INLET NOISE OF 0.5-METER-DIAMETER NASA QF-1 FAN AS MEASURED IN AN UNMODIFIED COMPRESSOR AERODYNAMIC TEST FACILITY AND IN AN ANECHOIC CHAMBER

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**Abstract**

Narrowband analyses revealed grossly similar sound pressure level spectra in each facility. Blade passing frequency (BPF) noise and multiple pure tone (MPT) noise were superimposed on a broadband (BB) base noise. From one-third octave bandwidth sound power analyses the BPF noise (harmonics combined), and the MPT noise (harmonics combined, excepting BPF's) agreed between facilities within 1.5 dB or less over the range of speeds and flows tested. Detailed noise and aerodynamic performance is also presented.
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INLET NOISE OF 0.5-METER-DIAMETER NASA QF-1 FAN AS MEASURED IN AN UNMODIFIED COMPRESSOR AERODYNAMIC TEST FACILITY AND IN AN ANECHOIC CHAMBER

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SUMMARY

The inlet noise from a 0.271-scale model (0.5-m or 20-in. diameter) of the NASA QF-1 fan was determined from measurements in the reverberant plenum chamber of an unmodified (i.e., no acoustic treatment) compressor aerodynamic test facility and from measurements in an anechoic chamber. These noise results are presented along with detailed aerodynamic performance recently published. Narrowband (50-Hz) noise analyses revealed grossly similar sound pressure level spectra in each facility. Blade passing frequency (BPF) noise and, at the higher tip speeds, multiple pure tone (MPT) noise were superimposed on a broadband (BB) base noise. Sound power levels were determined from one-third octave bandwidth analyses. On that basis the BPF noise (harmonics combined) and the MPT noise (harmonics combined, excepting BPF's) agreed between facilities within 1.5 dB or less over the range of speeds and flows tested. Trends in the total broadband noise with changes in speed and flow were similar in each facility but comparisons of the absolute power levels are questionable because of differing frequency spectra and maximum frequency limits analyzed.

The satisfactory determination of one-third octave based inlet tone power levels in the same installation and time period that the detailed aerodynamic performance is obtained allows early screening of designs. And coupled with narrowband spectra that are representative of free and far field spectra it also offers the potential for cause and effect relationships between aerodynamic and noise performance.

In the anechoic chamber the BPF noise was highest near peak efficiency operation. It propagated at all speeds despite a design to cut it off at low speeds and despite inlet flow with low free stream turbulence intensity and flow distortion. The MPT noise was only significant at 100 percent design speed where it dominated the spectrum. The broadband noise increased about 6 dB from 60 to 80 percent design speed then decreased about 1 dB from 80 to 90 percent speed, all on a calculated operating line passing through the design point.
Facilities utilized to determine the detailed aerodynamic performance of a fan or compressor are generally unsuitable for free and far field noise measurements. The test package is usually installed between an upstream plenum chamber and a downstream collector and exhaust system which have hard, noise reflecting walls throughout. However, it has been demonstrated (ref. 1) that the usual noise components of blade passing frequency tones, multiple pure tones, and broadband noise can be identified and sound power levels determined from noise measurements in the reverberant field environment of the inlet plenum chamber of an unmodified (i.e., no acoustic treatment) compressor aerodynamic test facility. These data contained no directivity information, no downstream or exit noise measurements, and were for rotors with blade passing frequencies at design speed of at least 10 kilohertz which eliminated any significant standing wave problems.

There is a real incentive to obtain meaningful noise data in the same installation and time period that the detailed aerodynamic data are obtained. Early screening of designs and the potential for cause and effect relationships between the aerodynamic and noise performance is thereby possible.

A 0.271-scale model (0.5-m or 20-in. diameter) of the NASA QF-1 fan has been tested for noise and aerodynamic performance in an unmodified compressor test facility. The detailed aerodynamic performance has been recently reported (ref. 2). In addition, the same QF-1 scale model, renamed stage 15-9 (rotor 15 - stator 9) for convenient reference, was recently tested for inlet noise in an anechoic chamber. This anechoic chamber is a new facility which belongs to the General Electric Co. It was designed and developed by them and is located at their Corporate Research and Development Center, Schenectady, New York. The cooperation of the General Electric Company and particularly that of C. T. Savell and R. J. Wells is gratefully acknowledged.

The purposes of this report are the following: (1) to compare the inlet sound pressure level spectra and the absolute sound power levels in each noise component as determined in an unmodified compressor aerodynamic test facility with that determined in an anechoic chamber and thereby establish the validity and limitations of the non-anechoic facility and (2) to document the inlet acoustic performance of a 0.271-scale model of NASA QF-1 fan over a wide range of speeds and flows for which detailed aerodynamic data are also available.

The design tip speed of the NASA QF-1 fan is 337 meters per second (1107 ft/sec) and design total pressure ratio is 1.50. The fan was tested over a range of speeds from 50 to 100 percent of design and weight flows between near choke and near stall. One-third octave bandwidth sound power spectra for all test conditions and narrowband (50-Hz) sound pressure spectra for selected conditions are presented.
All symbols and equations are defined in appendixes A and B, respectively. Abbreviations and units for the tabular data are defined in appendix C.

APPARATUS

Test Stage Design

The overall aerodynamic design parameters for stage 15-9 are listed in table I. Design total pressure ratio, efficiency, and weight flow per unit annulus area were 1.499, 0.848, and 201.8 kilograms per second per square meter (41.3 lb/(sec)(ft²)), respectively, at a tip speed of 337 meters per second (1107 ft/sec). There were 53 rotor blades and 112 stator blades spaced 3.5 rotor chords downstream of the rotor trailing edge. The flow path through the blading and aerodynamic instrumentation stations are shown in figure 1. A view of the stage with outer casing removed is shown in figure 2.

The blade element design parameters for rotor 15 and stator 9 are presented in tables II and III, respectively. The blade geometry is presented in table IV for the rotor and in table V for the stator. Both rotor and stator used multiple circular arc blade shapes. Further details of the aerodynamic and mechanical designs appear in reference 2. Stage 15-9 is a 0.271-scale model (0.5-m or 20-in. diameter) of the NASA QF-1 fan (refs. 3 and 4).

Test Facilities

Compressor aerodynamic test facility and instrumentation. - The compressor test facility has been previously described (e.g., refs. 2 and 5), but pertinent features are repeated here for convenience. An overall schematic view is shown in figure 3(a) while rotor and microphone locations are detailed in figure 3(b). The drive system consists of a 3000-hp electric motor with a variable-frequency speed control. The drive motor is coupled to a 5.521-to-1 ratio speed-increaser gearbox that drives the test rotor.

Atmospheric air enters through a filter house (not shown) into a line on the roof of the building. The air passes successively through a flow measuring orifice, inlet throttle valves, two cascades of turning vanes which reverses the direction of flow, and then into the 183-centimeter-(72-in.-) diameter plenum chamber. As shown by figure 3(b), the air then enters a 122-centimeter-(48-in.-) diameter pipe leading to a bell-mouth which then reduces the flow path to the 49.5-centimeter-(19.49-in.-) diameter of the rotor tip. Downstream of the stator, the air is turned into a toroid-shaped collector. A cylindrically shaped and translatable sleeve valve at the collector entrance was used
exclusively to throttle the airflow for the present tests. The air is finally exhausted to either a low- or high-vacuum receiver, as required.

The walls of the plenum chamber and all piping to and from it are rolled steel plate about 1.3 cm (1/2 in.) thick with no acoustic treatment. The volume of the chamber between the rotor and the turning vanes in the first 90° bend upstream is about 13.3 cubic meters (470 ft³). The corresponding wall surface area is about 36 square meters (388 ft²).

Hereafter, noise data from the microphone locations of figure 3(b) are referred to as those from the plenum chamber.

The acoustic instrumentation was the same as that detailed in reference 1. A 0.64-centimeter - (1/4-in. -) diameter condenser-type microphone was positioned by remote control to two different radii in the plenum chamber in a plane 236 centimeters (93 in.) upstream of the rotor as shown in figure 3(b). A pistonphone-type microphone calibrator was routinely used. The microphone signal was recorded in the FM-mode at a tape speed of 19.05 centimeters per second (7-1/2 in./sec) with a frequency capability to 25 kilohertz. Playback from the tape recorder was connected to either a continuous 50 hertz constant bandwidth wave analyzer geared to its graphic level recorder, or to a continuous one-third octave constant percentage bandwidth analyzer geared to its graphic level recorder.

The aerodynamic instrumentation is pictured in figure 4(a) and its location is given in figure 4(b). The wedge probes were used to determine static pressure and the combination probes were used to determine total pressure, total temperature, and flow angle. These probes were automatically aligned with the direction of flow. Radial traverses of the flow were made at three axial stations labeled 1, 2a or 2b, and 3 in figure 1. Further downstream at station 4 were four fixed rakes for measuring total pressure. Each fixed rake contained five radially spaced tubes with equal circumferential spacing between rakes. Two combination probes and two 8° wedge probes (fig. 4) were radially traversed at each of the stations 1 to 3. The combination probes at station 3 were also circumferentially traversed across one stator blade gap (3.2°) from the nominal values shown in figure 4(b). Calibrated transducers were used to measure all pressures. The total pressures at station 4 were used to monitor online overall performance. The traversable probes at station 1 to 3 were used for more accurate determination of overall performance and for the blade element performance. The data were recorded by a central data recording system.

Anechoic chamber test facility and instrumentation. - A three view schematic of the General Electric Company's anechoic chamber is shown in figure 5. The structural enclosure of the chamber is approximately 10.4 meters (34 ft) wide, 7.2 meters (23.5 ft) long, and 4.1 meters (13.5 ft) high. All enclosing surfaces are covered with an array of polyurethane foam wedges about 0.7 meter (2, 3 ft) long. A photograph of the anechoic chamber taken from the air intake opening is shown in figure 6. The anechoic chamber
was designed to test fans in both intake and exhaust modes. In the intake mode the test fan is mounted so that air flows into the anechoic chamber and out through the muffler and inlet noise may be measured. In the exhaust mode the test fan and airflow are reversed and exhaust noise may be measured. For the present tests only the intake mode was used. All the anechoic chamber walls were made porous by leaving small spaces between the foam wedges. By distributing the intake air with ducting to all the porous walls, spherical sink-type flow was simulated in the intake mode of operation. This was to minimize inlet flow distortion and turbulence level.

Test fans in the anechoic chamber are driven by a constant speed motor of 2500 hp. A gearbox for speeds to 19 000 rpm was used for stage 15-9. The airflow was throttled about 43 meters (141 ft) downstream of the fan (fig. 5), and a muffler was installed about 2 meters (6.5 ft) upstream of this throttle. A flow measuring orifice was 7.6 meters (25 ft) upstream of the muffler.

Acoustic calibration tests of the chamber utilized a horn driver with pure tone inputs. Microphone traverses were made from about 1 to 6 meters (3 to 20 ft) along different azimuthal rays emanating from the fan inlet location. Results of these tests indicated a standing wave ratio of ±1 dB or less for frequencies from about 400 to 40 000 hertz and for azimuthal angles from 0° to 90°. Fan far field noise measurements were made at a fixed radius of 5.18 meters (17 ft) (~7 bellmouth diameters) at driveshaft height and for azimuthal angles from 0° to 120°.

The acoustic instrumentation utilized in the anechoic chamber consisted of the following: Thirteen 0.64-centimeter- (1/4-in.-) diameter condenser-type microphones and pistonphone-type microphone calibrator. The acoustic data were recorded in the FM-mode at 152.4 centimeters per second (60 in./sec). The tape recorder was calibrated over the frequency range from 0 to 80 kilohertz. Only above 40 kilohertz were significant corrections to the data necessary and these have been incorporated in the data presented. These data were all processed by a one-third octave bandwidth analyzer with digital output. Selected data were further reduced by a 50 hertz constant bandwidth analyzer and corresponding graphic level recorder. Computers were utilized to process the digital one-third octave data into various standardized formats and also to calculate the sound power levels from the sound pressure levels measured by the azimuthal array of 13 inlet microphones.

The aerodynamic instrumentation in the anechoic chamber was minimal. It consisted of two five-element total pressure rakes at station 4 (fig. 1). These were two of the four rakes utilized in the compressor aerodynamic test facility to monitor overall performance. Only two rakes, 180° apart, were used in the anechoic chamber due to limitations in available data channels. Inlet total pressure was taken equal to anechoic chamber static pressure. Mass flow was measured by a 55.9-centimeter- (22-in.-) diameter orifice. Inlet mean velocity and turbulence intensity were measured by a radially traversable single-wire hot film probe in a plane 26.8 centimeters (10.6 in.)
upstream of the rotor (fig. 7). Four circumferential locations, 90° apart were surveyed with the hot film. The fluctuating velocity was measured by a true rms meter. All hot film data were recorded on tape for later processing.

Comparison of fan inlet configurations. - Above the fan centerline in figure 7 is shown the anechoic chamber inlet and below the fan centerline is shown the unmodified compressor test facility inlet. A nearly spherical screen encloses the well rounded bell-mouth in the anechoic chamber for most of the tests. The purpose of the screen was to homogenize the inflow to the fan and thus produce lower turbulence intensity levels. There is a flat screen in the plenum chamber of the other facility (figs. 7 and 3(b)). The screens for each facility utilized different wire and mesh sizes but the ratio of screen distance from rotor to mesh size was comparable. The unmodified compressor facility also utilizes four support struts in a relatively low velocity section about 60 centimeters (23.6 in.) upstream of the rotor. These struts are equally spaced, airfoil shaped, and have maximum thickness to chord ratio of about 23 percent. The contour of the case between the support struts and the rotor was designed to minimize boundary layer growth and prevent separation. The centerbody in the compressor test facility was fixed and longer than the rotating spinner utilized in the anechoic chamber.

PROCEDURES

Test

In both facilities the fan was tested over a range of speeds from 50 to 100 percent of design and weight flows between near choke and near stall. Fan rotative speed and temperatures were allowed to stabilize before any aerodynamic or acoustic measurements were made. Downstream throttle valves were then adjusted to the several desired weight flows. In the unmodified compressor test facility the aerodynamic data at stations 1 to 3 (fig. 1) were obtained at nine radial positions for each speed and weight flow tested. All the aerodynamic performance data presented herein are from mass weighted integrations of the traverse data taken in the non-anechoic facility. The anechoic chamber aerodynamic performance was related to this traverse data performance through the common rake measurements at station 4 and the respective flow measurements.

Hot film measurements in the anechoic chamber were recorded for 2 minutes at each location. Corrections for any temperature and pressure changes during testing were made from manufacturers' calibrations.

All 13-arc microphones in the anechoic chamber were calibrated with a pistonphone before and after each test. If these levels differed for any microphone, its average level was used to reduce the data from that microphone. Frequency response of the acoustic data acquisition system was calibrated by inserting constant amplitude sine waves at each
one-third octave center frequency. Anechoic chamber acoustic data from all microphones were recorded simultaneously for at least 1 minute at each operating point. No inlet probes (hot film) were in place during acoustic tests.

The plenum chamber microphone was calibrated with a pistonphone before each test. About 2 minutes of data at each operating point and for each of two radial positions (fig. 3(b)) were recorded.

Prior to taking noise data in the plenum chamber, all the aerodynamic probes at stations 1 to 4 were withdrawn from the flow path and the holes in the outer case smoothly plugged. Aerodynamic probes in the flow path can create extraneous noise sources as demonstrated in reference 1. Except for adding a microphone in the plenum chamber and the removal of all aerodynamic probes (except for a single pitot tube at station 4 for monitoring purposes), the compressor test facility was not otherwise modified for the present noise tests.

Noise Data Reduction

General. Sound power levels (PWL) rather than sound pressure levels (SPL) must be utilized for absolute value comparisons of stage 15-9 inlet noise determined in the anechoic chamber with those determined in the reverberant environment of the untreated plenum chamber in the compressor test facility. Inlet noise directivity is measured in the anechoic chamber but cannot be measured in the plenum chamber. In the latter a diffuse sound field exists (ref. 1). Thus a different calculation for inlet PWL from the measured SPL values will be described for each facility.

Fan noise is usually subdivided into the following three components (refs. 6 and 7): (1) the fundamental blade passing frequency (1×BPF) and its harmonics (2×BPF, etc.), (2) multiple pure tones (MPT), and (3) broadband (BB). One-third octave bandwidth analysis is most commonly used to display the spectra of fan noise and determine its noise components. However, MPT noise is generally not obvious from one-third octave bandwidth spectra alone. Significant MPT noise is usually associated with rotor blade relative Mach numbers that are supersonic. These MPT occur at harmonics of rotor speed frequency (rotor RPM/60, Hz) which usually cannot be identified without narrow (~50-Hz), constant bandwidth analysis. These narrowband analyses provide a continuous trace of the sound pressure level with frequency as measured at a particular microphone location. Such narrowband traces are rarely used to calculate a sound power level which would require a large amount of detailed interpretation and calculation.

A typical compromise in reducing fan noise data (refs. 4 and 8) is to process all of the data by one-third octave bandwidth SPL and PWL analyses. Then data from selected microphone locations are further reduced by narrowband analysis to continuous SPL against frequency traces. The narrowband results are then used to guide the
interpretation of the one-third octave bandwidth SPL and PWL spectra. Such a procedure was adopted for reducing the noise data from both the anechoic chamber and the plenum chamber as illustrated next.

Anechoic chamber. - Sample narrowband and one-third octave bandwidth noise spectra are shown in figure 8 for a speed high enough to generate all three noise components - BPF, MPT, and BB. In figures 8(a) and (b), the SPL from the 60° microphone are shown. But in figure 8(c), the inlet PWL based on all microphones is presented for one-third octave bandwidths. These PWL were obtained by assuming symmetry above and below the plane of the microphones (fig. 5) and integrating the SPL over the nearly hemispherical surface that could be generated by rotating the arc of 13 microphones through 180°. (The SPL from the 100° to 120° microphones was included in the PWL calculation but that sector had an insignificant influence on the overall level from 0° to 90°, the hemisphere of interest herein.)

In figure 8(a) the 50-hertz analysis extends from 0 to 25 kilohertz and the 1×BPF tone is clearly shown by the peak in SPL at about 11.6-kilohertz. The MPT noise is at integral multiples of rotor speed frequency of 219 hertz and is most significant at frequencies below 1×BPF. Peak MPT values are higher than values of 1×BPF and appear between 4 and 8 kilohertz. In figure 8(b) the one-third octave SPL analysis of the same data also shows a significant peak in the 4- to 8-kilohertz range. With the previous narrowband detail (fig. 8(a)) this hump in the one-third octave band data (fig. 8(b)) can be identified as MPT noise. Similarly, in the PWL spectrum from all inlet microphones (fig. 8(c)) the powerpeak in the 4- to 8-kilohertz range is attributed to MPT noise.

The 1×BPF noise at 11.6 kilohertz (fig. 8(a)) is near the dividing frequency of 11.3 kilohertz which separates adjacent one-third octave bands (indicated along abscissa of figs. 8(b) and (c)). To account for this adjacent band sharing or band splitting of the 1×BPF noise, the sound energy in the two bands is added. As will be evident in subsequent plots, when 1×BPF falls near the center frequency of the one-third octave band, band sharing does not occur. In the sample shown (fig. 8), 2×BPF noise is insignificant (at least 10 dB lower) relative to 1×BPF. At lower speeds it is not. For all speeds and weight flows, the 1×BPF and 2×BPF noise are added together in subsequent comparison plots of BPF noise from each facility.

A broadband noise base is indicated on all parts of figure 8. In figure 8(a) it is estimated to be along a line connecting the low points of the narrowband spectrum as shown. From this narrowband estimate a one-third octave bandwidth broadband level is calculated for figure 8(b) as indicated on the figure and discussed next.

A spectrum level (SL) for the broadband base is determined from the 50-hertz analysis at each one-third octave center frequency which are indicated along the abscissa of figure 8(a). The spectrum level, SL, is defined as the average sound pressure level of the broadband base in decibels referred to a 1-hertz-wide bandwidth. To each SL the
corresponding one-third octave bandwidth, \((bw)_{1/3 \text{ oct}}\), allowance was added to yield the broadband SPL in that band (fig. 8(b)).

The indicated broadband base in the one-third octave PWL spectrum (fig. 8(c)) is obtained by joining the low points in the PWL spectrum underlying the BPF's and MPT's which have been previously identified in narrowband SPL analyses like figure 8(a). The reasonably close agreement of the broadband base levels between figures 8(b) and (c) supports this technique.

All levels above the calculated broadband base in figures 8(b) or (c) are interpreted as the total noise in either \((\text{MPT + BB)}\) or \((\text{BPF + BB)}\). The MPT or BPF noise is determined by decibel subtraction of the underlying BB energy contribution from the total SPL or PWL values at that frequency.

The tabulations on figure 8(c) show a sample breakdown of the noise components and the broadband corrections to the indicated tones. The total BB noise indicated in figure 8(c), 135.8 dB, resulted from adding the energy at the centerline frequencies of each one-third octave band between 100 and 80 000 hertz. Also, tone indications, if any, below about 250 hertz were generally ignored because of poor narrowband resolution there and possible starting transient errors in the graphic level recorders.

Plenum chamber. - These noise data were reduced in a manner similar to the anechoic chamber data with the following exceptions: (1) the upper limit of frequency analysis was 20 kilohertz (instead of 80 kHz) because of tape recorder limitations, and (2) the calculation of PWL from SPL measurements was based on reverberant chamber relations (instead of free and far field integrations over a hemisphere) because of the diffuse sound field in the plenum. These relations are developed in reference 1 and result in the following equation:

\[
PWL = SPL + 10 \log (v) - 10 \log (\tau) - 19 \text{ dB}
\] (1)

where PWL is in dB (referenced to \(10^{-13} \text{ W}\)), SPL is in dB (referenced to 0.0002 \(\mu\text{bar}\)), \(v\) is chamber volume in cubic feet (470 \(\text{ft}^3\)), and \(\tau\) is reverberation time in seconds. The experimentally determined reverberation time is shown in figure 9(a) taken from reference 1. (The microphone locations in fig. 9(a) encompass those utilized in the present study (fig. 3(b)). Because reverberation time is a function of frequency and chamber volume is a known constant, the PWL-SPL relation can be plotted as shown in figure 9(b). Further details of this procedure are given in reference 1. An average SPL from the two radial positions in the plenum was utilized to calculate the one-third octave PWL spectra presented although such radial differences were usually within 1 dB for all conditions and center frequencies. Finally, separating out the MPT and BPF noise from the BB and adjusting the tone levels for the broadband contribution was exactly the same for the plenum chamber data as for the anechoic chamber data previously illustrated (fig. 8(c)).
RESULTS AND DISCUSSION

Aerodynamic as well as acoustic results are presented in this section. Some of the data are tabulated as well as plotted. The overall aerodynamic performance for eleven representative operating points with stage 15-9 are given in table VI. Blade element performance for these operating points is presented in table VII for the rotor and table VIII for the stator. These and other aerodynamic data for the stage can be found in reference 2 and are repeated here for convenience. Operating points for the acoustic data will be indicated. In general they are close to but not identical to those in table VI.

Acoustic data from each of the 13 microphones in the anechoic chamber reduced to one-third octave bandwidth spectra from 100 to 80 000 hertz and adjusted to standard day conditions at 30.48 meters (100 ft) are presented in table IX along with the acoustic power levels calculated from the microphone array. Subsequent plots will present all of the anechoic and plenum chamber results from one-third octave bandwidth analyses as well as narrowband (50-Hz) analyses for selected operating conditions and microphone locations.

Aerodynamic Performance

Overall pressure ratio and efficiency. - An overall performance map for stage 15-9 is presented in figure 10. The solid lines are fairings through the data of reference 2. Operating points for the acoustic data are indicated by arrowheads. At design speed and on an operating line calculated to pass through the design point with a fixed fan exhaust nozzle (see ref. 2), the stage pressure ratio, efficiency, and percent design weight flow were 1.475, 0.835, and 98.0, respectively; these compare favorably with design values of 1.499, 0.848, and 100.0 (table I). The near stall or near surge lines indicated are not much removed from the calculated operating line, particularly in the anechoic chamber installation. The near surge line in the anechoic chamber occurs at higher weight flows than in the compressor aerodynamic facility. This is believed related to the much larger volume between the stator trailing edge and the throttling valve in the anechoic facility (fig. 5) compared with the sleeve valve located in the collector inlet in the compressor test facility (fig. 3(a)). Also, the increased exit ducting and muffler in the anechoic chamber installation caused its minimum resistance line (wide open throttle) to occur at lower weight flows than that for the other facility. The combined result was a relatively narrow flow range of operation at a given speed in the anechoic chamber facility. Flow range was less than half that available in the compressor test facility. Power and vibration limits at design speed caused an additional restriction to the anechoic chamber operating range.
Rotor tip Mach number. - Speed is a primary variable in evaluating acoustic as well as aerodynamic performance. For convenient reference the Mach number relative to the rotor blade leading edge at 5 percent span from the tip, \( M_{1,05} \), is presented in figure 11 for all conditions tested. These data along with loadings (diffusion factor \( D \)), loss coefficients, incidence angles, and so forth, are available at nine spanwise locations for both rotor and stator blades in tables VII and VIII, respectively.

Inlet flow mean velocity and turbulence intensity in anechoic chamber. - These data were obtained from radial surveys with a hot film at four equally spaced circumferential locations, 26.8 centimeters (10.6 in.) upstream of the rotor in the anechoic chamber installation both with and without the inlet turbulence screen as indicated in figure 7. Comparable data were not taken in the compressor test facility. Results of the hot film surveys are shown in figure 12. A circumferentially averaged mean velocity without the turbulence screen is presented in figure 12(a). Circumferential variations were less than ±2 percent (within accuracy of measurement) and nonsystematic. (Hot film calibration problems with the screen in place made that data unreliable thus it is not shown). As indicated by the radial profile of mean velocity, the boundary layer from the well-rounded bellmouth inlet did not extend beyond a radius ratio of about 0.98 at the measuring station. Also, the free stream average velocity of about 97.5 meters per second (320 ft/sec) (fig. 12(a)) agrees within a few percent of an average value that was calculated from the measured flow, the cross-sectional area in the hot wire plane, and the local density deduced from static conditions measured in the anechoic chamber.

Circumferentially averaged turbulence intensities with and without the screen in place are presented in figure 12(b). With screen, the midstream levels are quite low, about 0.0045. (Nonsystematic circumferential variations ranged from 0.0035 to 0.0055). Similar midstream levels have been measured in outdoor model tests. Turbulence intensities within the boundary layer were much higher than in midstream, ranging from 2 to over 6 percent. Tests without the inlet screen show an average midstream intensity level of about 0.007. (Midstream circumferential variations ranged from 0.0065 to 0.0085.) Also without the screen, the region of intense turbulence near the case wall was thickened. There were no measurable differences in overall pressure ratio or weight flow in the anechoic chamber with or without the turbulence screen. The effects of the screen on the acoustic results are discussed next.

Inlet Noise Performance

Effect of turbulence screen. - As shown by one-third octave band sound power spectra in figures 13(a) to (d) for speeds of 70 to 100 percent of design, respectively, the screen in the anechoic chamber reduced the high frequency broadband noise (above about \( 2 \times 10^4 \) Hz) at all speeds by 3 to 5 dB. In general as speed was increased, the
effectiveness of the screen spread to lower frequencies. Blade passing tone levels were generally affected less than 2 dB. At design speed (fig. 13(d)) the screen was not effective in reducing the multiple pure tone noise occurring in the frequency range from 4 to 8 kilohertz. Because the screen was found from calibrations not to have significantly altered the sound from a speaker source, and because the screen was located in a low velocity region, the broadband noise reduction is believed to be a result of a reduction in the noise source levels. As previously discussed, the screen reduced the inlet freestream turbulence intensity and reduced the thickness of intense turbulence near the case wall.

The flat screen half way through the plenum chamber of the compressor test facility (fig. 3(b)) was not removed thus comparable data from that facility are not available.

As shown in figure 7, the distance between the screen and the rotor, divided by the mesh size (wire center to center distance) was about 960 for the anechoic chamber and about 850 for the compressor test facility with plenum chamber. Such large and comparable distance to mesh size ratios are an indication of comparable turbulence intensities at the rotor face (ref. 9). Thus the noise data from the two facilities, discussed next, is with their respective screens in place.

Typical noise spectra in each facility. - In the anechoic chamber the effect of speed on narrowband and on one-third octave band SPL from the 60° microphone is shown in figures 14 and 15, respectively. Comparable results from a microphone in the plenum chamber of the aerodynamic test facility are shown in figures 16 and 17. The 60° angle SPL was selected for comparison because it is generally at or near the peak azimuthal value for all operating conditions (see table IX) and is representative of the spectra which has the major influence on the inlet sound power.

The narrowband results from the anechoic chamber (fig. 14) show prominent 1xBPF tones at all speeds despite a design that should cut them off at low speeds (refs. 4 and 10). The MPT content increases as the speed is increased from 70 to 100 percent speed. High levels of MPT noise relative to the 1xBPF noise in the far field have been related to supersonic relative blade speeds (refs. 7 and 11). The blade relative Mach number (at 5 percent span from tip) at 100 percent design speed is about 1.15 and that at 70 percent speed is about 0.75 (see fig. 11). Also, figure 14 shows the 2xBPF tone decreasing relative to the 1xBPF level as speed is increased.

At 70 percent speed (fig. 14(c)), there is an extraneous tone near 2000 hertz, the source of which is unknown. Other fan designs tested in this anechoic chamber have not displayed such a tone. Also, at comparable speed and flow conditions, the same fan tested for noise in the compressor aerodynamic facility did not generate the stray tone (see fig. 16(c)). Fortunately the 2000-hertz tone is not a factor in evaluating the three noise components of interest.

Also at 70 percent speed in the anechoic chamber (fig. 14(c)) the 2xBPF and 3xBPF tones appear split into two discrete tones about 600 hertz (4 rev/sec) apart. This
phenomena also did not appear in the narrowband analyses of the plenum chamber data
(fig. 16(c)) nor at any of the higher speeds in either facility. Reasons for the split are
unknown. However, it is not a factor in the one-third octave analyses (fig. 15(c)) where
the wider bandwidths automatically combine the aforementioned tone splits.

Direct graphic comparison of the 50-hertz spectra from each facility (figs. 14 and
16) is a little difficult because of the different scales utilized by the different graphic
level recorders. To eliminate that difficulty and also to illustrate that MPT's (including
the BPF's) occur at multiples of the engine order \( E \) (rev/sec of the rotor shaft), fig­
ures 18 and 19 were constructed. Figure 18 is for 70 percent speed, and figure 19 is for
100 percent speed. Part (a) of each figure represents the anechoic chamber traces of
figures 14 (a) and (c); part (b) represents the plenum chamber traces of figures 16(a)
and (c). The peaks and valleys of each MPT, relative to the level of \( 1\times BPF \), were read
from the graphic traces. The peaks were plotted at the appropriate engine orders and
the valleys half way between. Straight lines were drawn between them. In regions with­
out MPT clusters (mainly the 70 percent speed data) the SPL at each engine order was
read from the respective analyzer traces then these levels were joined by straight lines.
Exact correspondence of noise spectra from any single microphone in an anechoic cham­
ber with that from any microphone in a reverberant chamber is of course not expected or
even possible. However, there are enough similarities in the narrowband spectra be­
tween the plenum chamber data and the anechoic chamber data to make the former a help­
ful representation of the free and far field frequency content and of relative dB levels.
For example, in either facility, the MPT's are similar in frequency content and in level
(relative to \( 1\times BPF \)) at 100 percent speed (fig. 19). At this speed the MPT's dominate the
spectrum. Likewise in either facility the MPT's are equally insignificant at 70 percent
speed (fig. 18).

With regard to \( 1\times BPF \) at 70 percent speed, (fig. 18) similar patterns are evident in
either facility although the tone is wider at the broadband base level in the plenum cham­
ber. Also at 70 percent speed, the \( 2\times BPF \) tone is lower relative to the \( 1\times BPF \) tone in the
plenum chamber than in the anechoic chamber. At 100 percent speed (fig. 19), the
\( 1\times BPF \) tone level is less above the broadband base in the plenum chamber data than in the
anechoic chamber data.

There are gross similarities in the narrowband (50-Hz) spectra from each facility at
comparable operating conditions. However, some of the finer details differ.

The one-third octave band results from either the anechoic chamber (fig. 15) or the
plenum chamber (fig. 17) are much easier to interpret when their corresponding narrow­
band results (figs. 14 and 16, respectively) are available. The MPT noise at 100 percent
design speed (figs. 15(a) or 17(a)) is mainly clustered in the one-third octave bands cen­
tered at 4, 5, 6.3, and 8 kHz. The \( 1\times BPF \) noise at 100 percent speed is shared by the
10 and 12.5 kilohertz centered bands and the \( 2\times BPF \) by the 20 and 25 kilohertz centered
bands. At 70 percent speed (figs. 15(c) or 17(c)) the \( 1\times BPF \) is near the center of the one­
third octave band centered at 8 kilohertz and no band sharing of this tone or its second harmonic is apparent. The one-third octave broadband base calculated from the narrow-band analyses (fig. 14) agrees with the direct one-third octave analysis for all speeds (fig. 15).

In the plenum chamber at 70 percent speed and 67 percent flow (figs. 16(c) and 17(c)) there is a broadband hump in the SPL spectra extending from about 500 to about 3000 hertz that is not present for comparable conditions in the anechoic chamber (figs. 14(c) and 15(c)). This is believed due to exit throttle generated noise in the compressor test facility discussed later.

One-third octave band power spectra comparisons. As previously discussed, the flow range at each speed is much less in the anechoic chamber installation than in the compressor test facility. Thus, in general there was only one flow at a given speed that was nearly the same in each facility. These four directly comparable operating conditions are shown in figures 20(a), (b), (c), and (d) for 70, 80, 90, and 100 percent speed, respectively.

In general, the broadband spectra are somewhat different between the two facilities as is the upper frequency limit of the analysis. There is the previously indicated low speed (70 and 80 percent), low frequency range (500- to 3000-Hz) hump in the plenum data. Also, above 1×BPF, the plenum broadband is less than the anechoic data. At 90 and 100 percent speed (figs. 20(c) and (d)), the plenum broadband is higher under the MPT noise than in the anechoic chamber. Above 1×BPF, the broadband noise switches to higher in the plenum at 90 percent speed and about equal at 100 percent speed relative to the anechoic chamber levels. Substantially different downstream throttle systems are believed responsible for the broadband differences below about 3000 hertz (see later discussion). Reasons for the inconsistent broadband relation between facilities above 1×BPF are not apparent. The overall result is that absolute value comparisons of broadband noise power are questionable because of the aforementioned differences. However, the broadband contribution to the indicated 1×BPF tone levels is not significantly different between facilities to adversely affect that tone noise comparison described next.

The 1×BPF noise component is nearly the same in both facilities for all speeds shown (fig. 20). At 70 and 80 percent speed the 2×BPF noise is higher in the anechoic chamber than in the plenum but the combined BPF noise agrees within less than 1.5 dB for speeds from 70 to 100 percent.

The MPT spectra are quite similar at 90 and 100 percent speed and the absolute values are in close agreement at 100 percent speed where the MPT component is dominant.

The satisfactory determination of one-third octave based inlet tone power levels (BPF's and MPT's) in the same installation and time period that the detailed aerodynamic performance is obtained allows early screening of designs. And coupled with narrowband
spectra that are representative of free and far field spectra it also offers the potential
for cause and effect relations between the aerodynamic and noise performance.

All of the one-third octave band power spectra from each facility are presented in
figures 21 to 26 for speeds of 50 to 100 percent of design, respectively. At 50 and 60
percent speed directly comparable data are not available as it is for 70, 80, 90, and 100
percent speed. The weight flows at each speed are shown and the absolute value of each
noise component tabulated.

In the anechoic chamber at 60 and 70 percent speed (figs. 22 and 23(a)) the second
harmonic (2×BPF) is about equal to the fundamental (1×BPF). In the aerodynamic test
facility at 70 percent speed (fig. 23(b)), the 2×BPF noise level is 7 to 9 dB below 1×BPF
for all weight flows tested. This implies that the stage 15-9 waveforms measured in the
reverberant plenum chamber are shaped nearly like sine waves while those in the
anechoic chamber are more irregular in shape. However the combined acoustic power
in 1×BPF and 2×BPF in one chamber is nearly equal to that in the other at comparable
operating conditions. Also, at the higher speeds (figs. 24 to 26), the 2×BPF noise levels
are nearly 10 dB lower than 1×BPF in both facilities.

Crossplots summarizing each of the noise components are presented and discussed
next. Following that, the throttle noise in the compressor aerodynamic test facility is
examined.

Noise components as functions of speed and flow. - The inlet sound power in blade
passing frequencies (BPF), in multiple pure tones (MPT), and in the broadband (BB)
noise are shown in figures 27, 28, and 29, respectively, for both test facilities. These
results are from the previously presented one-third octave analyses (figs. 21 to 26) and
cover the range of speeds and flows tested.

The levels of BPF noise (fig. 27) represent the combined power of 1×BPF and 2×BPF.
On this basis there is very good agreement between the two facilities over the entire
range studied. At a midthrottle setting, the BPF levels generally increase with increas­
ing tip speed from 50 to 80 percent speed and remain near the later level at 90 and 100
percent speed. The effect of flow or loading at a fixed speed on BPF levels is mixed. At
speeds between 70 and 100 percent the midthrottle settings associated with near peak ef­
ficiency operation (fig. 10) produce the highest level of BPF noise. Also, the near stall
flows in the aerodynamic test facility generally result in the lowest levels of BPF at a
given speed. Reasons for this unexpected behavior of BPF noise are not presently known.

The levels of the multiple pure tones are shown in figure 28 against a background of
blade passing frequency levels. Only at 100 percent speed are the MPT a significant
noise source (relative to the BPF) and there the agreement between the two facilities is
very good. There is some MPT contribution at 90 percent speed where the relative Mach
number is near 1.0 but it is less than the BPF. The MPT levels at 90 percent speed are
about 5 dB less in the anechoic chamber than in the plenum for unknown reasons. At 100
percent speed the combined MPT levels exceed the combined BPF levels. It appears that
some of the acoustic energy in the blade passing frequency is increasingly shifted into multiple pure tones as the blade relative Mach number increases above unity. Evidence for this is the leveling off of the BPF noise near 1.0 relative Mach number concurrent with increasing MPT noise as Mach number increases beyond about 1.0. At design speed there is no effect of loading (flow changes) on the MPT levels for the range of flows that could be tested.

The broadband noise levels for each facility are presented in figure 29. As previously discussed, the plenum chamber data show a broadband frequency spectra that generally differs from the anechoic chamber data as does the upper frequency limit analyzed thus absolute value comparisons of total broadband power are questionable. However, trends with speed and flow may be valid and are similar in each facility. At constant speed, the broadband noise increases steadily with decreases in flow. Such flow decreases mean increased blade loading with possibly increased flow separation and thus increased turbulence from blade and wall boundary layers. The allowable flow range at constant speed was small in the anechoic chamber thus the range of broadband noise was only a few dB. The broadband noise in the anechoic chamber increased about 6 dB from 60 to 80 percent design speed (about fifth power of speed dependence) then decreased about 1 dB from 80 to 90 percent speed. These values apply along a fan operating line calculated to pass through the design point with a fixed fan exhaust nozzle. Design speed data could not be run at this throttle setting (fig. 10). Reasons for the lower broadband noise at 90 percent speed are not known.

A summary of the one-third octave based inlet sound power from the 0.271-scale model of the NASA QF-1 fan tested in an anechoic chamber revealed the following: the blade passing frequency noise was highest near a midthrottle, peak efficiency, setting. It propagated to the far field at all speeds despite a stator to rotor blade number ratio satisfying the cutoff criteria (ref. 10) and despite low levels of free stream inlet turbulence intensity and flow distortion. The MPT noise was not significant at 90 percent speed (takeoff condition, ref. 3) but was dominant at 100 percent speed. And the broadband noise increased with speed between 60 and 80 percent design speed but declined about 1 dB from 80 to 90 percent speed.

**Throttle noise in unmodified compressor test facility.** - As previously mentioned there is a broadband hump in the noise spectra from about 500 to 3000 hertz for the midthrottle data at 70 and 80 percent speed (figs. 20(a) and (b)) that is not apparent from the anechoic chamber data. The source of this broadband hump is believed to be the sleeve throttle valve at the entrance to the collector about 60 centimeters (23.6-in.) downstream of the stator in the compressor test facility (fig. 3(b)). At maximum flow, the sleeve valve is translated forward and completely out of the flow path. Under these conditions (see figs. 23(b) to 26(b)), the plenum chamber noise spectra do not show a low frequency hump and are similar to the anechoic chamber spectra. However, to reduce weight flow, the sleeve valve must be translated rearward and into the flow path. Then the broadband
noise hump is present as shown (figs. 23(b) to 26(b)). On the other hand in the anechoic chamber installation, the throttle valve is remote from the stator and also there is a muffler in the line to reduce its upstream noise (fig. 5).

To further identify possible secondary noise sources, additional data from the aerodynamic compressor test facility without stage 15-9 installed is presented in figure 30. A range of weight flows was drawn by vacuum exhaust equipment (fig. 3(a)) through the compressor flow path and throttled by the collector entrance sleeve valve. The overall sound powers measured in the plenum as a function of flow are shown in figure 30(a). In figure 30(c) are the one-third octave power spectra for a range of flows, while figure 30(b) presents the average Mach number of the flow in the minimum area section (station 3 of fig. 1). Noise levels increased with increasing flow until the annulus was nearly choked and then the noise dropped off over 10 dB when the average Mach number approached 0.9. The noise spectra were similarly shaped for all flows with the highest levels in the range of frequencies between about 500 and 3000 hertz. These highest absolute levels are about the same as those with stage 15-9 operating at conditions resulting in about the same average Mach number at station 3 (fig. 1). By choking the flow at station 3 in the vacuum exhaust tests without stage 15-9 installed, the noise decrease extends across most of the spectrum (fig. 30(c)). In particular, the broadband noise between about 500 and 3000 hertz is substantially reduced. Thus the noise that has been choked off is believed to originate from the partly closed sleeve throttle.

The high broadband noise at the near stall flows in the aerodynamic test facility (figs. 21 to 26) are believed generated by stage 15-9. The continuously increasing level with increasing frequency (up to $1 \times$ BPF) is not characteristic of the facility operated without the stage (fig. 30(c)). Increased regions of flow separation from the highly loaded rotor and stator blades is a possible source of the increased broadband noise. In the anechoic chamber, similarly low weight flows and the correspondingly high blade loadings were not attainable thus acquiring noise data under such conditions was not possible.

**CONCLUDING REMARKS**

There are some obvious limitations to the noise measurements taken in the reverberant inlet plenum chamber of the present or any similar aerodynamic compressor test facility. No noise directivity information is possible from reverberant facilities which is required for effective perceived noise level or noise footprint calculations. Also, fan exit as well as inlet noise data are essential in evaluating its overall noise performance and these are not reported herein. Although 1.32-centimeter- (1/8-in.-) diameter microphones were radially traversed behind the stators of stage 15-9 (and others), there
are presently no anechoic or other free and far field data with which to compare and thus evaluate it.

The high blade passing frequencies of stage 15-9 (about 11 kHz at design speed) eliminated any significant standing wave problems in the symmetrical plenum chamber (ref. 1). Rotors with much lower blade passing frequencies (due to lower numbers of blades or lower tip speeds) may introduce such problems. Then modifications to the plenum or to the method of acquiring a good space average of the noise level will probably be required. Finally, the presently described contamination by exit throttle noise may be reduced by using a more remote and perhaps muffled throttle than one at the collector entrance.

**SUMMARY OF RESULTS**

The inlet noise from a 0.271-scale model (0.5-m or 20-in. diameter) of the NASA QF-1 fan was determined from measurements in the reverberant plenum chamber of an unmodified compressor aerodynamic test facility and from measurements in an anechoic chamber. The principle results of the study were the following:

1. Narrowband (50-Hz) analyses revealed grossly similar sound pressure level spectra in each facility. Blade passing frequency (BPF) noise and, at the higher tip speeds, multiple pure tone (MPT) noise were superimposed on a broadband (BB) based noise.

2. Sound power levels were determined from one-third octave bandwidth analysis. On that basis the BPF noise (harmonics combined) and the MPT noise (harmonics combined excepting BPF's) agreed between facilities within 1.5 dB or less over the range of speeds and flows tested. However, the sound power difference between 1×BPF and 2×BPF was not the same in each facility at low speed. Trends in the total broadband noise with changes in speed and flow were similar in each facility but comparisons of the absolute power levels are questionable because of differing frequency spectra and maximum frequency limit analyzed.

3. The satisfactory determination of one-third octave based inlet tone power levels in the same installation and time period that the detailed aerodynamic performance is obtained allows early screening of designs. And coupled with narrowband spectra that are representative of free and far field spectra it also offers the potential for cause and effect relations between the aerodynamic and noise performance.

4. In the anechoic chamber the BPF noise was highest near peak efficiency operation. It propagated at all speeds despite a design to cut it off at low speeds and despite free stream inlet flow with low turbulence intensity and flow distortion. Also the MPT noise was only significant at 100 percent design speed (tip relative Mach number of about 1.10) where it dominated the spectrum. The broadband noise increased about 6 dB from
60 to 80 percent design speed then decreased about 1 dB from 80 to 90 percent speed, all on a calculated operating line passing through the design point.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 22, 1975,
505-04.
APPENDIX A

SYMBOLS

\( A_{an} \) annulus area at rotor leading edge, 0.144 \( m^2 \); 1.55 \( ft^2 \)
\( A_f \) frontal area at rotor leading edge, 0.192 \( m^2 \); 2.07 \( ft^2 \)
\( C_p \) specific heat at constant pressure, 1004 \( J/(kg)(K) \); 0.24 \( Btu/(lb)(^0R) \)
\( C \) aerodynamic chord, cm; in.
\( D \) diffusion factor
\( E \) engine order, rev/sec
\( i_{mc} \) mean incidence angle, angle between inlet air direction and line tangent to blade mean camber line at leading edge, deg
\( i_{ss} \) suction-surface incidence angle, angle between inlet air direction and line tangent to blade suction surface at leading edge, deg
\( M \) Mach number
\( N \) rotative speed, rpm
\( N_D \) design rotative speed, 13 020 rpm
\( P \) total pressure, \( N/cm^2 \); psia
\( PWL \) sound power level, dB (referenced to \( 10^{-13} W \))
\( p \) static pressure, \( N/cm^2 \); psia
\( r \) radius, cm; in.
\( SM \) stall margin
\( SPL \) sound pressure level, dB (referenced to 0.0002 \( \mu \)bar)
\( T \) total temperature, K; \( ^0R \)
\( U \) wheel speed, m/sec; ft/sec
\( U' \) fluctuating velocity from hot film probe, m/sec; ft/sec
\( \bar{U} \) mean velocity from hot film probe, m/sec; ft/sec
\( V \) air velocity, m/sec; ft/sec
\( W \) weight flow, kg/sec; lb/sec
\( W_D \) design weight flow, 29.16 kg/sec; (64.3 lb/sec)
\( Z \) axial distance referenced from rotor blade hub leading edge, cm; in.
\( \alpha_c \) cone angle, deg
\( \alpha_s \) slope of streamline, deg
\( \beta \) air angle, angle between air velocity and axial direction, deg
\( \beta'_c \) relative meridional air angle based on cone angle, \( \arctan (\tan \beta'_m \cos \alpha_c / \cos \alpha_s) \), deg
\( \gamma \) ratio of specific heats (1.40)
\( \delta \) ratio of rotor inlet total pressure to standard pressure of 10.13 N/cm\(^2\)
(14.69 lb/in.\(^2\))
\( \delta^o \) deviation angle, angle between exit air direction and tangent to blade mean camber line at trailing edge, deg
\( \eta \) efficiency
\( \theta \) ratio of rotor inlet total temperature to standard temperature of 288.2 K
(518.7\(^o\) R)
\( \kappa_{mc} \) angle between blade mean camber line and meridional plane, deg
\( \kappa_{ss} \) angle between blade suction surface at leading edge and meridional plane, deg
\( \sigma \) solidity, ratio of chord to spacing
\( \bar{\omega} \) total loss coefficient
\( \bar{\omega}_p \) profile loss coefficient
\( \bar{\omega}_s \) shock loss coefficient

Subscripts:
\( \text{ad} \) adiabatic (temperature rise)
\( \text{id} \) ideal
\( \text{LE} \) blade leading edge
\( \text{m} \) meridional direction
\( \text{mom} \) momentum rise
\( \text{p} \) polytropic
\( \text{R} \) rotor
\( \text{ref} \) reference
\( \text{stall} \) stall
\( \text{TE} \) blade trailing edge
\( \text{tip} \) tip
z  axial direction
θ  tangential direction
05 5 percent span from tip of rotor
1 instrumentation plane upstream of rotor (fig. 1)
2a instrumentation plane nearest rotor trailing edge (fig. 1)
2b instrumentation plane nearest stator leading edge (fig. 1)
3, 4 instrumentation planes downstream of stator (fig. 1)

Superscript:

'  relative to blade
APPENDIX B

EQUATIONS

Suction-surface incidence angle

\[ i_{ss} = (\beta_c')_{LE} - \kappa_{ss} \quad (B1) \]

Mean incidence angle

\[ i_{mc} = (\beta_c')_{LE} - (\kappa_{mc})_{LE} \quad (B2) \]

Deviation angle

\[ \delta^0 = (\beta_c')_{TE} - (\kappa_{mc})_{TE} \quad (B3) \]

Diffusion factor

\[ D = 1 - \frac{V'_{TE}}{V_{LE}} + \left| \frac{(rV_\theta)_{TE} - (rV_\theta)_{LE}}{(r_{TE} + r_{LE})\sigma(V'_{LE})} \right| \quad (B4) \]

Total loss coefficient

\[ \bar{\omega} = \frac{(P'_{id})_{TE} - (P')_{TE}}{(P')_{LE} - (p)_{LE}} \quad (B5) \]

Profile loss coefficient

\[ \bar{\omega}_p = \bar{\omega} - \bar{\omega}_s \quad (B6) \]

Total loss parameter

\[ \bar{\omega} \cos \left( \beta_m' \right)_{TE} \quad \frac{2\sigma}{(B7)} \]
Profile loss parameter

\[ \frac{\bar{\omega}_p \cos(\beta_m)}{2\sigma} \]  \hspace{1cm} (B8)

Adiabatic (temperature-rise) efficiency

\[ \eta_{ad} = \frac{(P_{TE})^{(\gamma-1)/\gamma} - 1}{\frac{T_{TE}}{T_{LE}} - 1} \]  \hspace{1cm} (B9)

Momentum-rise efficiency

\[ \eta_{mom} = \frac{(P_{TE})^{(\gamma-1)/\gamma} - 1}{\frac{(UV\theta)_{TE}}{T_{LE}C_p} - \frac{(UV\theta)_{LE}}{T_{LE}C_p}} \]  \hspace{1cm} (B10)

Equivalent weight flow

\[ \frac{W\sqrt{\theta}}{\delta} \]  \hspace{1cm} (B11)

Equivalent rotative speed

\[ \frac{N}{\sqrt{\theta}} \]  \hspace{1cm} (B12)

Weight flow per unit annulus area

\[ \frac{W\sqrt{\theta}}{\delta\ A_{an}} \]  \hspace{1cm} (B13)
Weight flow per unit frontal area

\[ \frac{(W \sqrt{\theta})}{\delta} \times \frac{1}{A_f} \]  

Head-rise coefficient

\[ C_{pT,LE} \left[ \left( \frac{P_{TE}}{P_{LE}} \right)^{(\gamma-1)/\gamma} - 1 \right] \]  

Flow coefficient

\[ \left( \frac{V_z}{U_{tip}} \right)_{LE} \]  

Stall margin

\[ SM = \left[ \left( \frac{P_{TE}}{P_{LE}} \right)_{stall} \times \left( \frac{W \sqrt{\theta}}{\delta} \right)_{ref} - 1 \right] \times 100 \]  

Polytropic efficiency

\[ \eta_p = \frac{\ln \left( \frac{P_{TE}}{P_{LE}} \right)^{(\gamma-1)/\gamma}}{\ln \frac{T_{TE}}{T_{LE}}} \]
APPENDIX C

ABBREVIATIONS AND UNITS USED IN TABLES

(Aerodynamic and acoustic parameters listed separately)

Aerodynamic Parameters

ABS  absolute
AERO CHORD  aerodynamic chord, cm
AREA RATIO  ratio of actual flow area to critical area (where local Mach number is 1)
BETAM  meridional air angle, deg
CONE ANGLE  angle between axial direction and conical surface representing blade element, deg
DELTA INC  difference between mean camber blade angle and suction-surface blade angle at leading edge, deg
DEV  deviation angle (defined by eq. (B3)), deg
D-FACT  diffusion factor (defined by eq. (B4))
EFF  adiabatic efficiency (defined by eq. (B9))
IN  inlet (leading edge of blade)
INCIDENCE  incidence angle (suction surface defined by eq. (B1) and mean defined by eq. (B2)), deg
KIC  angle between blade mean camber line at leading edge and meridional plane, deg
KOC  angle between blade mean camber line at trailing edge and meridional plane, deg
KTC  angle between blade mean camber line at transition point and meridional plane, deg
LOSS COEFF  loss coefficient (total defined by eq. (B5) and profile defined by eq. (B6))
LOSS PARAM  loss parameter (total defined by eq. (B7) and profile defined by eq. (B8))
MERID  meridional
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>MERID VEL R</td>
<td>meridional velocity ratio</td>
</tr>
<tr>
<td>OUT</td>
<td>outlet (trailing edge of blade)</td>
</tr>
<tr>
<td>PERCENT SPAN</td>
<td>percent of blade span from tip at rotor trailing edge for design streamlines</td>
</tr>
<tr>
<td>PHISS</td>
<td>suction-surface camber ahead of assumed shock location, deg</td>
</tr>
<tr>
<td>PRESS</td>
<td>pressure, N/cm²</td>
</tr>
<tr>
<td>PROF</td>
<td>profile</td>
</tr>
<tr>
<td>RADI1</td>
<td>radius, cm</td>
</tr>
<tr>
<td>REL</td>
<td>relative to blade</td>
</tr>
<tr>
<td>RI</td>
<td>inlet radius (leading edge of blade), cm</td>
</tr>
<tr>
<td>RO</td>
<td>outlet radius (trailing edge of blade), cm</td>
</tr>
<tr>
<td>RP</td>
<td>radial position</td>
</tr>
<tr>
<td>RPM</td>
<td>equivalent rotative speed, rpm</td>
</tr>
<tr>
<td>SETTING ANGLE</td>
<td>angle between aerodynamic chord and meridional plane, deg</td>
</tr>
<tr>
<td>SOLIDITY</td>
<td>ratio of aerodynamic chord to blade spacing</td>
</tr>
<tr>
<td>SPEED</td>
<td>speed, m/sec</td>
</tr>
<tr>
<td>SS</td>
<td>suction surface</td>
</tr>
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<tr>
<td>TM</td>
<td>thickness of blade at maximum thickness, cm</td>
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<tr>
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<td>velocity, m/sec</td>
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<tr>
<td>WT FLOW</td>
<td>equivalent weight flow, kg/sec</td>
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<td>X FACTOR</td>
<td>ratio of suction-surface camber ahead of assumed shock location of a multiple-circular-arc blade section to that of a double-circular-arc blade section</td>
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**Acoustic Parameters**

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<td>DBC</td>
<td>Decibels using C weighted frequency response network (ref. 12)</td>
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<td>Perceived noise level, PN dB</td>
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### TABLE II. - DESIGN BLADE-ELEMENT PARAMETERS FOR ROTOR 15

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### TABLE III. - DESIGN BLADE-ELEMENT PARAMETERS FOR STATOR 9

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### TABLE VII. - BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(a) 100 Percent of design speed; intrablade row instrumentation at station 2a; reading number 558

| RP | ABS VEL | REL VEL | MERID VEL | TANG VEL | WHEEL SPEED | ABS MACH NO | REL MACH NO | MERID MACH NO | MERID PEAK SS | VEL R MACH NO |
|----|---------|---------|-----------|----------|-------------|-------------|-------------|---------------|---------------|---------------|---------------|
| 1  | 3.558   | 0.622   | 1.146     | 0.799    | 0.558       | 0.529       | 0.030       | 0.028         | 1.439         | 1.439         |
| 2  | 3.592   | 0.631   | 1.143     | 0.786    | 0.592       | 0.539       | 0.030       | 0.028         | 1.439         | 1.439         |
| 3  | 3.611   | 0.642   | 1.154     | 0.775    | 0.611       | 0.546       | 0.030       | 0.028         | 1.439         | 1.439         |
| 4  | 3.642   | 0.669   | 1.103     | 0.708    | 0.642       | 0.550       | 0.030       | 0.028         | 1.439         | 1.439         |
| 5  | 0.554   | 0.719   | 1.022     | 0.659    | 0.654       | 0.567       | 0.030       | 0.028         | 1.439         | 1.439         |
| 6  | 0.646   | 0.800   | 0.935     | 0.614    | 0.646       | 0.600       | 0.030       | 0.028         | 1.439         | 1.439         |
| 7  | 0.627   | 0.905   | 0.667     | 0.656    | 0.627       | 0.635       | 0.030       | 0.028         | 1.439         | 1.439         |
| 8  | 0.621   | 0.925   | 0.845     | 0.640    | 0.621       | 0.632       | 0.030       | 0.028         | 1.439         | 1.439         |
| 9  | 0.612   | 0.928   | 0.822     | 0.626    | 0.612       | 0.610       | 0.030       | 0.028         | 1.439         | 1.439         |

### Percent Incidence

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TABLE VII. – Continued. BLADE-ELEMENT DATA AT BLADE

EDGES FOR ROTOR 15

(b) 100 Percent of design speed; intrablade row instrumentation at station 2a; reading number 539

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37
TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(c) 100 Percent of design speed; intrablade row instrumentation at station 2a; reading number 551

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TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(d) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 564

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### TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE

#### EDGES FOR ROTOR 15

- (e) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 567

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TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(f) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 545

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(g) 80 Percent of design speed; intrablade row instrumentation at station 2a; reading number 572

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TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(h) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 573

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TABLE VII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(i) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 575

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TABLE VII. – Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR ROTOR 15

(j) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 550

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TABLE VII. - Concluded. BLADE-ELEMENT DATA AT BLADE

EDGES FOR ROTOR 15

(k) 50 Percent of design speed; intrablade row instrumentation at station 2a; reading number 579

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| 1           | 5.00 | 20.7 | 17.4 | 14.7 | 0.495 | 1.001 | -0.001 | -0.001 | -0.000 | -0.000 |
| 2           | 10.00 | 22.9 | 19.4 | 13.5 | 0.493 | 1.209 | -0.172 | -0.172 | -0.038 | -0.038 |
| 3           | 15.00 | 16.6 | 13.0 | 12.3 | 0.487 | 1.094 | -0.076 | -0.076 | -0.017 | -0.017 |
| 4           | 30.00 | 14.1 | 8.9 | 12.3 | 0.563 | 0.810 | 0.145 | 0.145 | 0.034 | 0.034 |
| 5           | 50.00 | 14.7 | 9.2 | 11.0 | 0.556 | 0.756 | 0.227 | 0.227 | 0.056 | 0.056 |
| 6           | 70.00 | 17.1 | 9.3 | 11.3 | 0.520 | 0.762 | 0.285 | 0.285 | 0.069 | 0.069 |
| 7           | 85.00 | 19.5 | 9.2 | 10.1 | 0.424 | 0.789 | 0.321 | 0.321 | 0.071 | 0.071 |
| 8           | 90.00 | 20.7 | 9.1 | 9.7 | 0.376 | 0.821 | 0.291 | 0.291 | 0.061 | 0.061 |
| 9           | 95.00 | 22.3 | 9.2 | 9.4 | 0.350 | 0.810 | 0.334 | 0.334 | 0.066 | 0.066 |</p>
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**TABLE VIII.** - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(b) 100 Percent of design speed; intrablade row instrumentation at station 2a; reading number 539

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TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(c) 100 Percent of design speed; intrablade row instrumentation at station 2a; reading number 551

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TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(d) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 564

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TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(e) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 567

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TABLE VIII. — Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(f) 90 Percent of design speed; intrablade row instrumentation at station 2a; reading number 545

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TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(g) 80 Percent of design speed; intrablade row instrumentation at station 2a; reading number 572

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53
TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(h) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 573

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TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(i) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 575

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### TABLE VIII. - Continued. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(j) 70 Percent of design speed; intrablade row instrumentation at station 2a; reading number 550

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TABLE VIII. - Concluded. BLADE-ELEMENT DATA AT BLADE EDGES FOR STATOR 9

(k) 50 Percent of design speed; intrablade row instrumentation at station 2a; reading number 579

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<th>MERID MACH NO</th>
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<td>IN OUT</td>
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<td>TOT PROF</td>
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57
### TABLE IX. NOISE OF STAGE 15-9 IN ANECHOIC CHAMBER

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(a) Percent speed, 60; fan actual rotative speed, 7730 rpm; percent weight flow, 62.5

<table>
<thead>
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<th>Angle from inlet, deg</th>
<th>PWL, dB (re 0.0002 μbar)</th>
</tr>
</thead>
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<tr>
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<tr>
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<td>180</td>
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<td>59.7</td>
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<tr>
<td>280</td>
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<td>59.7</td>
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<td>62.2</td>
<td>59.7</td>
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<tr>
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<tr>
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<td>360</td>
<td>62.2</td>
<td>59.7</td>
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One-third octave band sound pressure level, dB (re 0.0002 μbar)
<table>
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<th>PWL, dB (re 0.002μbar)</th>
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<td>58.0</td>
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<tr>
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<td>58.0</td>
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<td>58.0</td>
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<tr>
<td>60 - 70</td>
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<tr>
<td>70 - 80</td>
<td>58.0</td>
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<td>80 - 90</td>
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<td>90 - 100</td>
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One-third octave band sound pressure level, dB (re 0.002μbar)

NFA 7724 RPM
NFK 7603 RPM
NFD 13020 RPM

NUMBER OF BLADES 93

TAMB 48 DEG F.  THET 45 DEG F
HACT 7.35 GM/M3
BAR 29.2 HD

TABLE IX - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(b) Percent speed, 60; fan actual rotative speed, 7724 rpm; percent weight flow, 55.7

RPM
<table>
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<th>1750</th>
<th>2000</th>
<th>2500</th>
<th>3150</th>
<th>4000</th>
<th>5000</th>
<th>6300</th>
<th>8000</th>
<th>10000</th>
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</thead>
<tbody>
<tr>
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<td>41.5</td>
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<td>45.5</td>
<td>47.5</td>
<td>49.5</td>
<td>51.5</td>
<td>53.5</td>
<td>55.5</td>
<td>57.5</td>
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<td>61.5</td>
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<tr>
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<td>39.5</td>
<td>41.5</td>
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<td>45.5</td>
<td>47.5</td>
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<td>55.5</td>
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<td>39.5</td>
<td>41.5</td>
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<td>49.5</td>
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<td>37.5</td>
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<td>41.5</td>
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<td>35.5</td>
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<td>49.5</td>
<td>51.5</td>
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NFA 7724 RPM
NFK 7603 RPM
NFD 13020 RPM

NUMBER OF BLADES 93

TAMB 48 DEG F.  THET 45 DEG F
HACT 7.35 GM/M3
BAR 29.2 HD
TABLE IX. - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(c) Percent speed, 60; fan actual rotative speed, 7749 rpm; percent weight flow, 51.2

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<td>50</td>
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<td>70</td>
<td>80</td>
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<td>120</td>
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<td>47.9</td>
<td>46.4</td>
<td>44.8</td>
<td>43.2</td>
<td>41.7</td>
<td>40.2</td>
<td>38.7</td>
<td>37.2</td>
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<td>34.4</td>
<td>33.1</td>
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<td>One-third octave band sound pressure level, dB</td>
<td>60.9</td>
<td>49.4</td>
<td>47.9</td>
<td>46.4</td>
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<td>41.7</td>
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<td>37.2</td>
<td>35.8</td>
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NFA 7748 RPM
NFX 7825 RPM
NFD 8020 RPM

NUMBER OF BLADES 63

TAM 46 deg F
TMT 46 deg F
HACT 3.35 m/s
BAR 24.2 Hg
TABLE IX. - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(d) Percent speed, 70; fan actual rotative speed, 8976 rpm; percent weight flow, 72.8

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</table>

**NFA**

- 6976 RPM
- 9800 RPM
- 13060 RPM

**NUMBER OF Richards 53**

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<thead>
<tr>
<th><strong>NFA</strong></th>
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**TABLE X.**

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<tr>
<td><strong>NFE</strong></td>
<td>13060 RPM</td>
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</tbody>
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**NUMBER OF Richards 53**

- **TANK** 48 DEG F
- **TEAP 48 DEG F**
- **HAT** 7.3% GRM/F
- **HAT** 7.3% MG
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<th>80</th>
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One-third octave band sound pressure level, dB (re 0.0002 pbar)

Table IX - Continued.
[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(e) Percent speed, 70; fan actual rotative speed, 8991 rpm; percent weight flow, 66.8
<table>
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<th>Frequency (Hz)</th>
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<th>PWL (dB) (re 0.0002 pbar)</th>
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TABLE IX. - Continued.

(Model SPLS for standard day (59° F; 70 percent RH) at 100-ft radius.)

(f) Percent speed, 70; fan actual rotative speed, 9017 rpm; percent weight flow, 62.7
### TABLE IX. - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(g) Percent speed, 80; fan actual rotative speed, 10287 rpm; percent weight flow, 83.4

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One-third octave band sound pressure level, dB (re 0.0002 μbar)
TABLE IX. - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(h) Percent speed, EO; fan actual rotative speed, 10 280 rpm; percent weight flow, 76.4

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One-third octave band sound pressure level, dB (re 0.0002 μbar)

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TAMB 47 DEC F TET 44 DEC F

HACT 7-19 GM/M3

BAR 29.2 KG

NFA 10280 RPM

NFK 10397 RPM

NFD 13200 RPM

NUMBER OF BLADES 53
### TABLE IX. - Continued.

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(i) Percent speed, 90; fan actual rotative speed, 11564 rpm; percent weight flow, 93.8

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| DBB | 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 50.4 |
| BBC | 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 60.5 |
| PHL | 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 92.3 |
| PALT | 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 97.3 |

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NFA: 11564 RPM  
NPF: 11702 RPM  
NFO: 11722 RPM

**NUMBER OF BLADES:** 53
**TABLE IX. - Continued.**

[Model SPLS for standard day (59°F; 70 percent RH) at 100-ft radius.]

(j) Percent speed, 90; fan actual rotative speed, 11 570 rpm; percent weight flow, 89.4

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One-third octave band sound pressure level, dB (re 0.0002 μbar)
TABLE IX. - Continued.

[Model SPS1 for standard day (69°F; 70 percent RH) at 100-ft radius.]

(k) Percent speed, 100; fan actual rotative speed, 12,800 rpm; percent weight flow, 99.88

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One-third octave band sound pressure level, dB (re 0.0002 Dbar)

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DBB 80.8 62.0 61.4 61.7 62.5 66.0 69.2 72.4 76.7 81.4 84.9 82.0

DCC 59.8 62.0 61.3 61.5 62.5 65.9 69.1 73.4 78.5 84.9 82.0 78.5

PNL 99.2 100.0 99.9 99.9 99.9 100.0 100.0 100.0 100.0 100.0 100.0 100.0

PNLT 99.2 100.0 99.9 99.9 99.9 100.0 100.0 100.0 100.0 100.0 100.0 100.0

NFA 12505 RPM

NFK 12956 RPM

NFD 13023 RPM

NUMBER OF BLADES 53

TAMB 46 DEG F  TMTET 44 DEG F

MACT 7.09 GM/H3

BAR 29.2 HG
### Table IX - Concluded.

[Model SPLS for standard day (69°F; 70 percent RH) at 100-ft radius.]

1. Percent speed, 100; fan actual rotative speed, 12 737 rpm; percent weight flow, 99.5

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One-third octave band sound pressure level, dB (re 0.0002 μbar)

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### Notes

- DB: D, B, C, PN, PLT
- MFB: 12737 RPM
- MFB: 12912 RPM
- MFB: 13220 RPM
- Number of Blades: 53

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Figure 1. - Flow path for QF-1 fan model.
Figure 2. Rear quarter view of stage 15-9.
Inlet throttle valves

Flow

Vacuum

CD-10916-11

(a) Overall view.

Collector sleeve

valve (translates)

Gear box

Drive motor

Collector

Test stage

Plenum chamber (untreated)

(b) Rotor and microphone locations. (All dimensions are in cm.)

Figure 3. - Compressor aerodynamic test facility with noise measuring locations.
(a-1) Combination total pressure, total temperature, and flow angle probe (double barrel probe).

(a-2) Static pressure probe (8° wedge).

(a) Sensing probes.

(b-1) Station 1 (see fig. 1).

(b-2) Station 2a.

(b-3) Station 2b.

(b-4) Station 3.

(b) Circumferential location of probes at measuring stations, view facing downstream.

Figure 4. - Aerodynamic Instrumentation.
Figure 5. Schematic of anechoic chamber. (All dimensions in m unless indicated otherwise.)
Figure 6. - Interior photograph of anechoic chamber; view looking at fan from air intake opening (intake mode), inlet screen not in place.
Figure 7. - Comparison of fan inlet configurations in anechoic chamber and in modified compressor test facility with plenum chamber. (All dimensions in cm.)

Inlet screen, 0.035 wire 
50 percent open 
(7.9 by 7.9 wires/cm²) 
distance/mesh size = 960

Anechoic chamber with 
well rounded bellmouth inlet

Fan centerline

Compressor test facility with 
plenum chamber (untreated)

Screen, 0.095 wire 
55 percent open 
(2.4 by 2.4 wires/cm²) 
distance/mesh size = 850

Plenum wall

CD-11892-11
(a) 50-Hertz constant bandwidth analysis, 60° microphone.

(b) One-third octave bandwidth analysis, 60° microphone.

(c) One-third octave bandwidth analysis with noise components resolved.

Figure B. Sample sound pressure and sound power spectra from anechoic chamber. 100 Percent design speed; 99.8 percent design weight flow.
Microphone location from rotor face, cm,

Axial   Radial

- 213  0
- 325  66

One-third octave center frequency, Hz

(a) Reverberation time of plenum chamber (from ref. 1).

(b) Relation of PWL to SPL in plenum chamber. PWL = SPL + 10 log v - 10 log τ - 19, dB (re 10^{-13} W) (ref. 12, p. 177) where v = 470 ft^3; τ = reverberation time, sec (see fig. 9a). \therefore PWL = SPL + 26.7 - 19 - 10 log τ = 8 - 10 log τ.

Figure 9. - Determination of sound power level, PWL, from sound pressure level, SPL, measured in plenum chamber of unmodified compressor test facility.
Operating points for acoustic data:
- Plenum chamber
- Anechoic chamber

Estimated

Figure 10. - Overall aerodynamic performance for stage 15-9 with operating points for acoustic data indicated.
Operating points for acoustic data:
- Plenum chamber
- Anechoic chamber

---

Figure 11. Relative Mach number 5 percent span from tip of rotor 15 (from ref. 2).

(a) Mean velocity without turbulence screen.

(b) Turbulence intensity with and without turbulence screen.

---

Figure 12. Radial profiles of mean velocity and turbulence intensity 26.8 centimeters upstream of rotor in anechoic chamber installation with well rounded bellmouth.

80 Percent of design speed, 83.4 percent of design weight flow.
Figure 13. - Effect of inlet turbulence screen on inlet sound power spectrum in anechoic chamber.

(a) 70 Percent of design speed; 72.8 percent of design weight flow.

(b) 80 Percent of design speed; 83.4 percent of design weight flow.
(c) 90 Percent of design speed; 93.8 percent of design weight flow.

(d) 100 Percent of design speed; 99.8 percent of design weight flow.

Figure 13. - Concluded.
Figure 14. - Inlet sound pressure level spectra in anechoic chamber; 60º microphone. Typical 50-hertz constant bandwidth analysis.
Figure 15. - Inlet sound pressure level spectra in anechoic chamber; 60° microphone. Comparison of direct one-third octave band analysis of total noise with values of broadband component calculated from 50-hertz constant bandwidth analysis.
Figure 16. - Inlet sound pressure level spectra in unmodified compressor test facility. Typical 50-hertz constant bandwidth analysis.
Figure 17. - Inlet sound pressure level spectra in unmodified compressor test facility. Comparison of direct one-third octave band analysis of total noise with values of broadband component calculated from 50-hertz constant bandwidth analysis.
Figure 18. Typical continuous 50-hertz constant bandwidth spectra (simulated) in anechoic chamber at 60° inlet angle and in inlet plenum chamber of unmodified compressor test facility. 70 Percent of design speed; P/R = 1.21; relative Mach number at inlet rotor tip, $M_{1,05} = 0.75$. 
Figure 19. - Typical continuous 50-hertz constant bandwidth spectra (simulated) in anechoic chamber at 60° inlet angle and in inlet plenum chamber of unmodified compressor test facility. 100 Percent of design speed.
Figure 20. - Inlet sound power spectra as measured in anechoic chamber and in unmodified compressor test facility at comparable conditions.
Figure 20. Concluded.
Figure 21. - Inlet sound power spectrum as measured in unmodified compressor design speed.

Figure 22. - Inlet sound power spectrum as measured in anechoic chamber. 60 Percent of design speed.
Figure 23. - Inlet sound power spectrum as measured in anechoic chamber and in unmodified compressor test facility. 70 Percent of design speed.
Figure 24. - Inlet sound power spectrum as measured in anechoic chamber and in unmodified compressor test facility. 80 Percent of design speed.
Figure 25. - Inlet sound power spectrum as measured in anechoic chamber and in unmodified compressor test facility. 90 Percent of design speed.
Figure 26. - Inlet sound power spectrum as measured in anechoic chamber and in unmodified compressor test facility. 100 Percent of design speed.
Figure 27. - Blade passing frequency noise (1xBPF + 2xBPF) as measured in unmodified compressor test facility and in anechoic chamber. One-third octave analysis.

Figure 28. - Multiple pure tone noise (BPF's excluded) as measured in unmodified compressor test facility and in anechoic chamber. One-third octave analysis.
Figure 29. - Broadband noise as measured in unmodified compressor test facility and in anechoic chamber. One-third octave analysis.

Figure 30. - Effects of corrected weight flow induced without rotor or stator in unmodified compressor test facility with collector sleeve valve.
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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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