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ABSTRACT

Preliminary results are presented for a reverberant-field noise investigation of three fan stages designed for the same overall total pressure ratio of 1.21 at different rotor tip speeds (750, 900, and 1050 ft/sec). The stages were tested statically in a 15-inch-diameter model lift fan installed in a wing pod located in the test section of a wind tunnel. Although the fan stages produced essentially the same design pressure ratio, marked differences were observed in the variation of fan noise with fan operating speed. At design speed, the forward-radiated sound power level was approximately the same for the 750 ft/sec and 900 ft/sec stages. For the 1050 ft/sec stage, the design-speed forward-radiated power level was about 7 dB higher due to the generation of multiple pure tone noise.

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INTRODUCTION

The high bypass ratio fan is currently considered as the most appropriate device for providing either horizontal thrust or vertical lift for civil conventional (CTOL) and short-haul (STOL and VTOL) transport aircraft. Quiet operation is essential for such aircraft during takeoff and landing. Although it is generally agreed that rotor design tip speed is a significant design variable with respect to fan noise, there is some question whether low or high tip speed fans can yield quieter engines for a given fan pressure ratio. Involved in the noise consideration are both the generated noise and the effect of changes in noise character on suppressor design. Since rotor design tip speed is also a major engine and turbine design variable, optimum compromises between aerodynamic and noise requirements require a knowledge of the effect of rotor design tip speed on fan noise.

This paper presents preliminary noise test results of a program designed to investigate the aerodynamic and noise performance of three 15" model fan stages with a range of rotor design tip speeds. Three single stages were designed to produce an overall total pressure ratio of 1.21 at rotor design tip speeds of 750, 900, and 1050 ft/sec. Rotor-stator axial spacing was a minimum of two chord lengths. The fan stages were installed in a wing pod located in the test section of the NASA Lewis Research Center 9' x 15' V/STOL Propulsion Wind Tunnel. The investigation involved measurement of reverberant noise at upstream and downstream tunnel locations during static (no tunnel flow) conditions. Aerodynamic performance of the three fan stages in both static and crossflow conditions was reported in reference 1.[1]

A comparison of the results of the reverberant noise measurements for the three fan stages obtained under static conditions is presented in terms of spectral and overall parameters. Static noise data were obtained with a silencer attached to the outlet of the fan drive turbine. This permitted a direct measure of the noise generated by the fan stage. Thus, the rotor design tip speed effects on fan noise as measured should be applicable to fans in general.

APPARATUS AND TESTS

Fan Stage Design

The major aerodynamic and mechanical features of the test fan assembly are illustrated in the sketch of figure 1. The fan rotor was driven by a compact two-stage supersonic turbine located within the inner casing of the assembly. The turbine was driven by high-pressure air supplied through passages in the six support struts that connected the inner and outer parts of the assembly. Axial separation of the rotor and stator rows was at least twice the rotor tip axial chord length. A part span damper was located at the 65 percent passage height point on the rotor blades.

The inlet bellmouth and nosepiece were axisymmetric sections with axial depth to rotor leading edge equal to 0.165 of the rotor diameter (15.0 inches).

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[1] Stockman, N. O.; Loeffler, I. J.; and Lieblein, S.: Effect of Rotor Design Tip Speed on Aerodynamic Performance of a Model VTOL Lift Fan Under Static and Crossflow Conditions. Paper No. 73-GT-2 presented at ASME Annual Gas Turbine Conference, Washington, D. C., April 8-12, 1973 (also NASA TM X-68169).

The axial depth and surface curvature were designed to minimize the possibility of local separation over the forward portion of the bellmouth at high forward velocities.

The three individual stages were designed for a nominal total pressure ratio in the discharge duct of 1.21 and a nominal corrected weight flow per unit inlet flow area of 37.2 lbs/sec/ft^2 (0.53 average axial inlet Mach number). The nominal design corrected thrust per unit inlet flow area was 684 lb/ft^2. Design outlet Mach number was 0.53 with axial discharge from the stators. The hub-tip ratio at the inlet to the rotor was 0.46.

All blade sections on the rotor and stator were double circular arc profiles. The ratio of chord length at the tip to chord length at the hub was 1.3 for the rotor blades. The corresponding taper ratio for the stator blades was 1.1. Both the rotor and stator blades had an aspect ratio of 3.1 based on average chord and span lengths. For economy, only one set of stator vanes was used, with stagger angle reset as required. Maximum thickness ratio for the rotor varied from 0.08 at the hub to 0.05 at the tip. For the stator the corresponding variation was 0.06 to 0.07.

Table 1 lists the major design characteristics of the three stage configurations. Further design details are given in reference 1. Although the axial spacing between rotor and stator (2.5 in.) and the true rotor blade chord length at the tip ($\sim$1.4 in.) were approximately the same for all three stages, there was a significant variation in the ratio of axial spacing to axial tip chord length as shown in Table 1. The spacing ratio in terms of axial projections is believed to be a more valid measure of the ratio of the true decay length of the rotor wake to the rotor chord. The number of stator blades was not selected to provide for propagation cutoff.

The principal effect of the variation in rotor design speed with regard to noise generation is the variation in rotor tip relative inlet Mach number and aerodynamic blade loading. Design values of relative inlet Mach number in the rotor tip region are listed in Table 1. The 750 ft/sec design is subsonic ($M \approx 0.9$) while the 1050 ft/sec design is transonic ($M \approx 1.13$). Blade-element diffusion factor across the passage at design conditions for both rotor and stator is shown in figure 2 for the three stages. There is a significantly larger difference in diffusion factor between the 750 ft/sec and 900 ft/sec stages than there is between the 900 ft/sec and 1050 ft/sec stages.

Test Setup

The test fan stage assemblies (fig. 1) were installed in a pod attached to a two-dimensional wing that spanned the height of the test section of the Lewis 9' x 15' V/STOL Propulsion Wind Tunnel[2] as shown in figure 3. This low-speed test section was located within the return leg of the Lewis 8' x 6' Supersonic Wind Tunnel as shown in the drawing of figure 4.

The low-speed test section was designed primarily for the aerodynamic testing of VTOL and STOL propulsion and powered lift models under static and tunnel flow conditions. However, preliminary tests indicated that reverberant-field acoustic data could be obtained in certain regions in the tunnel. Upstream and downstream microphone locations were selected as shown in figure 4, for which the measured sound pressure level was essentially invariant with spacial location. The chosen sites were also distant from the source at least several times the calculated hall radius. Upstream and downstream

[2] Yuska, J. A.; Diedrich, J. H.; and Clough, N.: Lewis 9-by-15-Foot V/STOL Wind Tunnel. NASA TM X-2305, 1971.

arrays of four microphones each were employed. A computer program was used to select and average the four data sets to yield a single set representative of either the upstream or downstream location.

For the static noise tests, the wing was turned with its chord normal to the axis of the test section. The upstream microphones were used when the fan inlet was facing upstream (as in fig. 4). Noise measurements were also made with the downstream microphones when the wing was turned with the fan inlet facing the downstream direction. Total pressure rakes in the fan discharge duct recorded stage total pressure ratio. In addition, a static pressure measurement was made on the inlet bellmouth 0.33 inch upstream of the rotor leading edge.

For the noise measuring tests, a silencer was attached directly to the exit of the drive turbine. The purpose of this silencer was to lower the turbine exhaust velocity and absorb some of the internally-generated turbine noise, so that the fan stage noise content could be isolated. The turbine silencer was essentially an annular diffuser with a single splitter. The inner and outer flow surfaces, as well as the splitter surfaces contained honeycomb absorber material tuned to 14 kHz, which was the average blade passing frequency of the drive turbine stages (see Table 2). The silencer with acoustic absorber walls and splitter attached to the exit of the fan drive turbine was effective in suppressing noise from the drive turbine over a broadband of high frequencies. A peak suppression of 16 dB was measured at 14 kHz.

The shape of a reverberant field sound pressure spectrum measured in the tunnel differs from the source power spectrum at the fan because of frequency-selective attenuation in the reverberant field. For a valid comparison of sources which contain varying degrees of high-frequency noise, the frequency-selective attenuation (which is a property of the tunnel geometry and its atmosphere) must be removed. In a reverberant field the significant acoustic parameter is the sound power level (PWL). The sound power level is a characteristic of the source alone and is independent of test site variables.

For each 1/3 octave band frequency PWL values were calculated according to the relations given by Lambert[3] for sound in large enclosures. For a reverberant field, the source power at a given frequency was calculated from the sound pressure level according to the relation

$$PWL = SPL + 10 \log_{10}\left(\frac{R_T}{4}\right)$$

where R_T is the total room constant for the enclosure, computed from the temperature and humidity of the atmosphere and the geometric and acoustic properties of the enclosure.

Since an experimentally-determined value of the room constant was not yet available, it was necessary to make assumptions concerning the acoustic properties of the ends of the tunnel enclosure (cooler on upstream side, and open end on downstream side). Calculations indicated that the relative comparisons of the power spectra from the three fan stages were essentially unaffected by these input values. Also, a preliminary check of the total sound

[3] Beranek, L. L.: Noise Reduction. McGraw Hill, New York, 1960. Chapter 11, "Sound in Large Enclosures", R. F. Lambert.

power of the stages (upstream plus downstream radiated power) indicated reasonably close agreement with predicted values from far field fan noise correlations.

RESULTS AND DISCUSSION

Fan Stage Performance

The aerodynamic performance of the three stages under static conditions was reported in reference 1. Results showed that all three stages closely attained their design performance with respect to stage total pressure ratio, corrected mass flow rate, and corrected thrust. Stage efficiency could not be precisely determined in the tests of reference 1. However, it appeared unlikely from the available measurements that there were any unusually large differences in efficiency at the design point for the three stages. Figure 5 shows the variation of measured overall total pressure ratio with corrected tip speed for the three stages as reported in reference 1. Stage static aerodynamic performance was verified during the noise tests by means of the exit duct rake and inlet static tap measurements.

Fan Stage Noise Results

The basic noise data for the three fan designs were taken as the variation of forward (inlet) radiated overall noise output against corrected tip speed for each stage. Two measurements of forward radiated noise were available (i.e., fan inlet facing the upstream chamber, and fan inlet facing the downstream duct section, fig. 4). In addition, comparisons at the two measuring stations were possible for both the overall sound pressure level (OASPL) and for the calculated overall source power level (PWL).

Figures 6(a) and (b) show the variations of forward radiated OASPL with corrected tip speed as measured in both the upstream and downstream sections. The corresponding variations in forward radiated overall PWL are given in figures 7(a) and (b). Fan design tip speed is indicated by the vertical bar on each curve. The lowest speed points are at 70 percent design speed, and the highest are at 110 percent speed for each fan. The data of figure 7 show a reduction in scatter compared to the data of figure 6 which did not include an adjustment for differences in humidity and temperature.

It is seen from figures 6 and 7 that the relative noise trends are essentially the same for all measurement approaches, and that there is a marked difference in the trends among the three fan designs. The noise levels of the 750 ft/sec fan increased and then leveled off with increasing tip speed, while the 1050 ft/sec fan showed a sharp rise in noise level to significantly higher values, again with a tendency to level off with further increase in tip speed. At design speed, the total forward-radiated power level (fig. 7) was approximately the same for the 750 and 900 ft/sec stages, while the design speed noise for the 1050 ft/sec stage was about 7 dB louder.

The relative noise values at the lowest and highest tip speeds for the three fans can be explained from inspection of the individual sound spectra as shown in figures 8 and 9. Figure 8 presents 1/3 O.B. PWL spectra for the three stages at 70 percent and 100 percent of design speed. The spectra are not very different at 70 percent speed (fig. 8(a)), which accounts for the approximately same noise levels for the lowest speed points in figure 7(a). At 100 percent design speed, (fig. 8(b)), the 1050 ft/sec stage showed a marked increase in power level in the frequency range above 2000 Hz. This increase was due to the appearance of multiple pure tone (MPT) or "buzz-saw" noise associated with the irregular shock patterns formed by the transonic relative inlet flow. The multiple pure tones are clearly evident in the narrow band spectral plot for the 1050 ft/sec stage at design speed shown in figure 9(c). The MPT's appeared predominantly in the frequency range from four times shaft frequency (107 Hz) to the rotor blade passing frequency at 9100 Hz. Higher-order MPT's at lower magnitudes were also apparent for all three stages at frequencies above the rotor blade passing frequency.

The leveling off of the sound power increase with tip speed for the 750 ft/sec stage shown in figure 7 is examined in figure 10. This figure shows the 1/3 O.B. spectra for the 750 ft/sec stage at 70, 85, 100, and 110 percent of design speed. The three higher speeds show comparable levels, especially in the 2 kHz to 6 kHz region associated with the fan broadband noise. Furthermore, the levels of the bands containing the blade passing frequencies are not much different in magnitude, and are also not appreciably higher than the broadband noise levels. Another interesting feature of the noise variation for the 750 ft/sec stage (as determined from the narrow band spectra of fig. 11) was a progressive reduction of harmonic tone amplitude with increasing speed. The start of a comparable leveling off trend before the onset of MPT noise generation can also be observed for the 900 ft/sec stage in figure 7.

Correlation with Design Parameters

The principal aerodynamic design parameters believed to be related to the fan stage noise generation are: (1) the total pressure rise (measure of specific work input to the air); (2) the relative inlet Mach number in the rotor tip region (measure of multiple-pure-tone and broadband noise generation); and (3) blade loading (measure of wake formation and interaction noise). In an attempt to factor out these parameters, comparison plots were made for the noise of the three stages against rotor tip relative inlet Mach number and stage total pressure rise ratio (pressure ratio minus one) in figures 12 and 13, respectively.

Figure 12 shows that the subsonic design stages (750 and 900 ft/sec) tended to produce a leveling off in forward radiated power level as tip relative inlet Mach number was increased to around 1.05. Beyond that value there was an increase in power level. A sharp rise in power level is especially pronounced for the 1050 ft/sec stage beyond a tip relative inlet Mach number of around 1.0. As indicated previously, these increases in noise power were the result of the appearance of multiple pure tone noise due to irregular shock wave formations at the rotor inlet.

At a given tip relative inlet Mach number below the "critical" value (i.e., formation of MPT noise), the sound power level tended to decrease with increasing rotor design tip speed in figure 12. However, it should be noted that both total pressure ratio and blade loading also decrease with increasing rotor design tip speed for a given tip relative inlet Mach number. It is therefore necessary to examine the corresponding plots of forward-radiated power level versus total pressure rise ratio as shown in figure 13.

The variations of figure 13 tend to suggest the existence of "subsonic" and "supersonic" noise trends. The 750 ft/sec stage results and the low-pressure-rise values for the 900 and 1050 ft/sec stages can be interpreted to represent a basic subsonic correlation in terms of pressure rise. In this region, it appears that blade loading may be a significant parameter, inasmuch as the highest design tip speed stage (lowest loading) tended to produce the lowest noise level, despite its higher tip relative inlet Mach number*. The attainment of the same power level for the 750 ft/sec and 900 ft/sec designs at their design tip speed may have been due to a counterbalancing of the relative velocity and blade loading effects in these two stages.

Departures from the subsonic correlation occur for a given stage when the rotor tip relative inlet Mach number exceeds the "critical" value. The critical tip relative inlet Mach numbers for these stages can be determined from the plots of figure 12. It is expected that the specific value for the critical Mach number and the magnitude of the rise in noise level above the subsonic base for a particular stage will depend upon the operating condition (back pressure) and rotor geometry (blade shape, solidity, stagger, etc.) of that stage.

SUMMARY OF RESULTS

The following principal results were obtained from reverberant-field measurements of the forward-radiated noise from three small-scale fan stages, each designed to produce a stage total pressure ratio of 1.21 at a different design tip speed (750, 900, and 1050 ft/sec):

1. Although the fan stages produced essentially the same design total pressure ratio, marked differences were observed in the variation of fan noise with fan operating speed.

*It should be noted that the 1050 ft/sec stage also had the largest effective separation distance between rotor and stator, as indicated in Table 1.

2. At design speed, the sound power level was effectively the same for the 750 ft/sec and 900 ft/sec stages. For the 1050 ft/sec stage, the design-speed power level was around 7 dB higher, due to the generation of multiple pure tone ("buzz saw") noise.

3. Sound power level increased, due to the appearance of multiple pure tone noise, when the relative inlet Mach number at the rotor tip exceeded a value of around 1.0 to 1.05.

4. The sound power level for the stages appeared to be composed of a subsonic base variation (dependent on total pressure rise and possibly blade loading), with an increase above this level due to multiple pure tones when the "critical" rotor tip relative inlet Mach number was exceeded.

TABLE 1. - FAN STAGE DESIGN VALUES: 1.21 PRESSURE RATIO

Corrected tip speed, ft/sec	750	900	1050
ROTOR			
Relative inlet Mach no. at tip	0.90	1.01	1.13
Number of blades	37	37	34
Tip solidity	1.1	1.1	1.0
Tip diffusion factor*	0.41	0.34	0.32
Camber angle (tip/hub), deg.	15.5/46.0	6.1/33.0	3.6/25.1
Chord angle (tip/hub), deg.	42.1/5.0	47.6/14.4	53.4/22.8
STATOR			
Relative inlet Mach no. at hub	0.69	0.62	0.59
Number of blades	42	42	36
Tip solidity	1.1	1.1	0.94
Hub diffusion factor*	0.42	0.33	0.29
Camber angle (tip/hub), deg.	35.0/38.5	35.0/38.5	35.0/38.5
Chord angle (tip/hub), deg.	13.8/14.4	10.8/11.4	8.3/8.9
Rotor-stator spacing ratio	2.3	2.8	3.1

* At 5 percent of span from wall

TABLE 2. - PURE TONE FREQUENCIES

Design tip speed (ft/sec)	No. fan rotor blades	Shaft speed, (rps)	Fan BPF, (Hz)	1st stage turbine BPF, (Hz)	2nd stage turbine BPF, (Hz)
100% Speed					
750	37	191	7,050	9,200	13,700
900	37	230	8,500	11,000	16,500
1050	34	267	9,100	12,800	19,200
70% Speed					
750	37	134	4,950	6,450	9,600
900	37	161	5,950	7,700	11,600
1050	34	187	6,370	9,000	13,500

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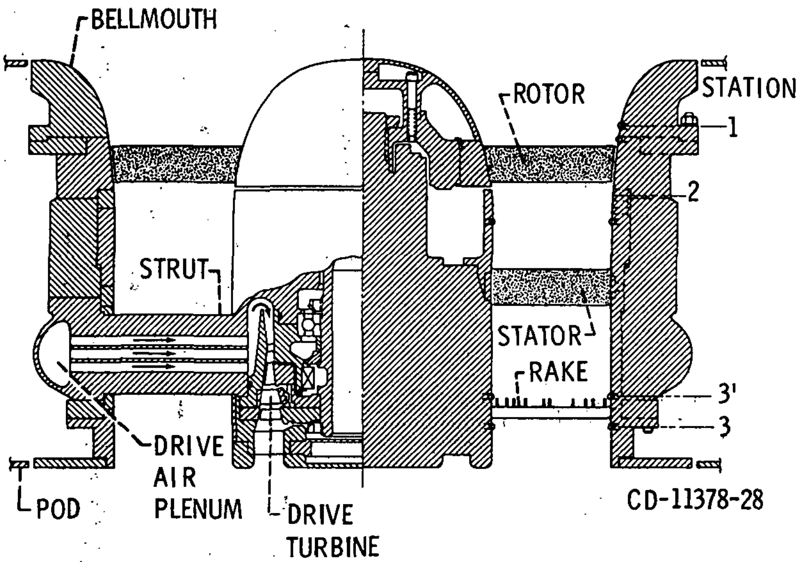

Figure 1. - Cross section of 15-inch model lift fan.

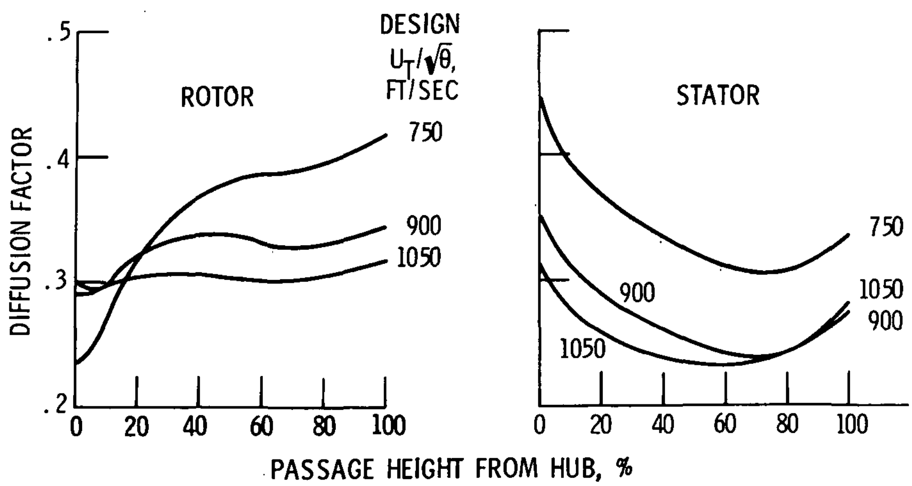

Figure 2. - Radial variation of design diffusion factor for three 1.21 pressure ratio fans.

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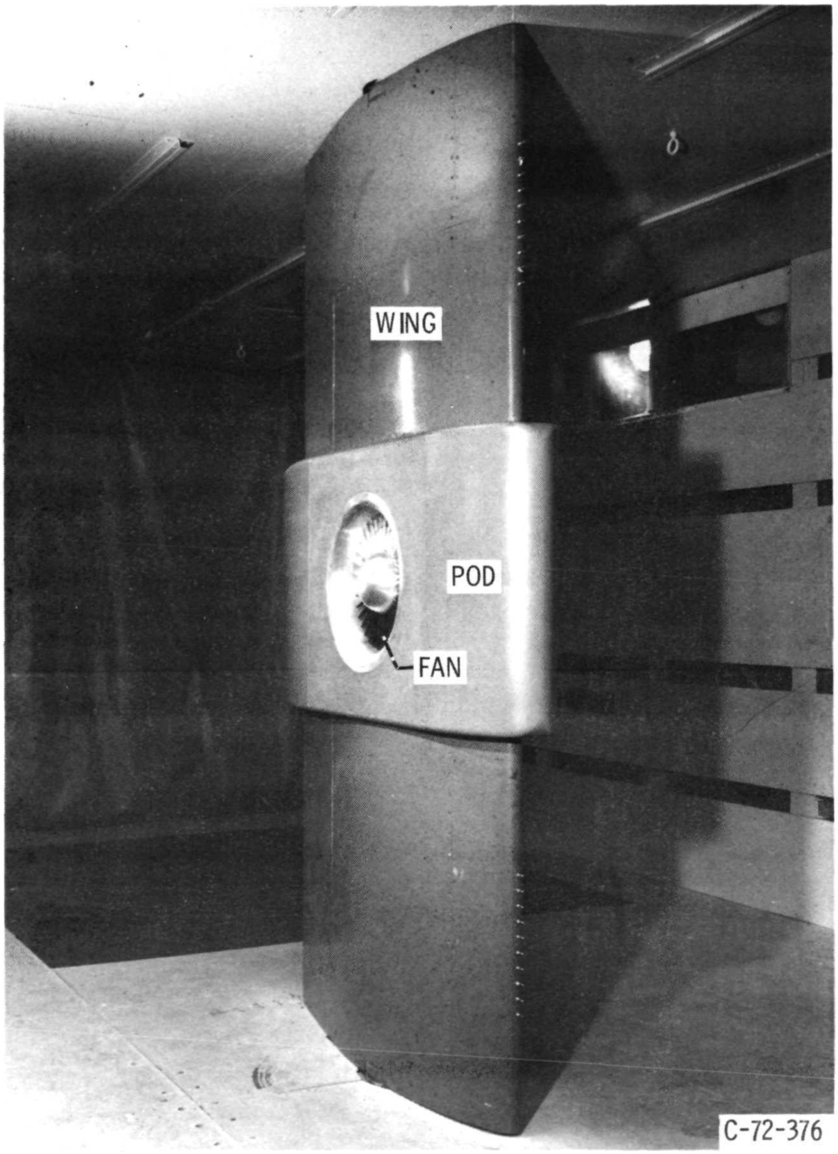

Figure 3. - Fifteen-inch fan-in-pod installed in the Lewis Research Center 9- by 15-foot V/STOL propulsion test section.

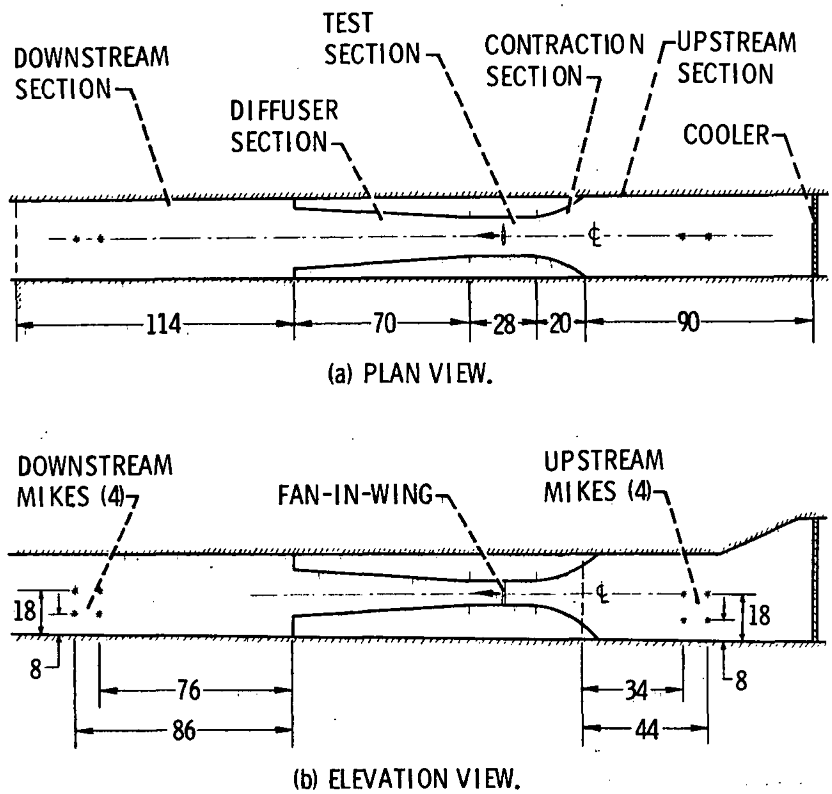

Figure 4. - Sketch of fan test section and microphone locations; Lewis 9' x 15' V/STOL wind tunnel. All dimensions in feet.

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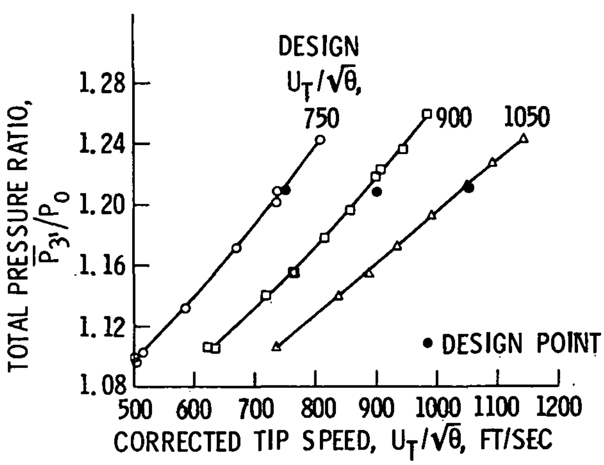

Figure 5. - Comparison of fan total pressure ratio under static operating conditions.

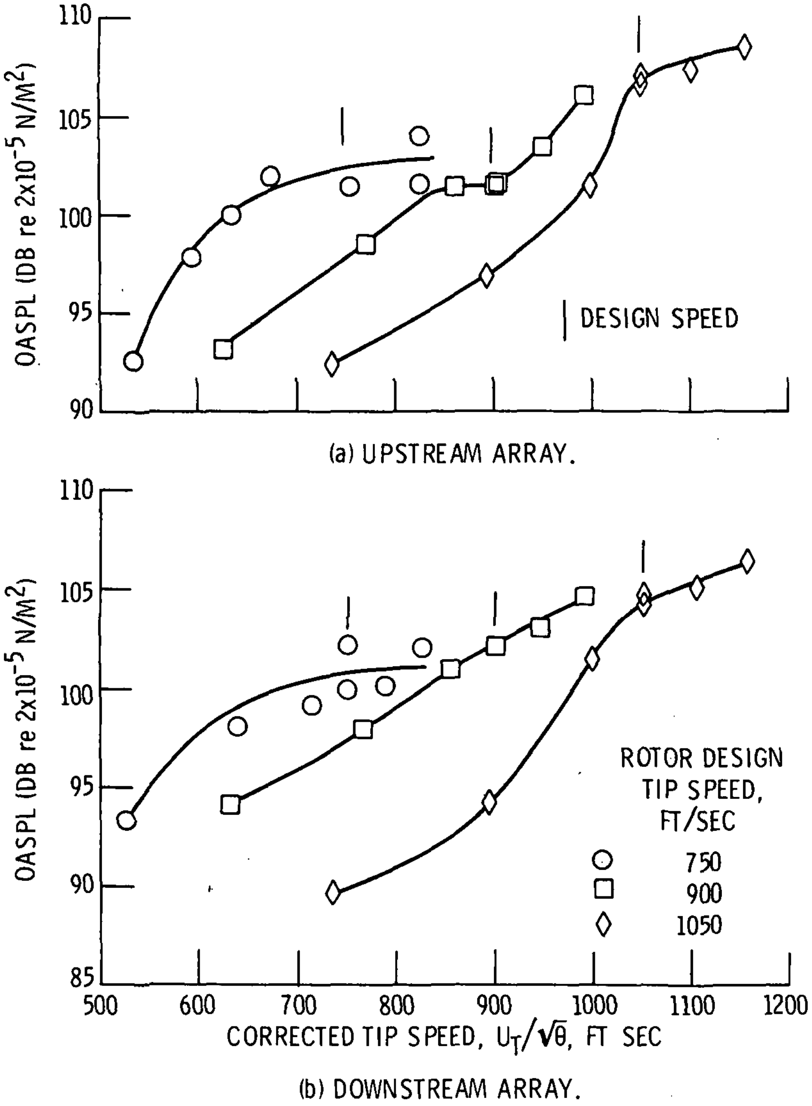

Figure 6. - Reverberant-field forward radiated OASPL versus corrected rotor tip speed for three 1.21 stage pressure ratio fans.

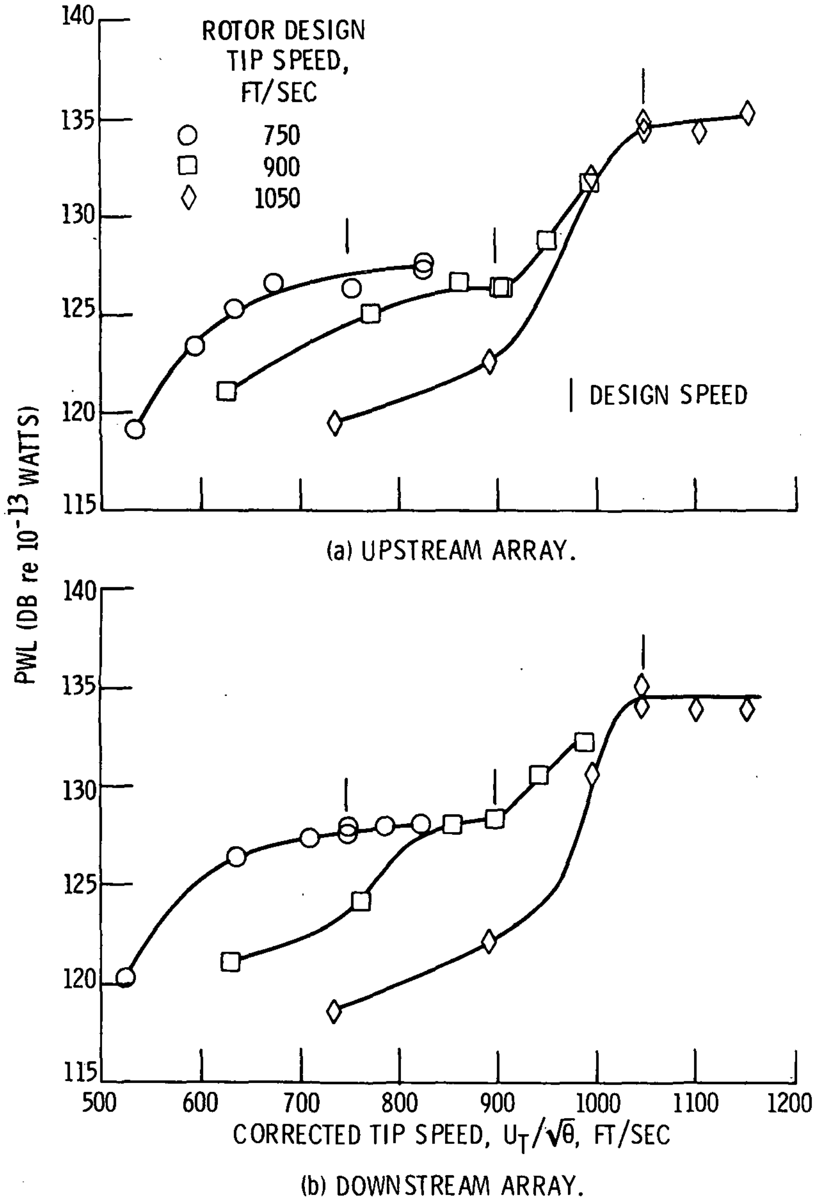

Figure 7. - Reverberant-field forward radiated sound power level versus corrected rotor tip speed.

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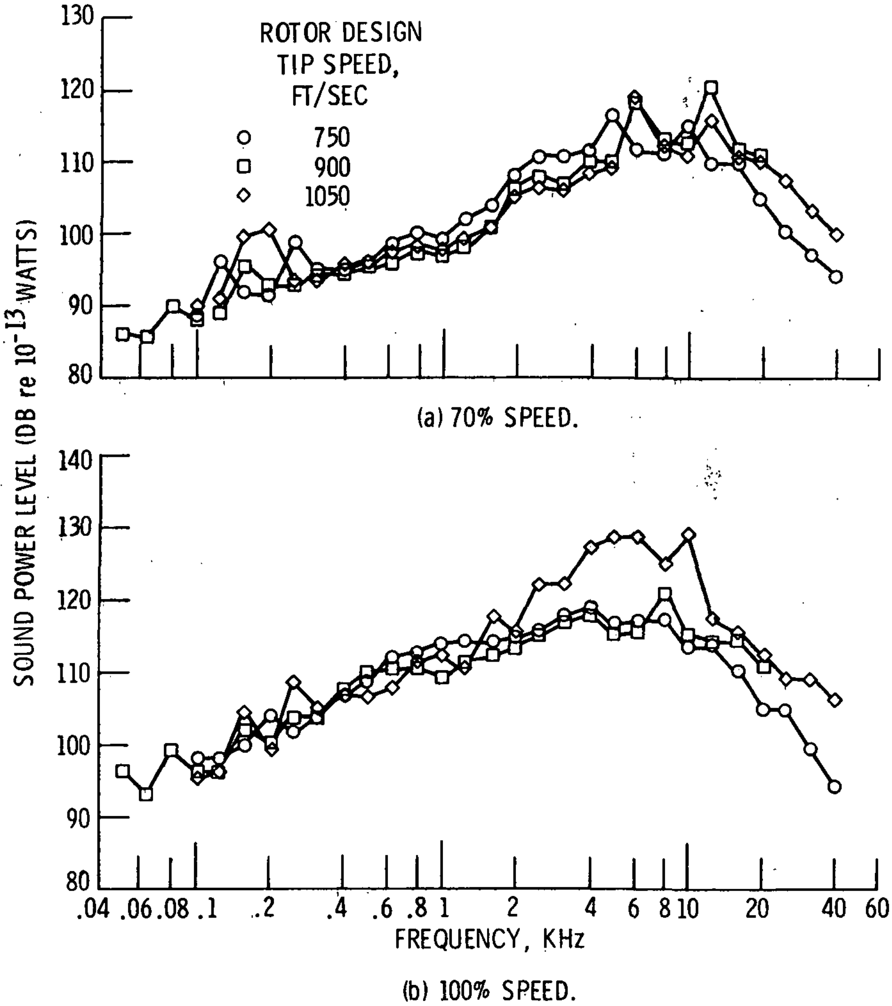

Figure 8. - Comparison of 1/3 O. B. sound power spectra of three fans.

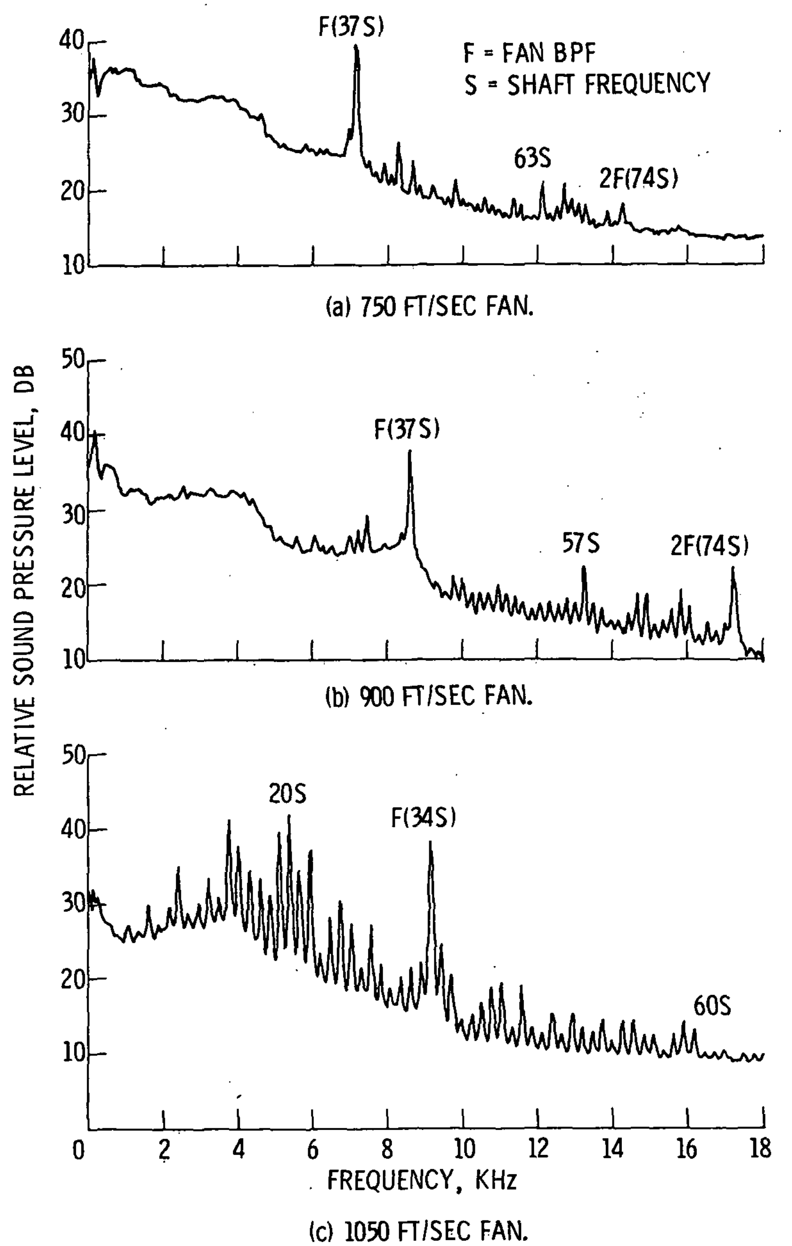

Figure 9. - Narrow band spectra at 100% design speed. Forward radiated noise.

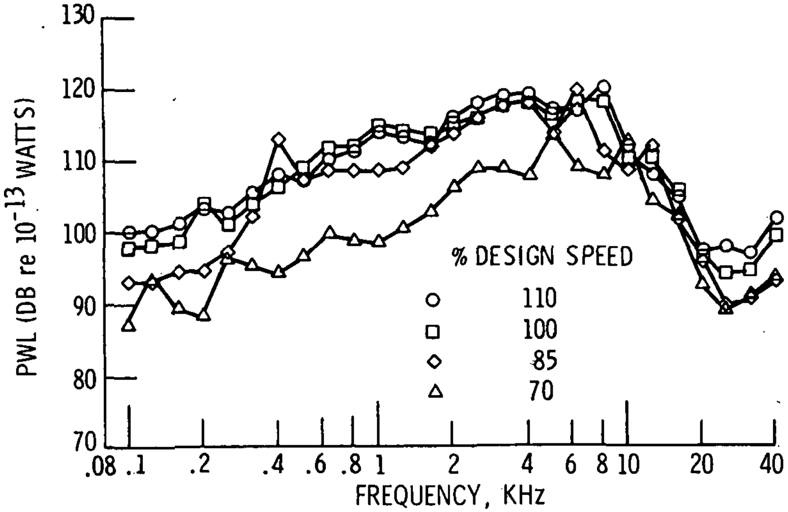

Figure 10. - Effect of operating speed on 1/3 O. B. spectrum of 750 ft/sec fan.

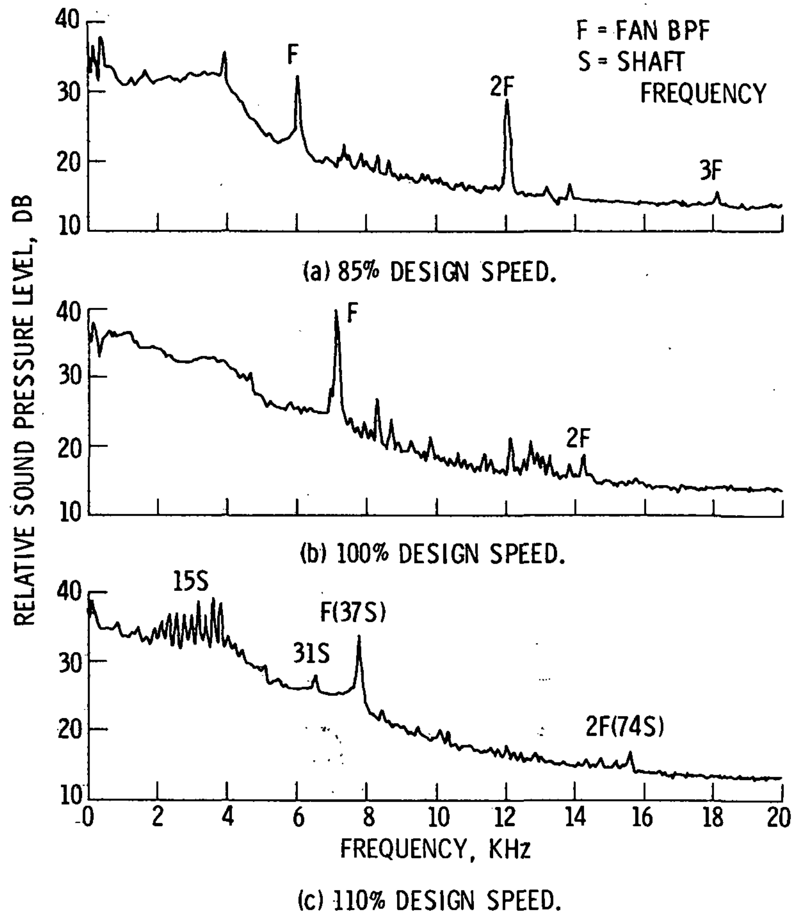

Figure 11. - Narrow band spectra at 85, 100, and 110% design speed. Forward radiated noise, 750 ft/sec fan.

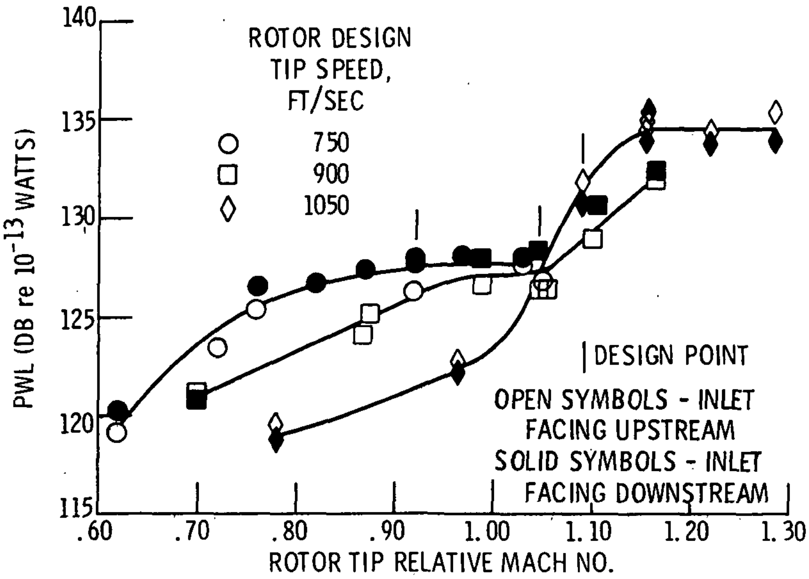

Figure 12. - Forward radiated sound power versus relative inlet Mach number at rotor tip.

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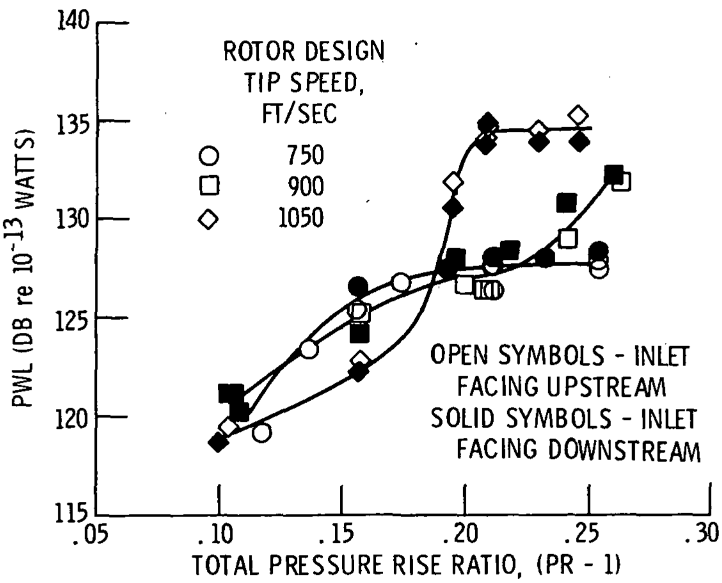

Figure 13. - Forward radiated sound power versus pressure rise ratio for three 1.21 stage pressure ratio fans.