High Bypass Ratio Fan Noise Research Test Vehicle

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A most critical factor in establishing noise levels from a high bypass ratio turbofan engine is the choice of fan design. Although a great deal of research work has been done in support of noise reduction programs for low bypass ratio two-stage fan engines, the single-stage fan without inlet guide vanes has been the subject of relatively limited noise research. To provide noise research capability, a fan test rig vehicle was designed and fabricated for the conduct of noise studies on single-stage high bypass ratio fans. This fan test rig is free turbine driven with a remote mounted JT3 engine providing the hot gas supply to the modified JT3D drive turbine. Flexibility has been incorporated into the design of this rig to allow fans of different designs to be tested over a range of speed and operating conditions, and a wide variety of design and installation features to be evaluated, which are pertinent to the noise output from advanced engine and nacelle designs.

I. Introduction

THE first commercial turbine engine developed at Pratt & Whitney Aircraft was the JT3C turbojet, which was introduced to airline service in 1958. When development of this engine started in 1953, noise research efforts were directed to the suppression of jet exhaust noise. The joint efforts of the engine and airframe engineering teams led to the development of jet exhaust noise suppressors that were available at the time the airplanes went into service.

In 1958, low bypass ratio fan engines were under development. Because of their lower jet velocities these engines produced significantly lower jet exhaust noise levels than that produced by existing turbojets. In 1959 the acoustics research effort at Pratt & Whitney Aircraft was directed to the reduction of fan noise from the JT3D turbofan engine. Soon after the JT3D powered aircraft entered service in 1961, a fan modification ("hush kit") was made available that reduced some of the annoying qualities of the noise from the two fan stages.

Fan noise research from 1959 through 1962 revealed that many design features can influence noise. Results of this research were used to minimize the noise of the JT8D low bypass ratio turbofan engine which was introduced into service in 1964. In that same year, design studies of a completely new powerplant concept were initiated that was to incorporate all the then known noise reduction features. This powerplant emerged in 1966 as the JT9D high bypass ratio engine which is now under development and scheduled for commercial transport service in 1970. In order to reduce fan generated noise, this engine incorporates features such as the omission of inlet guide vanes, a single-stage relatively low tip speed fan, optimum blade to vane spacing and optimum numbers of blades and vanes. This design has resulted in significant noise improvements. Further reductions in noise emanating from the fan, however, must be accomplished to produce the even quieter engines that are desired in the future. As can be seen from Fig. 1, a major feature of the JT9D fan design has been the elimination of noise sources which were significant in past engines. The current high bypass ratio engines, having only a fan rotor and exit vane assembly, represent a limit in the elimination of noise sources. To reach the goals of the future, research into the relationships between detailed fan aerodynamics and noise generation is necessary.

Although a great deal of research work has been done in support of two-stage fan noise reduction programs for low bypass ratio engines, the single-stage fan without inlet guide vanes has been the subject of relatively limited experimental noise research. From studies of advanced aircraft engines, however, it appears that the single-stage fan is well suited to a wide variety of commercial applications including lift fans for VTOL and STOL aircraft as well as for conventional aircraft. Noise criteria can be expected to present difficult design problems for most of these applications. To provide experimental facilities to conduct the necessary research, a series of design studies were initiated at Pratt & Whitney Aircraft that led to the design and fabrication of a new fan noise test vehicle, which recently was put into service.

II. Design Considerations

Before final design of the test vehicle could proceed, a choice had to be made as to the test site location. Basically, the choice was between an indoor or an outdoor site. Experience with the indoor fan noise test rig shown in Fig. 2 has indicated that although "free-field" noise measurement conditions essentially could be achieved by the installation of sound absorbing treatment on the test cell walls, the indoor environment did not lend itself to acceptable distortion and turbulence-free aerodynamic flow. Because these conditions of inlet distortion were almost impossible to rectify and could seriously hamper the study of broadband noise generation, the decision was made to construct an outdoor test facility. This provided natural free-field acoustic conditions in which inlet and fan duct radiated noise could be measured simul-

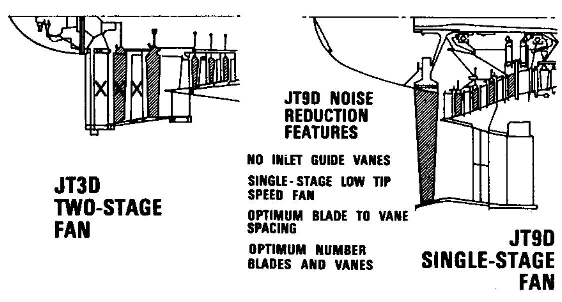

Fig. 1 Noise sources have been eliminated from advanced engines.

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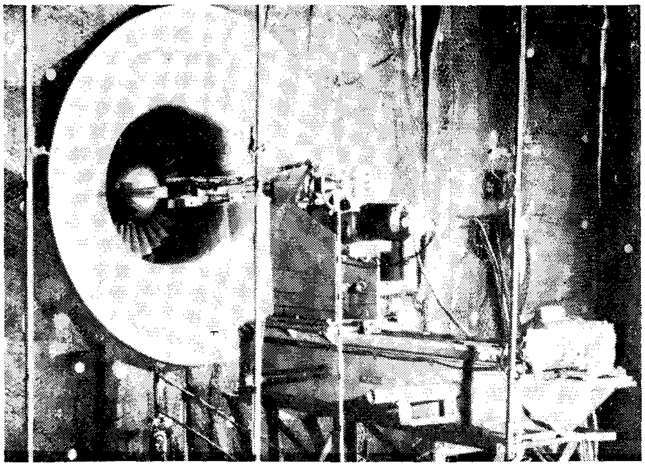

Fig. 2 The 28-in. diam single-stage fan indoor noise rig (in use since 1960).

taneously and, with the fan inlet elevated sufficiently above ground, aerodynamic inlet flow problems could be minimized.

Studies were made of a variety of noise test vehicle configurations that could provide the flexibility necessary to test a variety of fan designs over a wide range of speed, flow and pressure ratio conditions, and also could be used to evaluate a variety of inlet and fan discharge configurations.

The requirements established for the design of the noise research test vehicle that most influenced the final configuration were: 1) free-field acoustical conditions, 2) distortion-free inlet airflow, 3) ability to take measurements of both inlet and aft noise (fan inlet and discharge), 4) operation with large scale test fans, 5) duplication of realistic fan blade loading and flow conditions for both high and low tip speed fans, 6) generous range of rotor to stator spacing capability, 7) ability to operate either with or without inlet guide vanes, 8) ease of installation of acoustical treatment in the inlet and exit ducts, 9) provisions for variation of inlet and fan exit duct length and nozzle area, and 10) flexibility of operation to meet both current and long range test requirements.

Two fundamentally different mechanical arrangements for driving the rig were considered. In one configuration, an available PT-5 turboprop engine was placed in line with the rig and the test fan was driven through a reduction gearbox. In this design, part of the fan air was used to supercharge the drive engine, making the rig similar to a bypass engine. Maintaining the correct airflow "match" between the drive engine compressor inlet and the test fan discharge, however, posed limitations on the use of the test fan over an acceptably wide range of speed under varying fan exit nozzle conditions. The mechanical drive configuration and support structure likewise did not appear to lend itself to a simple design having the necessary flexibility for a research test rig.

The other alternative studied, and the one chosen, was to couple the test fan directly to a drive turbine, and power the drive turbine with hot exhaust gases from a remote mounted JT3C jet engine. This design entailed collecting and delivering the jet engine exhaust flow through a duct to the test vehicle turbine. This design presented no test fan to drive engine matching problems, contained no troublesome gearbox, and permitted more ideal conditions for measurement of fan exit noise. Schematic drawings of the two mechanical arrangements studied are shown in Fig. 3.

III. Mechanical Design

In the design study phase, it was decided to use an available JT3C (J57) turbojet engine as the power source for the rig. The JT3C engine is the heart of the GG3 industrial turbine power package which can deliver up to 22,000 hp, enough to drive single-stage test fans of well over 50-in. diam at realistic levels of flow and pressure ratio. With that amount of available horsepower, it was possible to select an existing 0.57-diam scale model of the JT9D engine fan as a baseline test fan. In addition to utilizing existing hardware having well-documented performance characteristics, this selection resulted in an opportunity to check the procedures used to "scale" noise characteristics for size as data from the test rig could be compared against full scale JT9D engine noise data. Having selected the horsepower source and the test fan, the next phase of the design was to provide a drive turbine from the existing inventory of Pratt & Whitney Aircraft turbomachinery if possible. This requirement was satisfied by selecting the last two turbine stages from a JT3D turbofan engine which could be used with only minor modifications in blade camber. Because of a mismatch in flow capacity between the JT3C engine and the turbine selected, however, it was found necessary to dump overboard about 40 lb/sec of the available hot gas supply. Although this resulted in a waste of available horsepower, the turbine could still supply about 15,000 hp to the test fan over a speed range from 4000 to 8000 rpm, which was more than adequate for the planned test program.

After selection of the major components for the test rig, it then became the job of the designer to evolve a mechanical layout that was free from mechanical vibration and thermal distortion problems, and yet had the flexibility to test a variety of fans and installation features without major structural changes. It was also desired that changes of test components in the field be facilitated by the rig design.

To determine the optimum configuration for the elbow-shaped turbine inlet duct, extensive model tests were conducted to arrive at a design having minimum pressure loss and present acceptable levels of flow distortion to the drive turbine. Because the JT3 gas generator exhaust enters the free turbine at a temperature of up to 1100°F and 34 psia, care had to be taken in the test vehicle design to avoid nonuniform thermal expansion of the vehicle structure where the drive engine exhaust duct entered from one side. This could cause the three-bearing shaft to become misaligned at operating conditions and produce excessive wear and vibration. Thermal isolation of the exhaust duct and turbine inlet elbow from the structure of the test vehicle successfully prevented this problem.

A schematic drawing of the rig cross section is shown in Fig. 4. As can be seen, the rotor shaft is supported by three bearings, one aft of the test fan, one in the plane of the rig front support, and one aft of the drive turbine. The overhung section of the rig forward of the front mount is not supported structurally by the fan exhaust ducts, which helps provide the required flexibility to vary the exhaust duct length or to add or remove treated panels. Individual ducts are provided to simulate the primary engine flowstream and the fan airstream. Separate nozzles can be installed on each stream to vary the operating lines. Shown in the drawing is the baseline 0.57 scale JT9D test fan with the fan exit guide vane assembly in the baseline position. Provisions have been

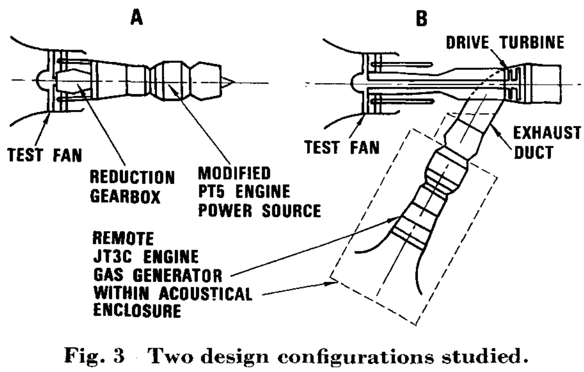

Fig. 3 Two design configurations studied.

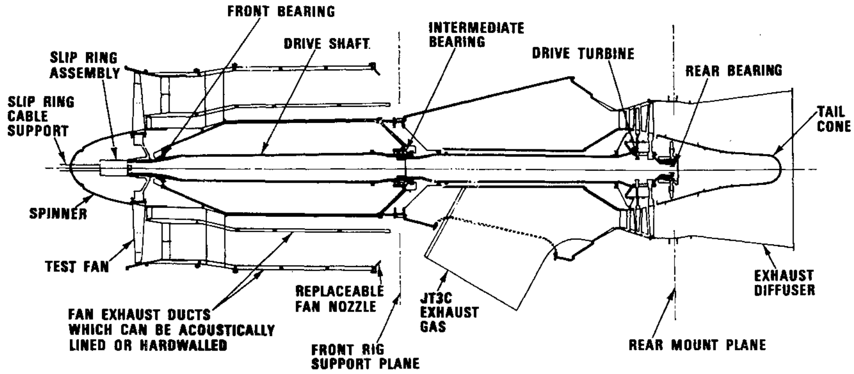

Fig. 4 Schematic of test vehicle construction.

made to allow this stator to be repositioned easily either closer or further from the rotor.

A photograph of the test rig mounted at the outdoor test site, taken from the microphone side, is shown in Fig. 5. Short fan discharge ducts are being simulated by the configuration under the test.

A rear view of the rig is shown in Fig. 6, which gives a view of the exhaust duct that supplies hot high-pressure gases to the rig drive turbine. The acoustically treated enclosure on the left that houses the JT3C drive engine has been sound proofed to ensure that drive engine noise does not contaminate the test rig noise measurements.

IV. Noise Vehicle Performance Measurement

In order to measure the test fan performance to relate the aerodynamics of the various configurations tested to noise generation, it was necessary to provide adequate performance instrumentation. To measure inlet flow, a bellmouth instrumented with Pitot static probes and thermocouples was calibrated at the Pratt & Whitney Aircraft Willgoos Facility. This calibration permits accurate calculations of inlet flow based on Pitot static probe and thermocouple readings and the calibration data. Thirty total pressure probes are located aft of the fan exit guide vanes (20 in the fan and 10 in the primary flow paths) to determine the pressure rise across the stage. Similarly, 30 thermocouples are provided to measure the stage temperature rise. From these data, parameters such as stage efficiency and bypass ratio may be calculated and plots of stage pressure ratio vs flow (typical compressor map) may be constructed. Provisions also have been made for insertion of additional pressure and temperature rakes or probes at other locations. These provisions enable measurements to be taken of the fan rotor performance, exclusive of the stator. In addition, a 60-tooth gear attached to the shaft is sensed by an impulse pickup to supply an accurate speed signal.

V. Test Area Features

The test vehicle is mounted in a large cleared area to insure satisfactory free-field conditions. An aerial view of the test site, located at Bradley International Airport and situated so as to be disturbed only occasionally by aircraft overflights is shown in Fig. 7. Being near the airport and immersed in a wooded area prevents the facility from becoming a community noise nuisance which might curtail its free operation.

Twenty far-field microphones are positioned, as shown in Fig. 8, along an arc 150 ft from the fan, set in at intervals of not greater than 10° from 0° on the rig forward centerline to 150°. Condenser microphones are used that have an acceptable frequency response up to 12 kHz. Cables linking the microphones to the recording room pass underground through conduit. Located at a convenient point near the rig mounting pad is a conduit terminal in which 20 additional microphone cables are available. These cables are routed to the recording room and provide the capability for noise measurement from a variety of near-field microphones, which may be placed close to the rig or within the rig itself for special testing as required.

One of the more important near-field measurement devices is the inlet probe microphone. A 0.125-in. condenser microphone is attached to a long probe that is capable of traversing the noise field in the fan inlet. The position of the probe is controlled using a remote traversing mechanism.

The probing device shown in Fig. 9 is designed to traverse in the radial, circumferential and fore and aft directions. With this device, studies can be made of the noise field inside the inlet duct and near the rotor face. The development of noise signals can be studied as they propagate forward in the inlet duct.

VI. Acoustic Measurements

Equipment for recording the microphone signals is housed in a control room at the test site. The noise data recording console includes power supplies for 20 microphones, signal conditioning equipment, calibration equipment, and a 14-channel magnetic tape recorder. Microphones from the far-field or near-field array may be switched into the console in groups of 20 each and recorded simultaneously in sets of 10.

Analysis of some data is made "on-line" by use of a narrow band spectrum analyzer located at the test site. These data

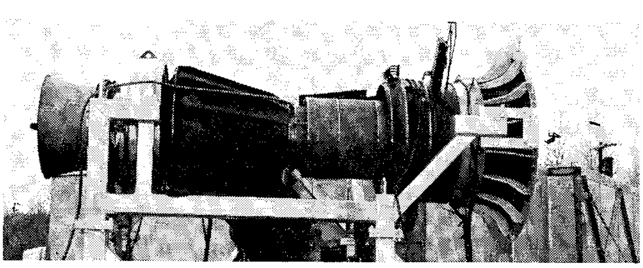

Fig. 5 Noise research test vehicle—view from noise measurement side.

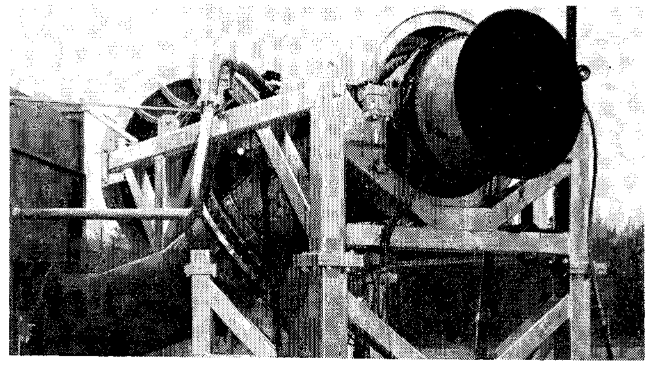

Fig. 6 Noise research test vehicle—view of free turbine exhaust area.

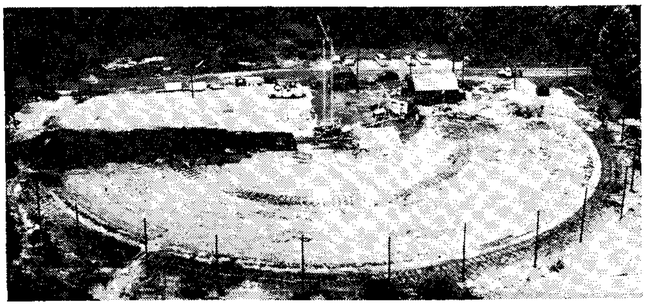

Fig. 7 Aerial view of rig test site.

can provide quick confirmation that the configuration under test is performing satisfactorily and that the measurement systems are operating properly. This confirmation is desirable prior to changing the test configuration to prevent costly and time-consuming repeat running. On-line data also provide early test results, aids in deciding analysis priorities, and can be used for later checks to confirm the validity of the recorded data.

VII. Acoustic Data Reduction

Recordings of the 150-ft radius microphones generally are reduced for all speed points using $\frac{1}{3}$ octave bandwidth filters.

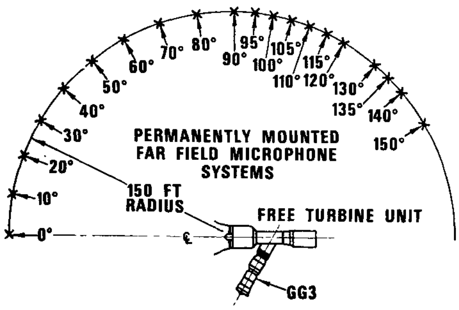

Fig. 8 Noise research test vehicle—outdoor far-field microphone layout.

For this purpose, an automated analyzing console is available that provides digitized results of the analog tapes along with system response information. These results are then input to a computer which first corrects the data for system and microphone response and then proceeds to calculate various extrapolated noise factors such as PNdb depending upon the options selected. Normally, data consisting of the tabulated levels at the microphone locations and plots of extrapolated sideline noise are requested. An example of extrapolated sideline noise at a given speed point is shown in Fig. 10. These data show the perceived noise levels along a sideline, extrapolated from the 150-ft radius measurement position taking into account the change in distance and extra air attenuation factors. These data can be used to predict flyover noise characteristics and to determine the predominant noise sources. For the case shown, the fan discharge is the peak noise source. Figure 11 shows the $\frac{1}{3}$ octave band sound

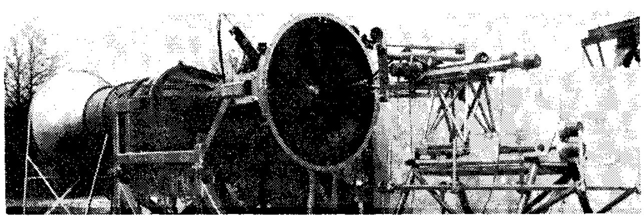

Fig. 9 Noise research test vehicle—inlet microphone traversing mechanism.

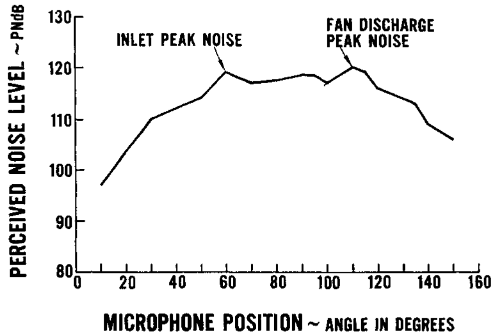

Fig. 10 Extrapolated sideline noise.

pressure levels associated with this peak noise. Further insight into the factors which contribute to the calculated perceived noise level at any one location are revealed in the Noys vs $\frac{1}{3}$ octave band plot. As shown in Fig. 12, the 22nd $\frac{1}{3}$ octave band having a 6300-Hz center frequency is controlling the calculated perceived noise (PNdb) level.

From these preliminary results, selections are made of data to be reduced in detail by narrow band analysis. This analysis defines the composition of signals which make up a given $\frac{1}{3}$ octave, and can be used to identify the source of the dominant noise. Blade passing frequency tones, combination tone

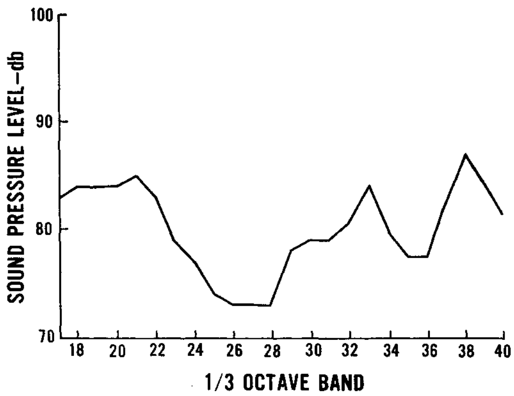

Fig. 11 Sound pressure level vs $^1/_3$ octave band plot.

and broadband noise levels can be identified from the narrow band analysis, shown in Fig. 13, of an inlet microphone recorded at a supersonic fan tip speed condition. A typical aft arc noise spectrum obtained from narrow band analysis at the same condition is shown in Fig. 14. All noises except combination tones that are radiated out the inlet only, can be observed. For reduction of data from the inlet probe microphone a different technique may be used. Although narrow band analysis at specific probe locations is frequently

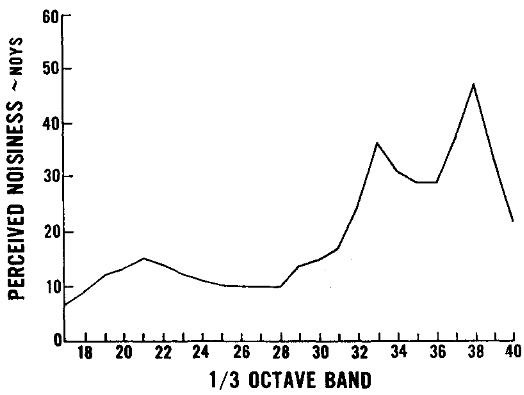

Fig. 12 Noys vs $^1/_3$ octave band plot.

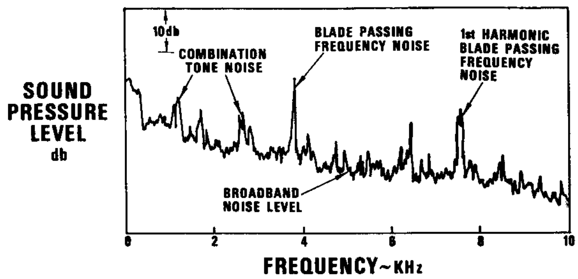

Fig. 13 Narrow band noise spectrum inlet arc noise—60° far-field microphone location, 50-Hz bandwidth.

accomplished, it is often desired to study the variation in level of a particular noise component as the probe is traversed in the inlet at a steady-state operating condition of the test fan. During the analysis of signals from the probe microphone, a recorded vehicle speed signal is used to tune and "track" a narrow band filter (10-Hz BW) onto the frequency of the noise component being studied. A typical plot, Fig. 15, illustrates the blade passing frequency signal level as the probe is traversed axially upstream of the rotor. A tachometer signal multiplier permits "tracking" of almost any noise component, revealing details of the propagation of the signal along the traversed path. These data are helpful especially in defining the characteristics of a noise generation source and in studying the propagation of the noise from the

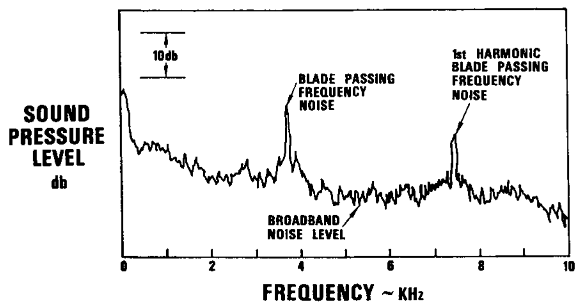

Fig. 14 Narrow band noise spectrum aft arc noise—110° far-field microphone location, 50-Hz bandwidth.

near field of the rotor to the entrance of the inlet duct where it is radiated to the far field.

A great many other analysis techniques can be used to investigate specific acoustic phenomenon. However, it should be pointed out that the preceeding analysis procedures are used widely and have been streamlined to permit rapid reduction of recorded data that form a basis for defining areas of special interest for further investigations.

VIII. Test Program

The test program planned for this new rig can be separated into two basic categories. One involves the examination of

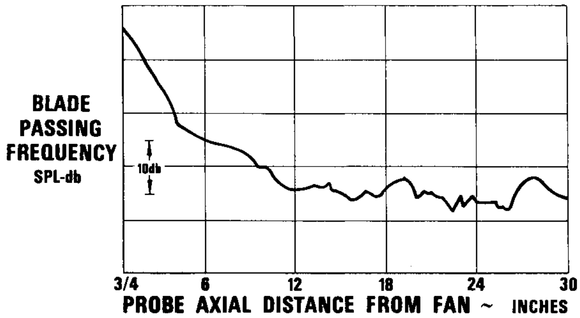

Fig. 15 Inlet duct microphone axial traverse plot.

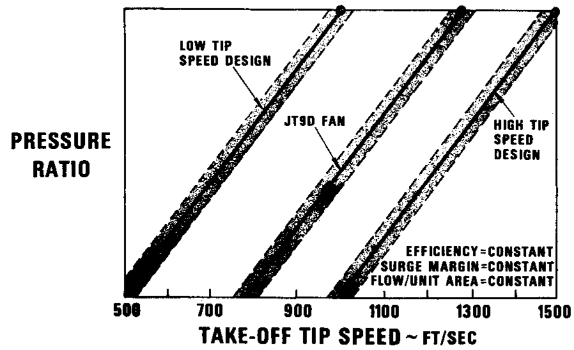

Fig. 16 FAA—fan noise test program.

the characteristics of sound-absorbing liners in various locations in the fan inlet and discharge ducts and the effects of these liners on fan performance. The other includes tests relating aerodynamic changes to changes in noise generation in order to understand more fully the relationships between noise and fan aerodynamics.

The baseline fan configuration includes a 46-blade rotor operating without inlet guide vanes and an exit guide vane assembly having 108 vanes, a configuration which is aerodynamically similar to the JT9D fan at a scale of 0.57. Several items scheduled for early noise testing on the baseline fan include: 1) stator to rotor spacing; 2) fan blade airfoil evaluations—circular arc design, multiple circular arc, and "J" blade; 3) effect of untreated fan duct length; 4) fan duct acoustical lining; 5) inlet wall lining; and 6) acoustically treated circumferential splitter rings in the inlet.

Some of the tests planned for this rig are in support of a contract awarded to Pratt & Whitney Aircraft by the Federal Aviation Administration (FAA). This contract has as its objective the development of improved compressor and fan noise prediction methods, the verification of these methods by means of a series of tests and measurements on different scales and types of vehicles, and the development of a deeper understanding of fan noise generation mechanisms. Under this contract, a series of three different rotors will be designed to operate at takeoff tip speeds of 1000, 1300, and 1500 fps. The design must maintain nearly the same pressure ratio, efficiency, surge margin and flow per unit area for all rotors, as illustrated by Fig. 16. Although attempts have been made in the past to separate the effects of tip speed and blade loading on fan noise generation, these attempts generally have been accomplished by running fan blades of one specific design at off-design points. Serious questions, however, can be raised as to the use of noise data from off-design operation to predict the noise of rotors having significantly different design performance characteristics. In this program, specific designs will be made for the three specific design tip speed conditions of interest to provide basic noise information which can be used in an improved system to predict fan engine noise.

IX. Conclusions

Operation to date of the new fan noise test rig has included the successful completion of mechanical and aerodynamic shakedown tests as well as baseline noise tests. Reliable operation of the rig over the desired range of speeds and pressure ratios has been demonstrated. Noise measurements have been taken that are free from contamination from noise from the drive engine or other extraneous sounds. Good agreement between rig noise data scaled to full-scale conditions and noise levels measured from a full-scale engine has been demonstrated. Results to date provide every encouragement that this new noise test facility will contribute substantially to the design of quieter turbofan powerplants of the future.