines. The high-bypass-ratio turbofan answered a large part of this need for noise reduction with its much lower jet velocity, because the jet noise is a very strong function of the jet velocity. With this once-dominant noise component now greatly reduced, the fan turbomachinery noise becomes a major contributor to the remaining noise, and it is this component that must be reduced to make gains in the reduction of overall engine noise.

Low tip speed fans, those that have rotor tip speeds not much more than sonic at the noise rating conditions of operation, have been used to minimize the production of multiple pure tones which are a consequence of shock generation in fans with supersonic tip speed. These tones are a component of noise in addition to the broadband and blade-passage-tone noises of the low-speed fan, and at high tip speeds they consitute the greatest part of the total noise production (ref. 1). However, the high-speed fan has the important advantage of permitting the fan turbine to be smaller in diameter with fewer stages and can eliminate the need for a speed-decreasing gearbox for the fan. Thus, the savings in weight, cost, and complexity can be important, and for these reasons there is an effort at NASA Lewis Research Center to find ways to reduce the noise characteristic of the high-speed fan.

Part of the noise reduction effort has involved the investigation at Lewis of three high-tip-speed fans, each of which incorporated a different concept for reduction of noise at the source. These fans were proposed and built by three separate companies under contract to NASA Lewis. Evaluations of the forward noise of two of these fans have been presented in references 1 and 2, and this report presents the forward noise evaluation of the third fan. This fan (designated QF-14) was proposed, designed, and fabricated by the Detroit Diesel Allison Division of General Motors Corporation.

In principle, fan noise can be reduced in the far field either by reducing the generated noise at the source, or by attenuating the generated noise with devices external to the fan, such as acoustic absorbers in the fan ducting and/or convergent-divergent inlets having a high average axial Mach number at the throat. Although the noise-reduction concepts embodied in these three fans were intended to reduce the generated noise at the source, the present fan also includes an element of the reduction-after-generation principle in its noise reduction scheme. The rotor of this fan is designed to operate at a very high specific inflow, which produces an average axial Mach number at the rotor-inlet face of about 0.714, compared with values of 0.6 or less for conventional fans. The high axial Mach number at the rotor face was expected by the designers to provide reduction of forward noise, similar to that of a convergent-divergent inlet with the same throat axial Mach number, but without the addition of external hardware and without the flow losses resulting from the outer wall diffusion in the divergent portion of the inlet. This concept would reduce all three components of forward-radiated noise: blade-passage tone, broadband, and multiple-pure-tone noise. Discussions of the noise-reduction concepts embodied in this fan design and its preliminary aerodynamic design are given in reference 3.

By operating this fan at its design point, at takeoff the expected forward noise reduction would be realized at this noise-rating condition. At the approach noise-rating condition, however, conventional procedure has the fan operating at part speed, typically about 60 percent of design, with correspondingly reduced flow to reduce the thrust. The designers of the present fan propose that it be kept at design speed during approach, with the thrust reduced by a considerable reduction in the fan total pressure ratio, which requires both an increase in exhaust nozzle area and a reset of the fan stators. Thus with the high flow and high axial Mach number maintained, the forward noise at approach should be reduced by about the same amount as at takeoff. This scheme has the additional advantage that an aborted approach would require only the resetting of the stator vanes and exhaust nozzle to design positions to reestablish takeoff thrust. This could require less time than increasing the speed of the conventional fan and thus provide an added margin of safety.

The QF-14 fan blading includes stator vanes of exceptionally long chord. Their design was carefully optimized to provide a reduction in the rear-radiated noise by lessening their response to the incoming pattern of rotating wakes generated by the rotor blades. It should be noted, however, that only the noise radiated forward from the inlet of the fan is reported herein, so the major acoustic effects of the long chord stators will be unidentifiable and, therefore, will not be discussed separately.

The fan resulting from the design by the contractor was constructed with a nominal tip diameter of 508 millimeters (20.0 in.). It was sized and configured for testing in the acoustic test facility at NASA Lewis. The present report documents principally the results of forward noise testing in the acoustic test facility and includes an overall evaluation of the aerodynamic performance. During testing, the fan was operated over the speed range from 60 to 100 percent of design corrected speed and over all or part of three operating lines. The tests were made using an inlet having simulated flight-type internal contours and a thicker lip for static testing. Additional tests were made using a turbulence-reducing honeycomb/screen flow-control device over the flight-type inlet in an attempt to reduce the excess blade-passage tone noise arising from interactions between the inflow disturbances and the rotor.

During testing of the fan, a failure occurred in the fan drive system which ended the testing before the planned program was completed. The failure was unrelated to the fan hardware and did not damage the fan, so it is possible to finish the program some time in the future. Most of the unfinished tests were those involving the resetting of the stator vanes to simulate the approach condition operating mode, so this valuable information will be lacking in the present evaluation of the fan's forward noise.

Fan Design

The fan (designated QF-14) used in this investigation was designed using conventional ranges and limits of most aerodynamic criteria such as solidity, diffusion factor, and losses. However, to obtain the desired high inlet axial Mach number, the rotor-inlet specific flow rate was specified to be higher than had previously been considered a practical design limit. Figure 1, taken from reference 3, which describes the preliminary design and acoustic evaluation of the concept, indicates the noise reductions that can be attained at various levels of Mach number at the throat of conventional inlets. The benefit of using the maximum practicable Mach number, and thus specific flow, is obvious. The specific flow selected for this design was 219.7 kg/sec-m^2 (45 lb/sec-ft^2), while the conventional limit at the time of this design was about 205 kg/sec-m^2 (42 lb/sec-ft^2). This high specific flow yields an average inlet axial Mach number of 0.714. The extension of specific flow was a serious concern during the aerodynamic and blading design of the QF-14 rotor because the flow capacity of blading at a high Mach

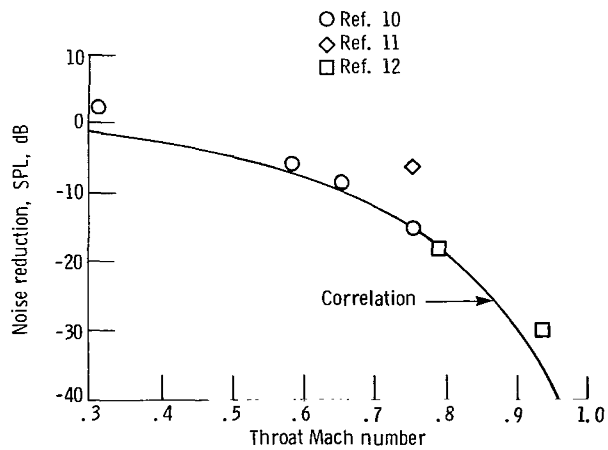


Figure 1. - Correlation and supporting data for noise reduction as function of inlet throat Mach number.

number is critically dependent on the fine details of both the blade design and its manufacture.

The flow path selected for this fan is shown in figure 2. The radial growth of the passage downstream of the rotor was required in this test fan to alleviate flow problems at the inlet to the stator vane at its hub. In an actual engine the rotor hub flow would be ducted into the core compressor without being turned back to the axial direction, thus eliminating the flow problem. In the actual engine the fan bypass duct stator vanes could then be brought to a lower mean radius and the stator tip radius would thus be closer to the rotor tip radius, as is conventional.

Rotor blades.—The rotor blades use conventional multiple-circular-arc sections over the inner 60 percent of the blade span where relative exit Mach numbers are subsonic. The outer 40 percent of the blade span, which has supersonic exit relative Mach numbers, uses airfoil sections of the started-contained-shock (swallowed) type which is shown schematically in figure 3. The minimum critical flow margins along the span varied from 2.1 to 4.5 percent, which was considered adequate to permit the unusually high design through-flow. The blade dampers conventionally used on high-speed fans to inhibit destructive blade vibration would have blocked enough flow area to prevent the attainment of the required high specific flow rate. Therefore, the rotor blades were designed with a lower aspect ratio (1.58 based on true mean chord and average span) to tune the low-order natural frequencies of vibration out of the ranges where excitation during normal operation would likely occur. Further detailed information on the design of the rotor blades can be found in reference 4. It should be noted here that the reference indicates that the titanium rotor blades were inserted into slots in a steel wheel. The rotor assembly actually tested used an alternative construction with the wheel and blades machined integrally from a titanium forging. A photograph of the wheel assembly is shown in figure 4.

Stator vanes.—The stator vane number was selected based on an analysis of the noise generated by interaction of the vane leading edges with the incoming rotating pattern of rotor blade wakes. As the vane number was decreased, with solidity remaining constant and thus chord increasing, the analysis indicated a continual decrease in both broadband and discrete tone noise. Based on these results, with consideration for a practicable maximum chord length in the test facility, the designer chose to use 10 vanes. At the approach condition, with low pressure ratio at design speed, the higher rotor-exit volume flow and the lower absolute swirl angle combine to choke the flow at the inlet of the

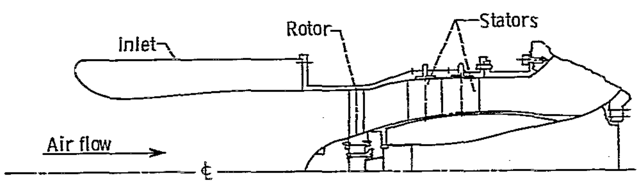


Figure 2. - Cross-section of QF-14 fan and inlet.

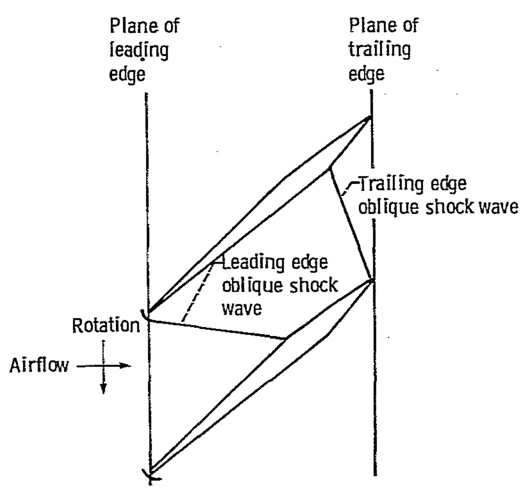


Figure 3. - Schematic diagram of started-contained-shock rotor blade section.

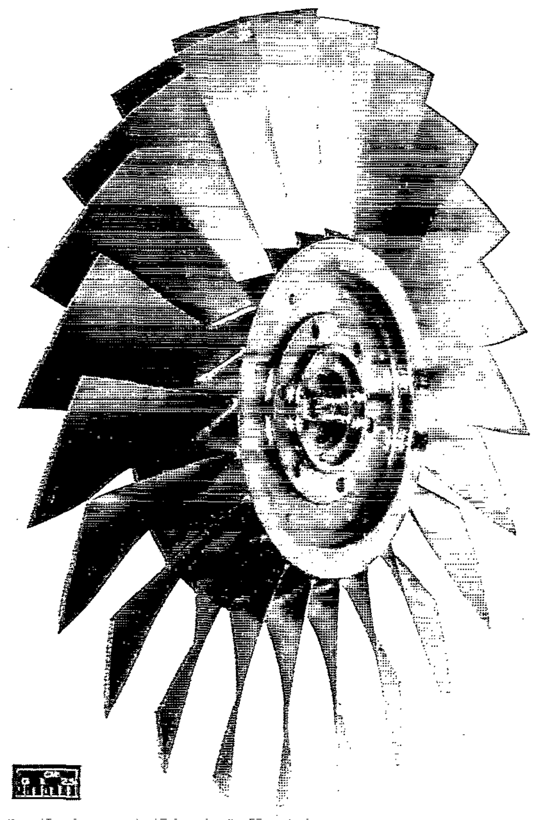


Figure 4. - QF-14 rotor viewed from upstream.

stators as designed. To alleviate this very undesirable condition some variable setting angle feature was required in the stators. The designers elected to split each long chord stator vane into two tandem stator vanes alined leading edge to trailing edge at the design (or takeoff) point and to open the forward vanes about 25° and the rearward vanes about 5° at the approach operating point. Analysis indicated this reset would allow the design flow to pass and that any increase in the reset angle would tend to increase the rearward-radiated noise. Figure 5 (from ref. 4) indicates the relationship of the two vane rows at both the design and approach operating points. A photograph of the vanes in the casing at the design setting angles is shown in figure 6.

The major items in the aerodynamic design of this fan of interest to the present acoustic investigation are summarized in table I. More detailed information can be found in references 3 and 4.

Apparatus and Procedure

Test Facility

The fan shown in figures 4 and 6 was installed for acoustic testing in the Lewis engine fan and jet noise facility that has been described in detail in reference 5. Figure 7 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 figure 8. Calibration of the chamber indicated that it can be considered anechoic within 1 decibel at frequencies above 500 hertz (ref. 5). The chamber may be operated with inlet flow either through the silencer (shown in fig. 8) 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 a speed-increasing gearbox located in an acoustically isolated room. The fan discharged 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. In addition, the fan inlet and discharge ducts each have a dynamic pressure sensor mounted flush with the duct wall.

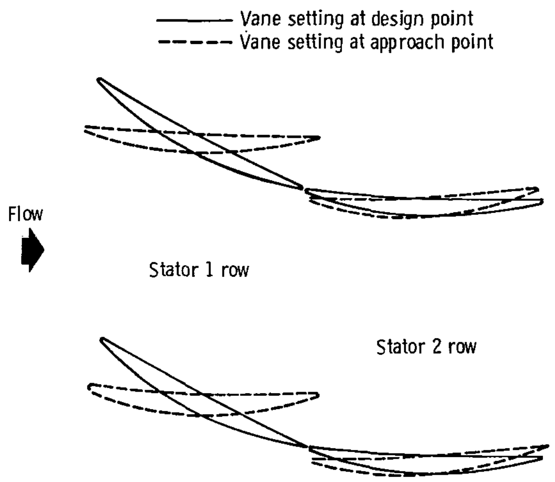


Figure 5. - Tandem stator vane relationship of QF-14 fan.

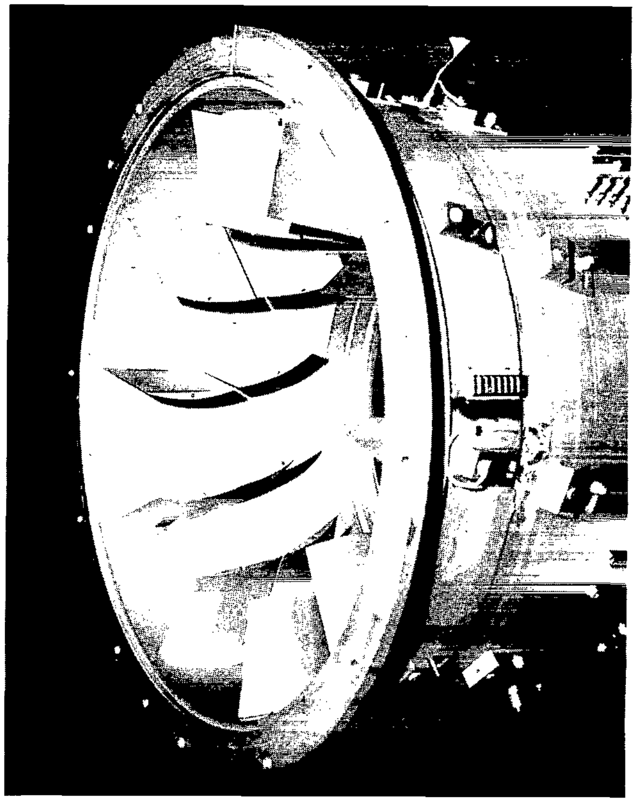


Figure 6. - QF-14 Stator assembly viewed from downstream.

TABLE I.—QF-14 FAN DESIGN CHARACTERISTICS

Total-pressure ratio	1.653
Rotor-tip diameter, m (in.)	0.508 (20)
Tip speed, m/sec (ft/sec)	533.4 (1750)
Hub-tip radius ratio	0.426
Stage adiabatic efficiency	0.839
Total flow, kg/sec (lb/sec)	36.45 (80.4)
Inlet specific flow, kg/sec-m^2 (lb/sec-ft^2)	219.7 (45.0)
Number of rotor blades	22
Number of stator vanes (each of 2 rows)	10
Rotor-tip inlet relative Mach number	1.797
Shaft speed, rpm	20 054
Rotor blade passage frequency, Hz	7353

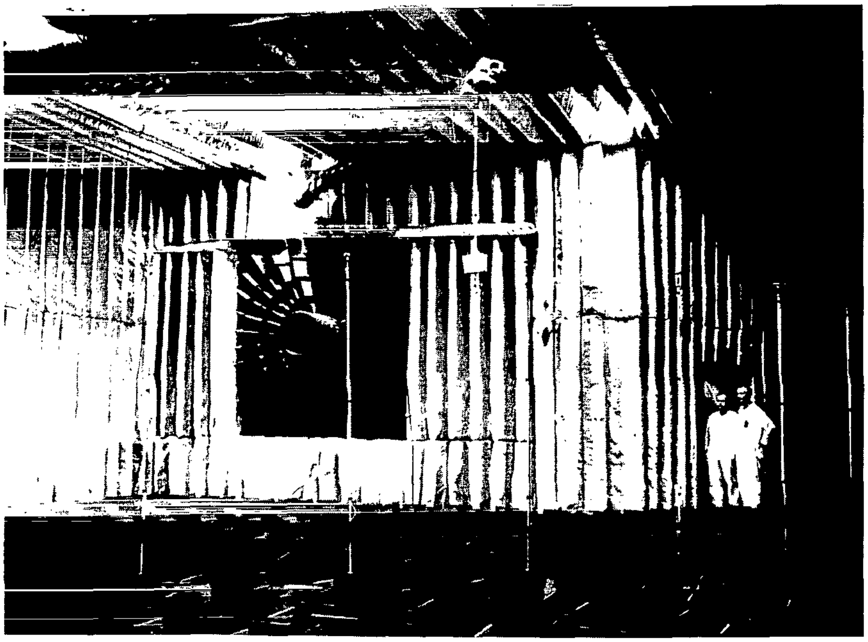


Figure 7. - Fan in acoustic test facility.

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 5. 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 9 and 10. For the present tests the inflow control device had an added inner layer of screen for additional turbulence reduction. This is shown in the diagram of the device in figure 10.

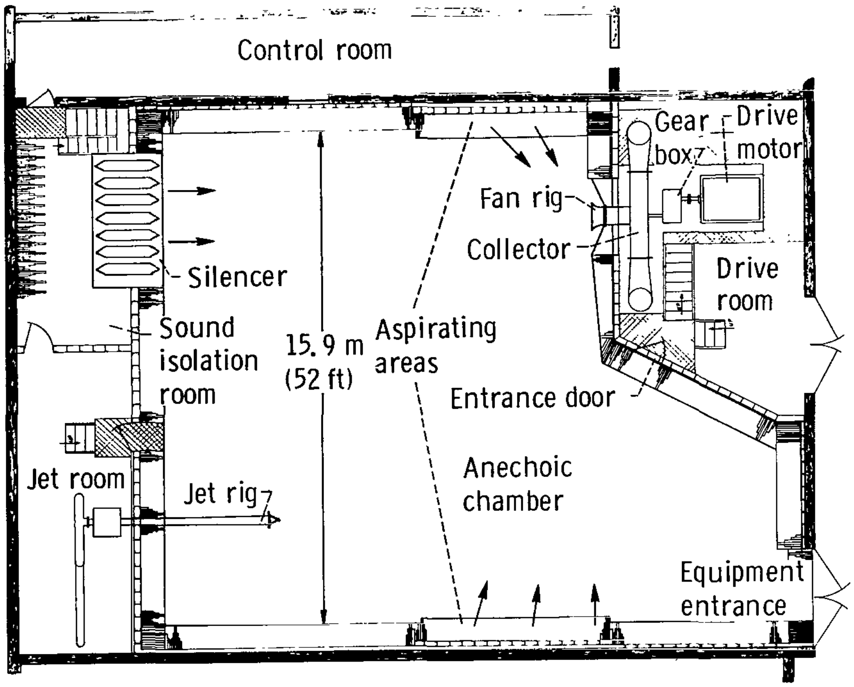
Although the testing of this fan was primarily for acoustic evaluation, sufficient aerodynamic instrumentation was provided to establish the overall operating point and to permit an approximate assessment of the fan's overall aerodynamic performance. The instrumentation included thermocouples and static 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. In addition, a brief investigation was made into the flow conditions in the annulus between the rotor and the stator using two radially actuated single-point probes. One probe measured total pressure, total temperature, and flow angle, while the other measured static pressure. 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

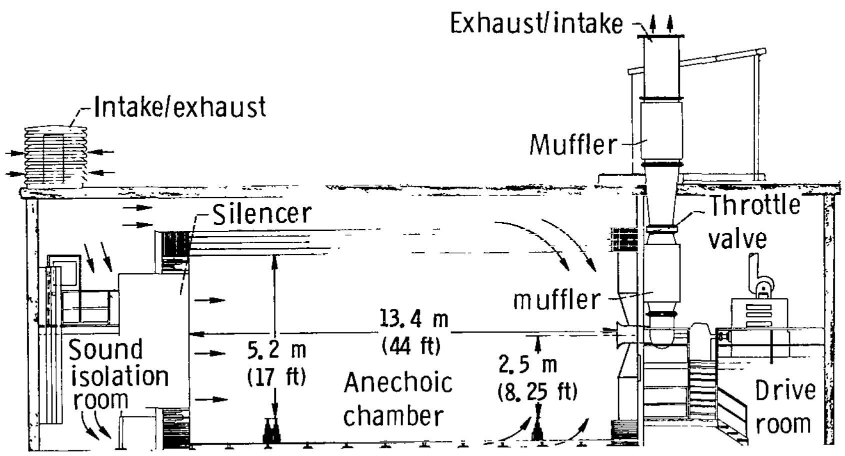
Each combination of an operating line with a particular inlet hardware set and with given stator vane setting angles was considered to be a specific test configuration. The fan was operated in each test configuration over the speed range from 60 to 100 percent of design in 5- or 10-percent increments, with the exception of several configurations for which fewer speed points were run.

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 three of the rotor blades and one stator vane in each row 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.



(a) Noise facility floor plan.



(b) Noise facility elevation.

Figure 8. - Anechoic chamber.

Acoustic data were obtained concurrently with the aerodynamic data. Three samples of the signals from each fixed microphone 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 off-line by computer using the analysis programs detailed in reference 7. Simultaneously with the online analysis, the microphone outputs were also recorded as analog signals on magnetic tape for offline analysis as desired.

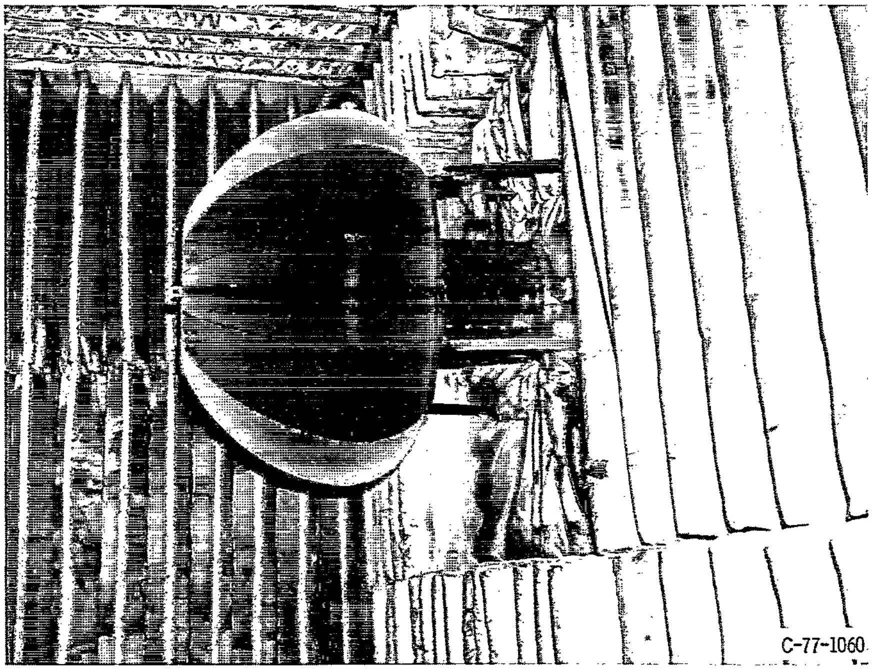


Figure 9. - Inlet flow control device installed on research fan in anechoic chamber.

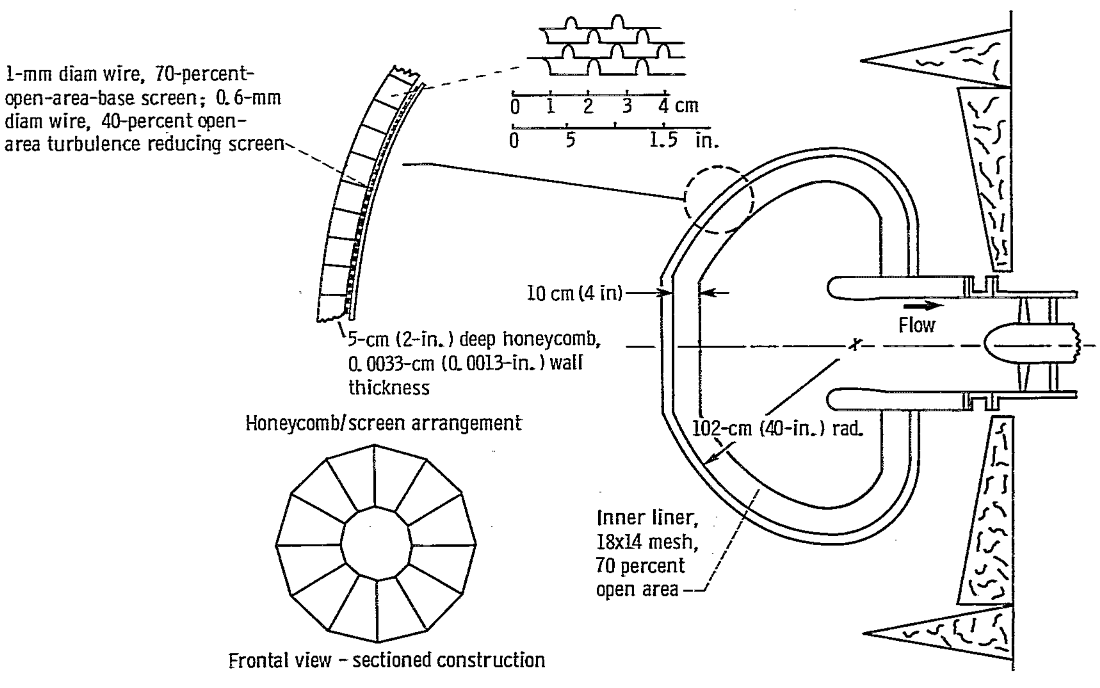


Figure 10. - Inlet flow control device.

Results and Discussions

Aerodynamic Performance

A reasonable assessment of the acoustic performance of a fan in comparison with the acoustic expectations of its design requires knowledge of its aerodynamic performance in comparison with the design. It must be determined if there are any differences between the aerodynamic design and performance, and if so, how they would be expected to affect the noise generation process and relate to the measured noise characteristics. While the amounts of aerodynamic data obtainable in the acoustic test facility do not yield a thorough aerodynamic

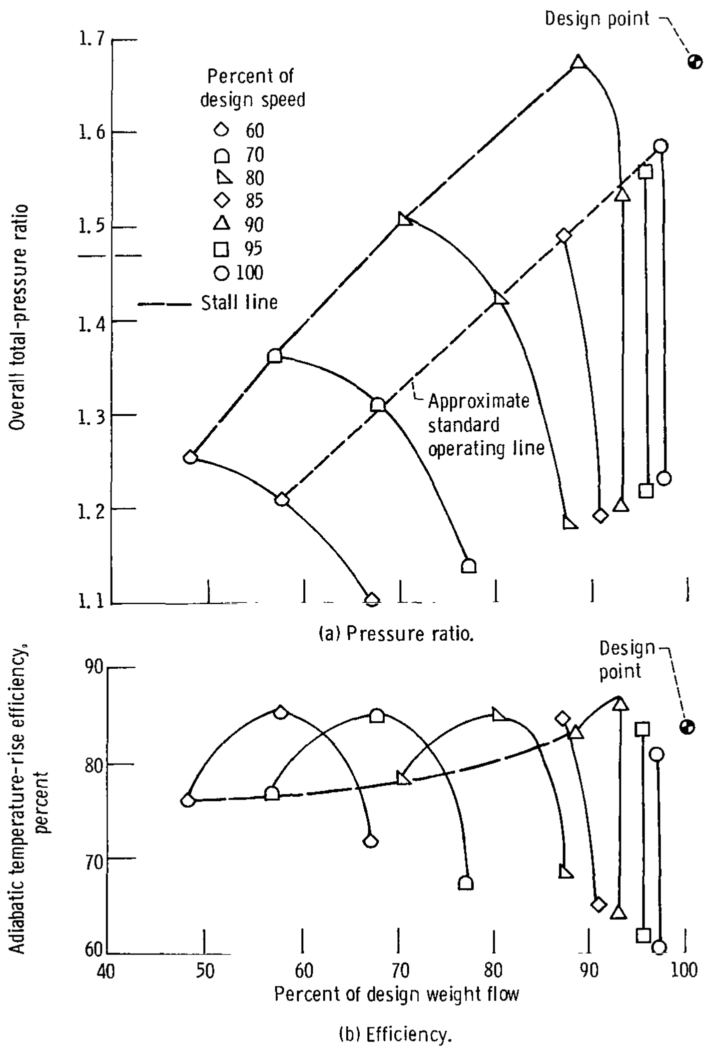


Figure 11. - Overall aerodynamic performance of OF-14 fan.

evaluation, they do permit an overall evaluation of the fan performance and a few pertinent details.

Figure 11 presents the fan stage overall aerodynamic performance without the inflow control device as curves of the total-pressure ratio and adiabatic efficiency against percent of design corrected inlet flow for various speeds. The flow capacity of the fan at design speed is about 3 percent below design. This low flow will reduce the rotor-inlet average Mach number from the design value of 0.714 to about 0.69, which would be expected to result in slightly less noise reduction. The acoustic data to be presented should be viewed with this potential for improvement in mind. Although insufficient data are available to define the peak efficiency at high speeds, it is apparent from figure 11(b) that the fan does exhibit generally good efficiencies and that the design efficiency at design speed is likely to be attained.

Figures 12 to 14 present radial gradients at the stator outlet of overall total-pressure ratio, overall total-temperature ratio, and overall efficiency, respectively, at the operating point closest to design at design speed and compare them with design gradients. The fan overall pressure ratio at this point was slightly lower than design (fig. 11(a)), which results in the difference in general level between design and data in these figures. While acknowledging the small number of data measurements represented in these calculated figures, it can be seen that the gradient of energy addition is reasonably close to design (fig. 13) and that the efficiency is quite good except at the end-walls (fig. 14). Figure 12 indicates that the total-pressure ratio across the stage is low near the walls and drops particularly sharply near the tip.

Figure 15 presents the radial gradient of total-pressure ratio across only the rotor equivalent to the stage pressure ratio of figure 12. At design speed the values are essentially the same as displayed for the stage except for a higher value across the rotor at the hub. This indicates that at design speed the stage total-pressure loss at the tip

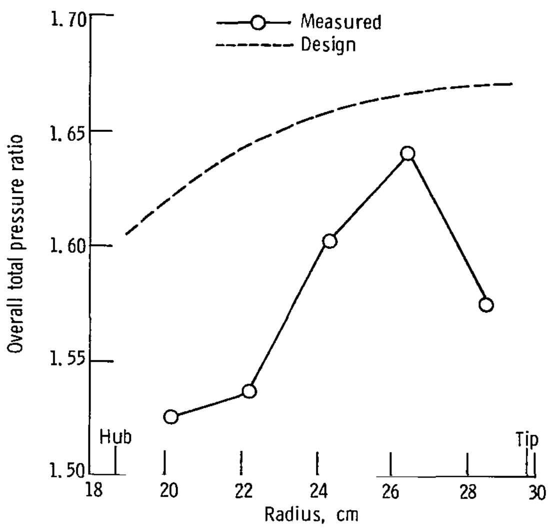


Figure 12. - Radial variation of QF-14 fan overall total pressure ratio on standard operating line at design speed compared with the design prediction.

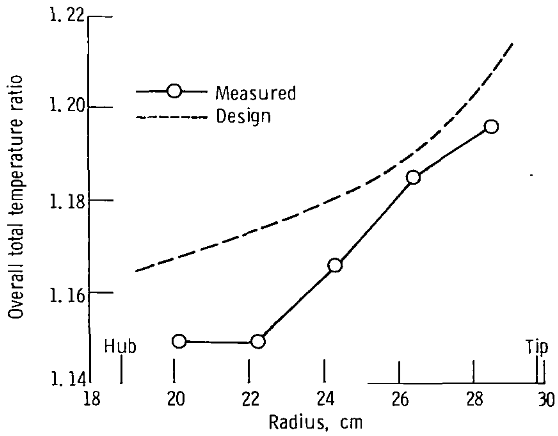


Figure 13. - Radial variation of QF-14 fan overall total temperature ratio on standard operating line at design speed compared with design prediction.

is caused by the rotor, while that at the hub is caused by the stator. It is interesting to note in figure 15 that, at speeds below design, the rotor-tip loss does not exist, which indicates that this loss is associated with high flow at design speed. The rotor temperature ratio distribution at design speed shown in figure 16 is close to design. The measured absolute flow angles into the stator shown in figure 17 referenced to the axial direction follow design quite well except near the tip. There is a marked change in angle near the tip at design speed compared with the lower speeds. This behavior is much the same as that of the rotor pressure loss, and both undoubtedly result from the details of the interblade flow in the rotor-tip region. It would seem likely that the noted discrepancies from design of the rotor-tip region interblade flow are related to the 3 percent reduction in flow from design.

The observed performance discrepancies from the aerodynamic design of the QF-14 fan are not serious for

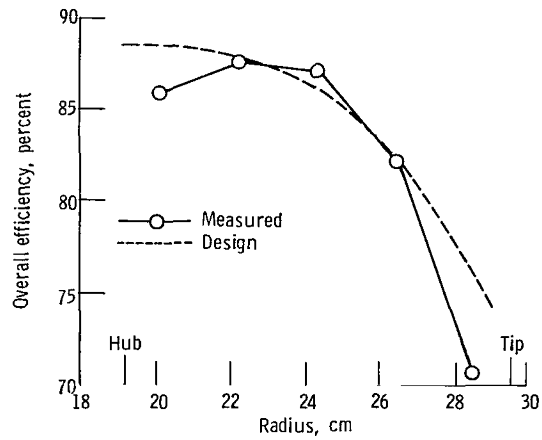


Figure 14. - Radial variation of QF-14 fan overall efficiency on standard operating line at design speed compared with design prediction.

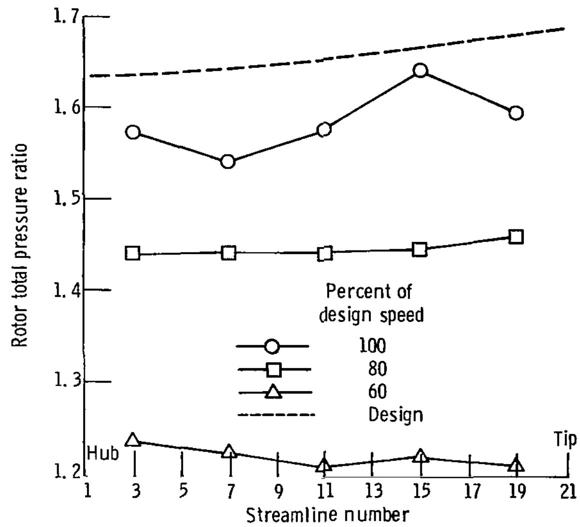


Figure 15. - Radial variation of measured rotor total pressure ratio of QF-14 fan on standard operating line.

the first build of a new design. They would not be expected to have a major effect on the noise generated by the fan, although a measurable effect could exist in the multiple-pure-tone-noise resulting from rotor leading-edge shocks, which are sensitive to small flow deviations from design within the rotor.

Acoustic Performance

Noise component resolution.—The three components of noise (broadband, blade-passage tone, and multiple pure tone) are seen in figure 18, which presents narrowband (80-Hz bandwidth) sound-power spectra of the QF-14 fan at five speeds. The tones at blade-passage frequency and its harmonics are particularly obvious at 60 and 70 percent of design speed, above the broadband

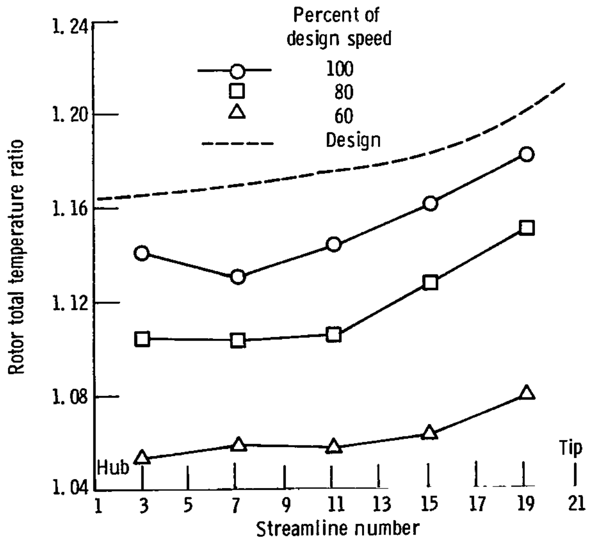


Figure 16. - Radial variation of measured rotor total temperature ratio of QF-14 fan on standard operating line.

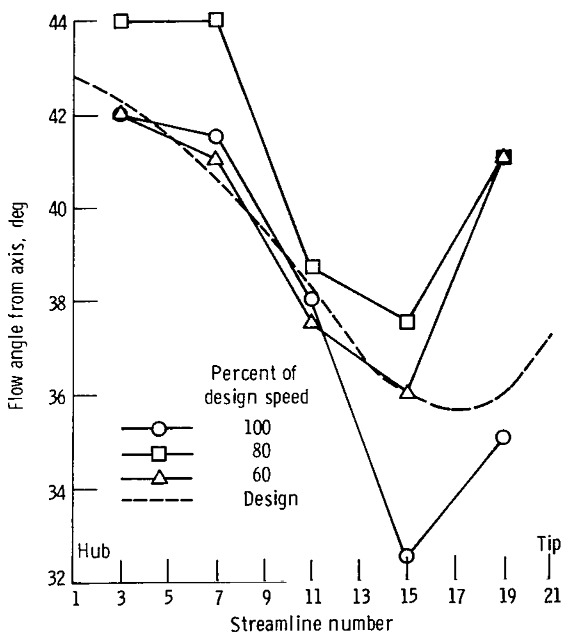


Figure 17. - Radial variation of stator inlet flow angle of QF-14 fan on standard operating line.

and multiple-pure-tone level. As the speed is increased, the blade-passage tone and harmonics decrease in level, and the broadband level increases slightly and then decreases again at design speed. Although the multiple pure tones do exist in each of the spectra (they are small enough in the 60 percent speed spectrum to be difficult to see in the reduced-size presentation of figure 18), their prominence increases rapidly above 70 percent speed. It is interesting to note that the general level of the spectrum and its features decrease as the speed is increased from 90 to 100 percent of design.

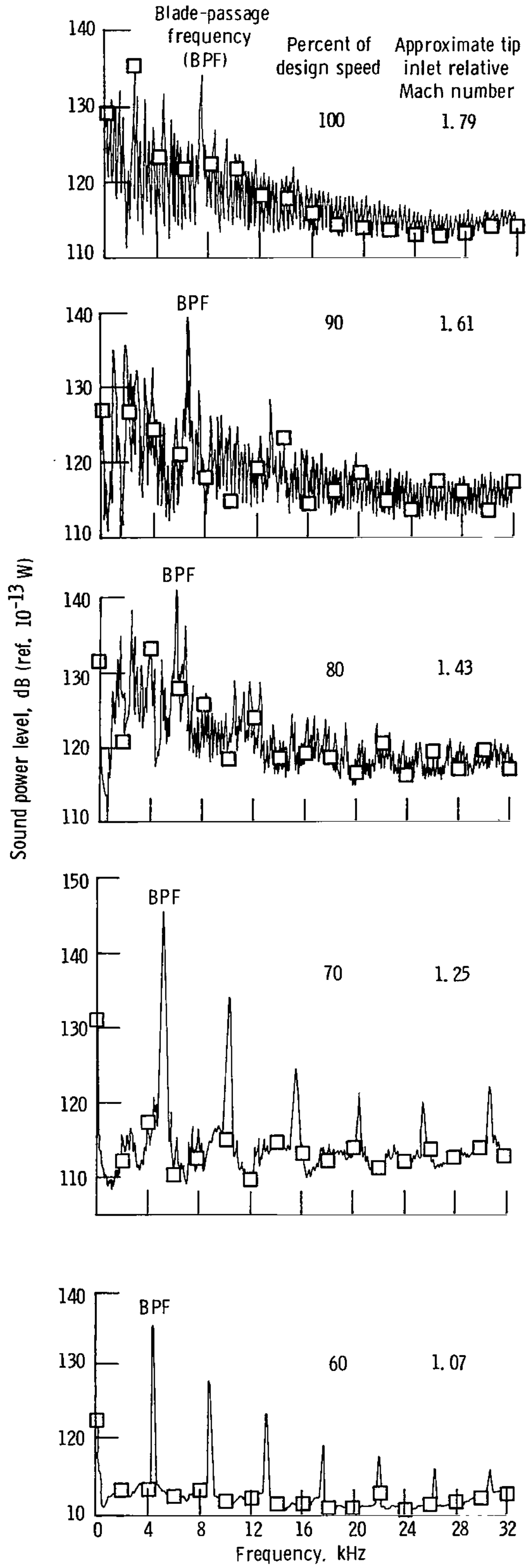
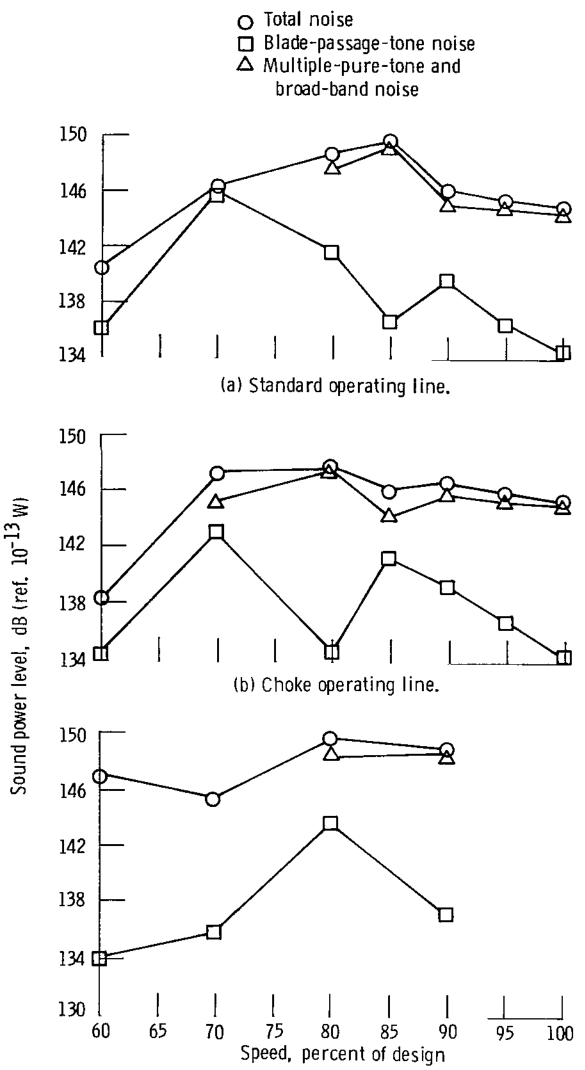


Figure 18. - Narrow band sound power level spectra of QF-14 fan on standard operating line without inflow control device.



(c) Stall operating line.

Figure 19. - Blade-passage and multiple-pure-tone noise components of QF-14 fan at several operating conditions.

Figure 19 presents total sound power and the narrowband sound power of the blade-passage tone and its harmonics as a function of fan speed on each of the three operating lines: standard, choke, and stall. In addition, there are sound power levels presented labelled as multiple-pure-tone noise, which are obtained by subtracting the noise of the blade-passage-tone and its harmonics from the total noise and which, therefore, include the broadband noise. These subtractions are presented only at the high speeds where multiple-pure-tone noise predominates over the broadband noise. Their levels are in general from 1 to 2 decibels higher than the true multiple-pure-tone noise levels, because of the broadband noise contamination. It is interesting to note that the total noise rises to about 80 or 85 percent speed, then drops several decibels to a lower level from which it falls much more slowly with increasing speed. The same behavior was noted with the fan of reference 1 wherein the rapid drop was attributed to the swallowing of the rotor leading-edge shock into the blade channel to form the design, weak oblique shock system. The QF-14 fan uses basically the same design rotor shock system, so it seems likely that the rapid drop in noise with increasing speed is also the result of initiation of the design rotor shock system.

It is also interesting to note that the blade-passage tone is decreasing at a fairly uniform rate with increasing speed above 70 percent of design, except for a rapid increase in this component coincident with the decrease in total noise over the speed range from 85 to 90 percent (fig. 19(a)) or from 80 to 85 percent (fig. 19(b)). At speeds below about 80 percent of design with the fan heavily loaded aerodynamically near stall, the noise is dominated by the broadband component (fig. 19(c)). From figure 19 it is obvious that, at speeds at or above about 80 percent of design, the multiple-pure-tone noise is the largest component and controls the total noise levels.

***Comparison with other high-speed fans.*—An adequate assessment of the noise producing characteristics of the QF-14 fan must involve a comparison with other fans of similar overall aerodynamic performance characteristics. For this purpose three fans have been selected that have tip speeds as close as possible to that of QF-14 and that thus should have about the same mix of noise generating mechanisms. The disparity of pressure ratio among the four fans is small enough that noise comparisons will still be valid. All of these fans are of modern design and incorporate various design features that are intended to minimize one or more components of the noise. A brief summary of pertinent aerodynamic design parameters for the four fans is presented in table II. A brief description of the fans' design features follows.**

The JT8D Refan is a scale model in 0.5-meter size of the full-scale JT8D Refan which was designed as a modernized, quieter replacement fan for the JT8D engine fan (ref. 5). The JT8D Refan has inlet guide vanes which were designed to lessen the radial gradient of rotor-inlet relative Mach number. The consequent lowering of the tip relative Mach number would slightly weaken the normally strong leading-edge shocks and, thus, could be expected to somewhat lessen the multiple-pure-tone noise generation. In addition, the presence of the guide vanes constitutes a flow area blockage that 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 four 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-13 and QF-14 fans.

TABLE II.—DESIGN SUMMARY FOR HIGH-TIP-SPEED FANS

Fan	Tip speed, m/sec (ft/sec)	Tip diameter, m (in.)	Pressure ratio
QF-14	553 (1750)	0.508 (20.0)	1.653
QF-13	489 (1603)	.508 (20.0)	1.5
JT8D Refan	488 (1600)	.508 (20.0)	1.67
GE-ATT	503 (1650)	.904 (35.6)	1.8

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 larger in diameter than the other three fans. Its noise data are reported in reference 8.

The QF-13 fan has a somewhat lower design pressure ratio than the other fans under consideration here. It was designed at a conventional level of inlet specific flow with swallowed, weak oblique shocks in the rotor tip region. It actually attained a specific inlet flow slightly higher than design, though not as high as that of the QF-14 fan. An evaluation of its forward acoustic performance is presented in reference 1.

The JT8D Refan and the QF-13 and QF-14 fans were all tested in the same facility and used the same inlet assembly with simulated flight-type internal contours. The GE-ATT fan was tested by the contractor in another facility and used a bellmouth inlet.

The forward acoustic performances of the four fans are compared in figure 20, which presents the thrust-corrected sound power level of each fan at speeds from 60 to 100 percent of design as a function of pressure-rise ratio on the standard operating line. The correlation is taken from reference 9 and was obtained for the total noise of fans with subsonic tip speeds. It has been used before (e.g., ref. 1) as a convenient basis for comparing the forward noise data of fans having supersonic tip speeds even though not all the noise-affecting mechanisms of such fans are represented in the correlating equation. At the lower speeds (lower pressure ratio) the QF-14 fan is quieter than the JT8D Refan and GE-ATT fans (fig. 20) but noisier than the QF-13 fan, which had been shown in reference 1 to be exceptionally quiet at low speeds. In the intermediate speed range the four fans produce about the same amount of noise.

At high speed the four fans exhibit quite similar rates of noise decay with increasing speed. However, QF-14 has the lowest level of forward noise propagation to the far field. If the 90-percent speed points are assumed to represent conventional takeoff operating points, then QF-14 is quieter at takeoff than QF-13 and JT8D Refan by about 4 decibels and quieter than the GE-ATT fan by about 9.5 decibels. While the reference fans were designed for conventional takeoff operation at about 90 percent speed, QF-14 was designed for takeoff at 100 percent speed. On this basis QF-14 at takeoff is quieter than QF-13 and Refan by about 5.5 decibels and quieter than the GE-ATT fan by about 11 decibels. Although the effect of high axial Mach number at the fan face cannot be completely isolated from other noise-affecting mechanisms, it appears from these comparisons that the high Mach number has had an appreciable beneficial effect in reducing forward noise.

Approach-condition forward noise.—During landing approach a turbofan engine's thrust must be reduced to about 30 to 50 percent of the takeoff thrust value.

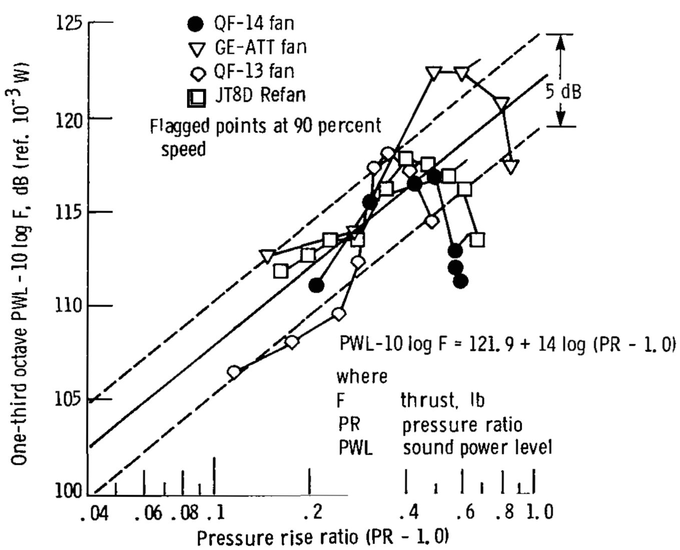


Figure 20. - QF-14 and other high-tip-speed fan inlet sound power levels without inflow control devices on correlation of total noise from low-tip-speed fans.

Conventionally, this is done by decreasing the fan speed to about 60 percent of design. The QF-14 fan concept maintains design speed at approach and reduces thrust by reducing the fan pressure ratio to about 1.15. This requires a fan exhaust nozzle that can be opened to reduce the back pressure on the fan and stators that can be opened to permit passage of the higher-than-design volume flow from the rotor. The test program on the QF-14 fan was ended by a drive system failure before the approach operating condition could be reached, so a precise evaluation of the fan's approach noise was not possible. However, some inferences about the approach noise can be drawn from data obtained during choked operation of the fan at design speed with the stators in the design position. The pressure ratio was 1.23 at this point (fig. 11(a)), and the thrust was about 66 percent of the design point value. To evaluate the QF-14 concept, the noise at this simulated approach condition should be compared with the noise found on the standard operating line at a speed that yields the same fan thrust. Figure 21 presents the fan thrust on the standard operating line and at the simulated approach point. The simulated approach point thrust is equaled on the standard operating line at 77 percent of design speed. The nearest point at which noise data were obtained is at 80 percent of design speed, and it is these data that will be used to represent the conventional approach noise.

Figure 22 presents narrowband spectra of sound power level for the QF-14 fan at the two approach conditions and at the takeoff condition for comparison. The takeoff and design-speed approach spectra (figs. 22(a) and (b)) are very similar. Although the broadband noise, as represented by the lower envelope, is somewhat different, the tonal features are almost identical, with nearly every shaft order tone maintaining its individual level. Clearly,

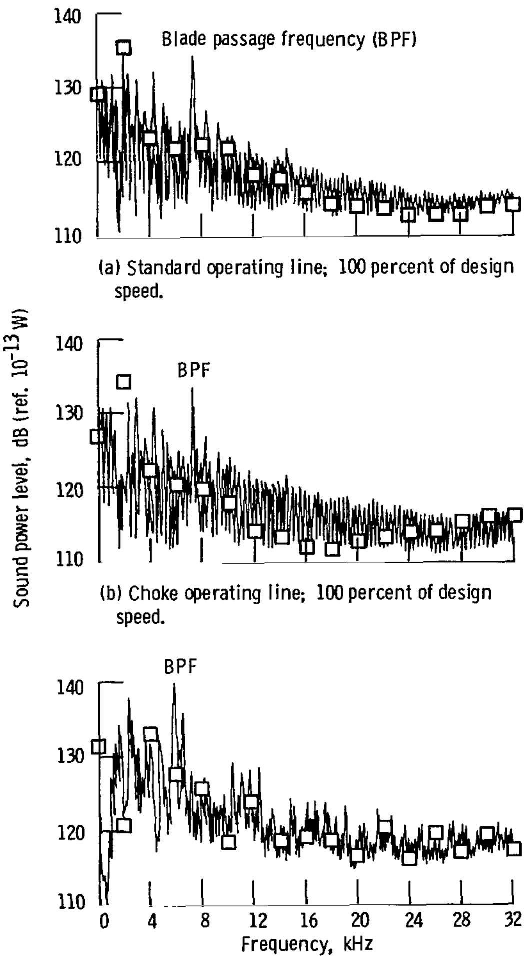


Figure 22. - Sound power spectra of QF-14 fan at three different operating conditions.

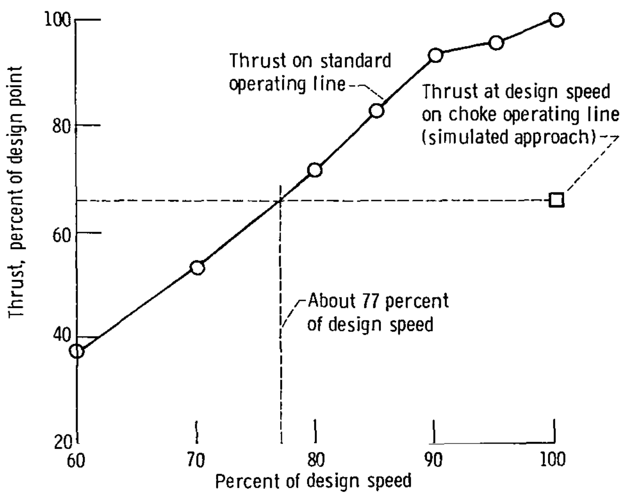


Figure 21. - Measured thrust of QF-14 fan on standard operating line and at the simulated approach operating condition.

the only significant spectral effect of this wide variation in aerodynamic loading is on the broadband noise component, with the lower loading of the simulated approach point causing a slightly lower broadband noise level. These effects are not unexpected because, with the speed and total flow remaining the same, the noise-producing aerodynamic conditions at the rotor inlet remain about the same, and noise generated downstream of the rotor cannot propagate forward through the rotor's internal shock field. A comparison of the conventional and design-speed approach sound power spectra (figs. 22(c) and (b)) indicates that the design-speed approach mode yields much lower broadband and blade-passage tone noise components, and apparently slightly lower multiple-pure-tone noise. The broadband spectra, the lower envelopes in the spectra of figure 22, are presented in figure 23 without their fine structure to indicate the major differences. The design-speed

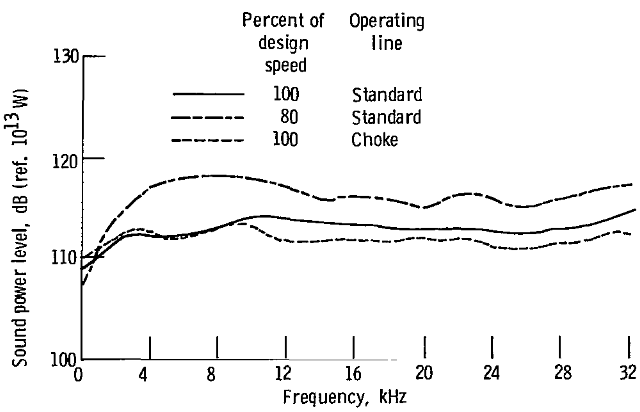


Figure 23. - Comparison of QF-14 forward broadband noise at three operating conditions.

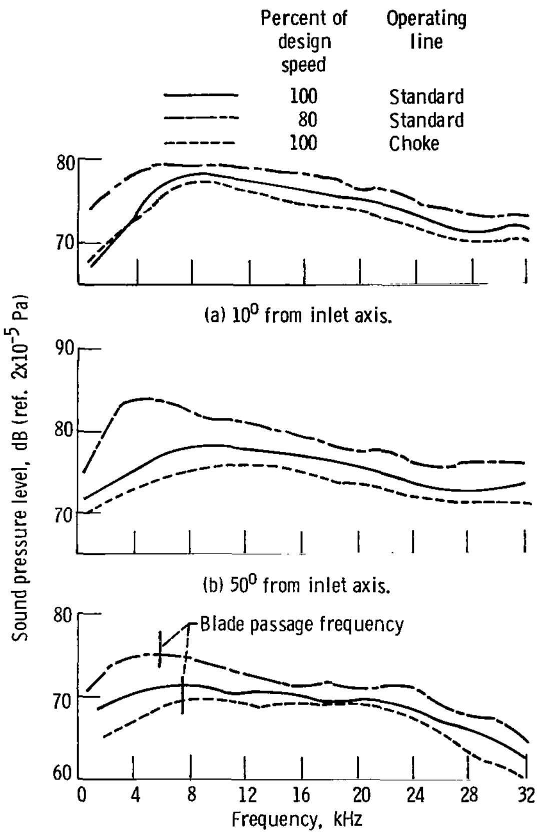


Figure 24. - Broadband sound pressure level spectra of OF-14 fan at three operating conditions.

simulated approach mode exhibits some 3 to 6 decibels less noise over nearly the entire spectrum when compared with the conventional mode. It also indicates a 1- to 2-decibel reduction from the takeoff operation mode at frequencies above blade-passage frequency. Figure 24, which presents related broadband sound pressure level spectra at three selected azimuth angles, indicates that the loading and speed effects on broadband noise noted from figure 23 are fairly well distributed over the forward arc. The smallest effect of loading and largest effect of speed change on broadband noise is at frequencies below blade-passage frequency.

The narrowband noise at the blade-passage-frequency for each of the three operating conditions under discussion is shown in figure 25 as a function of azimuth angle. As with broadband noise, the blade-passage-tone noise for the design-speed approach condition is notably lower (some 3 to 12 dB) than that for the conventional approach condition. The greatest differences are toward the sideline which would yield the maximum benefit to a ground-based observer. The effect of loading difference at design speed on blade-passage-tone noise is small, about a 1- to 2-decibel reduction near the axis with a reduction in loading.

A summary of the noise comparison between the two modes of approach operation is shown in figure 26 as overall sound power levels. The total sound power level of the design-speed approach is about 3 decibels lower than the conventional approach.

The comparisons made here of the noise differences between the two approach modes require a strong qualification. First, if the thrust of the conventional mode is reduced to a more normal value of about 40 percent of design, the noise is reduced about 7 decibels. Second, if the thrust of the design-speed approach mode is reduced to the 40 percent level by opening the stator vanes, the associated noise might be expected to reduce because of both the lower loading and the better aerodynamic matching of the stators with the incoming flow. This reduction, however, could be very small if the aerodynamic effects of loading and stator matching on the flow in the rotor blade entrance region are not appreciably affected. Whether this reduction in noise of the design-speed approach mode will be more or less than the 7-decibel reduction of the conventional approach mode is unknown at this time, so a final evaluation must await further tests.

Front-to-rear division of noise.—Although the test facility only permits the studying of either front or rear arc noise in the far-field at one time, it was possible to study the division of noise propagation between the front and the rear from dynamic pressure transducers mounted flush with the wall in the inlet and discharge ducts close to the fan. Spectra obtained from these two transducers at various speeds along the standard operating line are shown in figure 27.

At the lowest speeds and with exception of the very low frequencies, the broadband and tone noise components are both highest in the inlet duct. As speed is increased from 60 to 70 percent of design, the inlet blade-passage-tone and multiple-pure-tone components rise, while the broadband noise appears to remain reasonably constant. In the rear duct both tone and broadband noise rise with

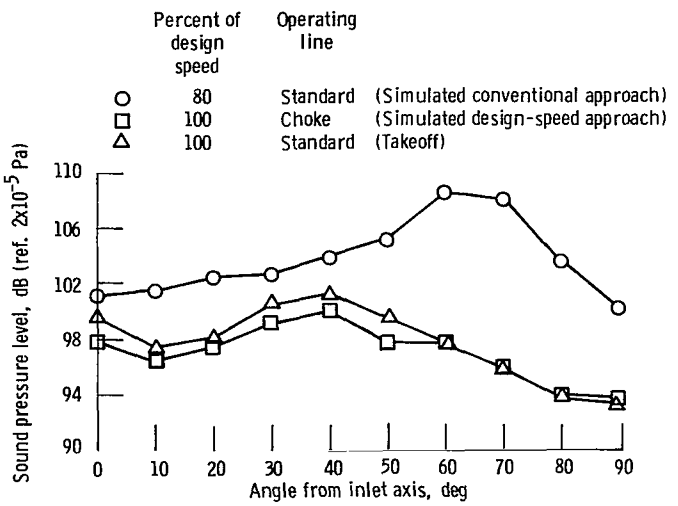


Figure 25. - Narrowband blade-passage-tone noise of QF-14 fan at three different operating conditions.

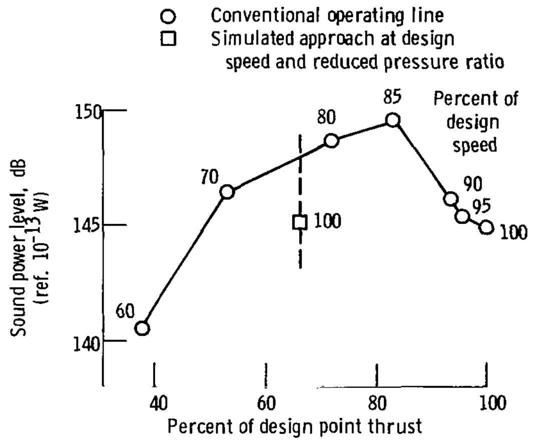


Figure 26. - Comparison of inlet sound power level of QF-14 fan using two different methods of reducing thrust ot simulate the approach condition.

speed. With speed increased to 80 percent of design the inlet blade-passage-tone noise decreases noticeably; the multiple-pure-tone noise increases considerably and becomes more evenly distributed in level among groups of tones; and broadband noise also increases, particularly at lower frequencies. The rear-duct blade-passage-tone noise increases as does broadband noise, which is now higher than inlet broadband noise at high frequencies. From 80 to 90 percent of design speed the inlet blade-passage-tone noise remains constant, although the overtones decrease in level, broadband noise appears to decrease somewhat, and multiple-pure-tone levels remain about the same. In the rear, both tone and broadband levels increase greatly, and some multiple-pure-tones begin to appear. From 90 to 100 percent of design speed all components of inlet noise decrease, while all components of rear noise increase and appear to be some 10 to 25 decibels above the corresponding inlet components except for multiple-pure-tones at the lowest frequencies.

With all forward components of noise decreasing and all rearward components increasing, it appears that at high speeds, with the incoming axial Mach number at the rotor approaching the design value, the noise is being diverted from the front to the rear. This, in combination with the observation (fig. 20) that the QF-14 fan has lower design-speed noise than the reference fans, verifies the forward-noise design concept of this fan. While it is not possible to make an exact quantitative evaluation of the concept without a reference fan identical in its aerodynamic and noise generation properties, yet having a lower level of inlet axial Mach number, it has been shown that the concept is at least qualitatively a success. From the actual forward noise advantage shown in figure 20, the forward noise reduction concept of the QF-14 fan appears to be not only proven, but also of useful magnitude.

Effect of inflow control device.—The inflow control device is designed to reduce the turbulence and some distortions in the fan inflow which are typical of static test facilities and thus to reduce the spurious blade-passage-tone noise generated by the interaction of these flow imperfections with the fan rotor. It has been shown to be beneficial in this respect with lower speed fans (refs. 1 and 6) and was used during limited tests of the QF-14 fan to find its effect on this high-speed fan. Figure 28 indicates the effect by comparing blade-passage-tone sound power levels at various speeds on the standard operating line both with and without the inflow control device. With the exception of some 0- to 6-decibel differences in the 82- to 90-percent speed range, the inflow control device lowers the blade-passage-tone noise about 2 to 4 decibels over the entire speed range. The reduction over most of the tested speed range is probably

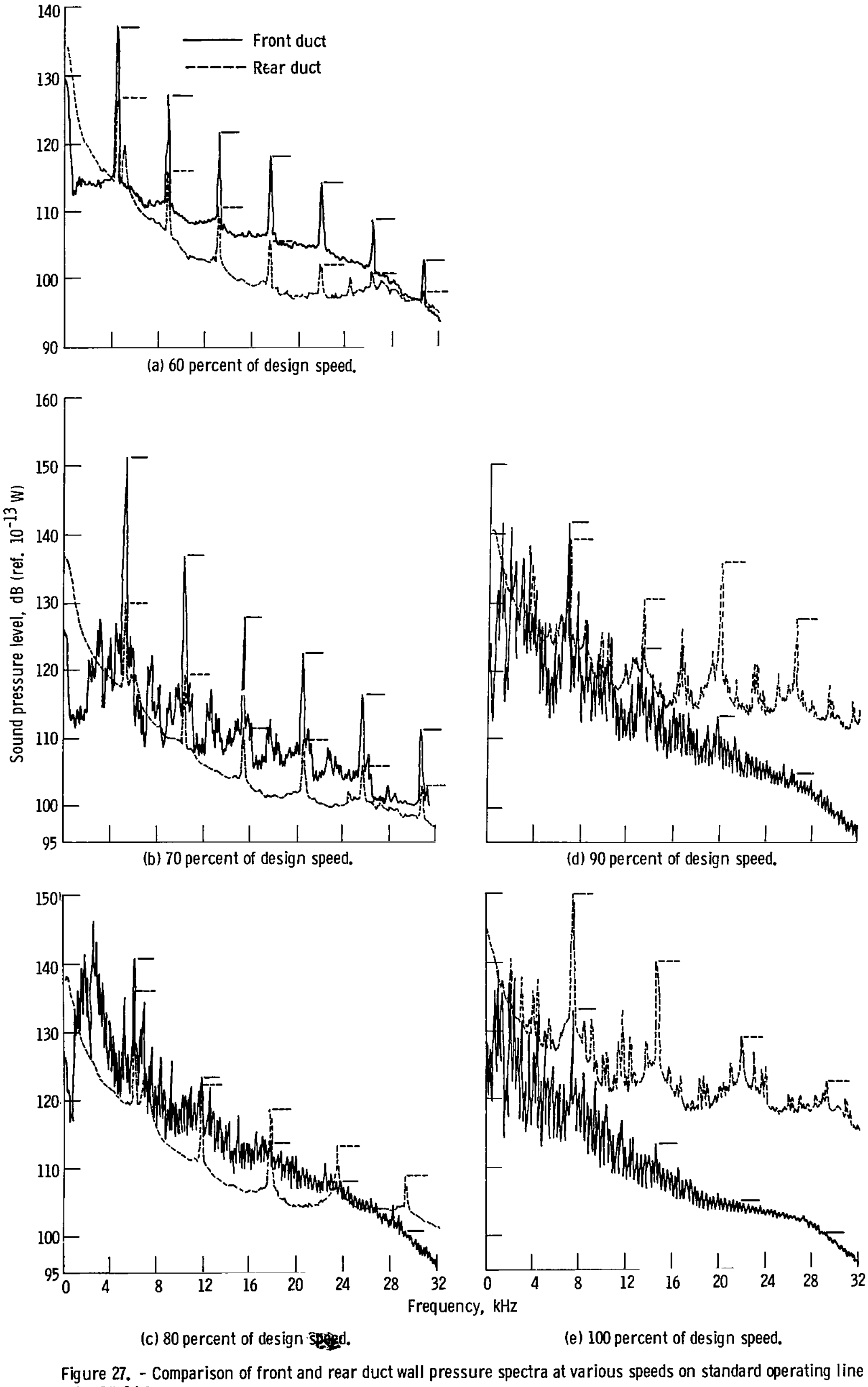


Figure 27. - Comparison of front and rear duct wall pressure spectra at various speeds on standard operating line for QF-14 fan.

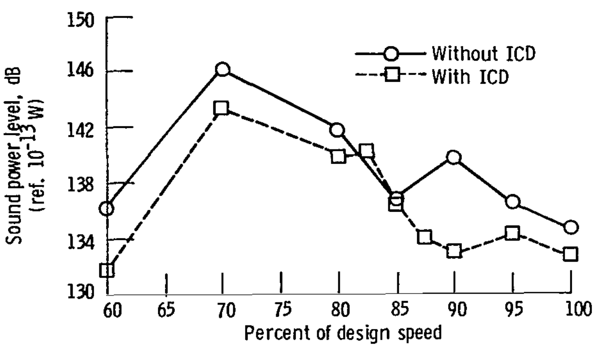


Figure 28. - Effect of inflow control device (ICD) on forward blade-passage tone noise of QF-14 fan on standard operating line.

due simply to interaction of the rotor with the less turbulent inflow, although one could speculate that the 6-decibel reduction at 90-percent speed possibly results from an alteration of the starting of the design rotor shock system by the lower turbulence.

Summary of Results

A high-tip-speed fan designed for exceptionally high axial Mach number at the rotor inlet with associated swallowed shocks was tested for its forward noise and aerodynamic performance in an anechoic chamber. The following results were noted:

1. The aerodynamic performance of the fan was generally close to its design, although the flow at design speed was about 3 percent lower than design. The flow loss appears to be related to small performance deficiencies near the tip of the rotor.

2. A separation of the forward noise into its components indicates that above 70 percent of design speed the overall noise level is controlled by the multiple pure tones. From 90 to 100 percent of design speed on the standard operating line, the levels of all components in the far-field decrease, apparently indicating that high incoming axial Mach number is inhibiting the forward propagation of takeoff noise.

3. In comparison with other modern, quiet, high-tip-speed fans on an equal thrust basis, the present fan produced 5.5 to 11 decibels less noise at the design takeoff operating point.

4. Although the test program did not include a test of the actual fan approach point, due to a facility failure unrelated to the fan, the data from the condition closest to approach indicated that the design-speed approach mode of this fan is 3 decibels quieter than the conventional mode. Until an assessment of the correct approach point can be made, this result must be considered tentative.

5. As speed is increased from 90 to 100 percent of design, dynamic pressure sensors in the inlet and discharge ducts indicate that all forward noise components decrease and all rearward noise components increase. This appears to add weight to the conclusion that the high Mach number at the rotor inlet face is providing a substantial and useful blockage of the forward propagation of fan noise.

6. The inflow control device reduces the blade-passage-tone noise over the full speed range, except from 82 to 85 percent speed.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 7, 1981

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15. Supplementary Notes

16. Abstract

Forward noise and overall aerodynamic performance are presented for a high-tip-speed fan having an exceptionally high average axial Mach number at the rotor inlet. This high Mach number is intended to attenuate forward noise at both the design-speed takeoff point, and at the unconventional low-pressure-ratio, design-speed approach point. As speed was increased near design, all forward noise components were reduced, and rear noise in the discharge duct was increased, indicating that the high Mach number flow at the rotor face is attenuating forward noise at takeoff. The fan at takeoff is some 5.5- to 11-dB quieter than several reference fans. A facility mechanical failure precluded testing at a true approach condition, but data at the point closest to approach indicated tentatively that the design-speed approach mode was 3 dB quieter than the conventional mode.

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