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Aeronautical Report (National Research Council Canada); no. LR-508, 1968-06

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AERONAUTICAL REPORT
LR-508

NOISE STUDIES FROM THE FAN-IN-WING MODEL

by

G. KRISHNAPPA
DIVISION OF MECHANICAL ENGINEERING

OTTAWA
JUNE 1968

NRC NO. 10605

NOISE STUDIES FROM THE FAN-IN-WING MODEL

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SUMMARY

Some preliminary measurements of noise from a highly loaded fan-in-wing configuration are reported. Measurements of the spectra are presented for fan speeds of 7500, 9750, and 13,125 rpm (corresponding to tip Mach number 0.35, 0.45, and 0.62) at an angle of 20° from the axis of the fan and at 5 feet from the inlet and efflux faces of the fan.

The experimental results show a discrete peak at blade-passing frequency, superimposed on a broad band noise that extends from 1000 cs to 15,000 cs. An analysis of the duct transmission of higher order modes at the above rotational speeds, as given by Tyler and Sofrin3), reveals high decay rates. This explains the absence of discrete tones at the harmonics of the blade-passing frequencies. The presence of high intensity broad band noise may be attributed to the turbulence in the wake and free stream turbulence ahead of the rotor blades.

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ILLUSTRATIONS

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SYMBOLS

Symbol	Definition
B	Number of rotor blades
k	Characteristic number
m	Number of pressure lobes
M_m	Circumferential tip Mach number
M_m^*	Critical tip Mach number
n	Order of harmonics
P_m	Radial pressure distribution for lobe pattern
$P_{m\mu}$	Pressure amplitude for circumferential lobes and radial modes
r_o	Radius of the outer wall of the duct
r	Radius of tip of the fan
t	Time
V	Number of stator blades
X	Distance along the duct axis
Ω	Shaft speed
ω	Circular frequency
θ	Angular co-ordinate
μ	Number of radial modes
v	Integer

NOISE STUDIES FROM THE FAN-IN-WING MODEL

1.0 INTRODUCTION

Studies of the design and aerodynamic performance of highly loaded, ducted fan-in-wing configurations have been in progress for the past few years in the Engine Laboratory. The ducted fan operates at subsonic tip speeds with a relatively heavy blade loading. With a limited space to house the fan and its accessories inside the wing, one may recognize the importance of noise measurements from this configuration.

During the past few years much research has been directed towards elucidation of the mechanisms of generation and propagation of noise from axial flow compressors and fans. The general nature of fan noise is revealed by the frequency spectrum.

Examination of a typical frequency spectrum of compressor or fan noise shows the discrete peaks superimposed on a broad noise spectrum extending over a range of frequencies.

1.1 Discrete Tones

Discrete tones occur at blade-passing frequency and its harmonics, and are produced by two possible mechanisms.

The first mechanism is very similar to the noise radiation from subsonic propellers, wherein an elemental area of air in the propeller plane experiences a force fluctuation each time a blade element and its associated pressure field passes. As a result of these force fluctuations, noise is radiated because of a distribution of dipole sources.

The second mechanism involves the rotor and stator blade interaction effects. The rotating wake shed by the rotor and stator blade row impinges on the succeeding blade row. Within the wake, there is a mean reduction in the velocity; this reduction causes a fluctuating incidence at the downstream blade, and unsteady lift fluctuations are produced that radiate dipole noise.

1.2 Broad Band Noise

The broad band noise is mainly produced because of the action of turbulence. Two main causes of the generation of broad band noise are:

1) The turbulence in the wake shed by the upstream blade row produces random incidences on the blades at the downstream blade row. These random incidences give rise to fluctuating lift on the blade. The turbulence in the wake is likely to consist of eddies with a wide range of frequencies, which causes the radiation of broad band noise.

2) Free stream turbulence ahead of the blades will set up additional lift fluctuations over the blade, which is radiated as dipole noise. However, experiments of Sharland1) have shown beyond doubt that free stream turbulence has a dominant effect in generating broad band noise.

An exhaustive review on the mechanism of generation and propagation of compressor noise may be found in Lowson[2)].

1.3 Propagation Inside the Inlet Duct

Ducted fans generate pressure patterns that spin about the duct axis. The transmission qualities of spinning higher-order modes of sound have been effectively demonstrated by Tyler and Sofrin[3)]. These spinning modes of sound have a distinct cut-off property that is not found in the propagation of plane waves. Spinning modes in a uniform duct fail to propagate if the frequency of the generated noise falls below a critical frequency. This critical frequency may be computed for any given combination of rotor and stator blades in a uniform duct.

1.4 Scope of the Present Work

This report presents the measurements of spectra of noise for three different speeds of the fan. The analysis of the measurements is reported in the light of the above-described mechanism of generation and propagation of fan noise.

The measurements must be regarded as preliminary, as they were not recorded under true free field conditions. However, under true free field conditions a large change in the pattern of the recorded spectra is not anticipated in the frequency range 1000 c/s to 15,000 c/s. Probably there is an increase in the noise level in the recorded spectra due to the effect of reflections from the tunnel walls.

2.0 DETAILS OF TEST EQUIPMENT

Figure 1 shows the experimental arrangement. Noise studies from ducted fan-in-wing configuration were made under static inflow conditions inside the NRC 10-ft × 20-ft Open Circuit Propulsion Tunnel. The main wing had an NACA 0015 basic profile. The wing had a chord of 40 inches and an aspect ratio of 3. A cross section of the fan-in-wing configuration is shown in Figure 2.

The fan was 12 inches in diameter with a hub-to-tip radius ratio of 0.5. It consisted of 18 rotor blades having C7 profiles with a chord of 1.5 inches, and 11 stator blades with double circular arc blade sections with a chord of 1.65 inches. The fan blade configuration at mid-span is shown in Figure 3. The spacing between the rotor and stator blades was 0.325 inches. The inlet to the fan had a bellmouth entry with a duct length of 2.5 inches. The fan was connected to the radial turbine drive outside the tunnel through helical and bevel gear sets.

3.0 INSTRUMENTATION

Figure 4 shows a block diagram of the instruments used.

The microphone was $\frac{1}{2}$ inch in diameter, with a sensitivity of 1 mv/μ bar. It had a flat frequency response from 20 cs to 35 Kcs. A nose cone supplied by the manufacturer was used in place of the protection grid in order to suppress the wind disturbance. Introduction of the nose cone alters the frequency response at the high frequency end, but gives the microphone more omnidirectional characteristics.

The cathode follower had a long multi core cable that permitted connection of the microphone to the narrow band frequency analyzer outside the tunnel. The whole system was periodically calibrated by using a piston phone.

The microphone unit was connected to a constant percentage bandwidth analyzer. The spectrograms were recorded in a level recorder that was connected both mechanically and electrically to the frequency analyzer.

4.0 EXPERIMENTAL RESULTS

Figures 5 to 7 show the recorded spectra of noise for fan speeds of 7500, 9750, and 13,125 rpm at 20° from the axis of the fan and 5 ft from the inlet duct. Figure 8 is the recorded spectrum for a fan speed of 13,125 rpm at 5 ft and 20° from the axis of the fan at the efflux side.

Note that there is no significant difference in the spectra recorded at inlet and efflux sides of the fan. When the spectra are recorded in an enclosure, the directivity becomes distorted because of the effect of reflections from the walls, and under true reverberation conditions the spectra would tend to remain independent of the position of the microphone.

The spectra indicate a frequency peak occurring at or around the blade-passing frequency. The discrete tones are not conspicuous at the harmonics of the blade-passing frequencies as in the case of noise from turbojet compressors, for example, as given by Bragg and Bridge4). The broad band noise extends from 1000 c/s to beyond 15,000 c/s.

Because no precautionary measures were taken to isolate the gear boxes, the noise from two sets of gears cannot be excluded from the total noise. The tooth contact frequency of the gear sets are 9603, 7161, and 5510 c/s for fan speeds of 13,125, 9750, and 7500 rpm respectively. However, the gear noise is probably not comparable with the noise from the fan, as one does not observe any significant peak at the gear tooth contact frequency. This is further supported by the measurements at Rolls-Royce (England), where investigators are reported to have found in their acoustic measurements that gears generate low levels of noise when compared with the noise from fans and compressors.

5.0 DISCUSSION

5.1 Discrete Tones

Discrete frequency noise is known to occur at the blade-passing frequency and its lower harmonics, as a result of lift fluctuation on rotor and stator blades. These unsteady forces may be divided into the oscillating forces due to the interaction of successive blade rows, and random forces due to turbulence.

The problem of blade interaction was studied by Kemp and Sears5, 6). They showed two possible interactions; the first, the unsteadiness in the potential flow of each blade row, and the second, because of the viscous wakes leaving the stator and rotor blade row impinging on the succeeding blade row on the downstream side.

The analysis of Kemp and Sears has shown that the magnitude of the forces due to potential flow interactions is inversely proportional to the square of the blade separation, while the forces due to wake interactions are inversely proportional only to the blade separation. Lowson2), in his recent paper on the reduction of noise radiation, has assembled experimental data from a number of investigators. Figure 9 shows the assembled data on the effect of rotor and stator blade spacing. All the data have been adjusted to zero at a spacing/stator chord ratio of 1.0. It may be observed in the Figure that there is an increase of 10 db in the fundamental tone when the spacing ratio is decreased from 1.0 to 0.2.

The spacing between the rotor and stator blades in the present fan is 0.2 stator chord length. The above evidence may suggest that the discrete tones are generated as a result of rotor-stator blade interaction effects.

Spikes at the harmonics of the blade-passing frequencies are not very conspicuous. However, the following analysis of the propagation of discrete tones in the inlet duct would reveal high decay rates for the harmonics of the blade-passing frequencies.

5.2 Inlet Duct Transmission

The analysis given by Tyler and Sofrin2) reveals the importance of the inlet duct in propagating the discrete tones produced by fan blades.

Rotor blades generate circumferential and radial variation of pressure patterns. A number of circumferential lobes in terms of the multiples of the number of rotor blades, are formed. These pressure lobes spin at the shaft speed Ω, giving a pressure fluctuation with a circular frequency

$$\omega = m\Omega$$

where m is the number of pressure lobes around the circumference. In an annular duct, based on the equation describing the propagation of waves, the radial pressure variations may be expressed as a combination of Bessel functions. The pressure at a point in the plane of the rotor blades may be represented by

$$P_m (r, \theta, t) = P_m(r) \operatorname{Cos} \left[m (\theta - \Omega t) \right] \tag{1}$$

where $P_m(r)$ is the radial pressure distribution for m circumferential lobe pattern

t is the time

θ is the angular co-ordinate.

Tyler and Sofrin have shown that in an annular duct the higher-order spinning modes decay or propagate according to the characteristic number

$$M_m{}^2 \lesseqgtr k^2$$

where k is a characteristic number

M_m is the circumferential tip Mach number.

k is associated with Bessel functions describing the radial pressure distributions. The value of k depends upon the number of circumferential lobes m, radial pressure distribution, and hub-to-tip radius ratio of the fan. $M^*_m = k$ is called the critical tip Mach number. When the tip Mach number of the fan is below the critical tip Mach number, the higher-order spinning modes decay along the inlet duct. The decaying pressure field at a distance X from the reference plane may be calculated from

$$P(r,\theta,X,t) = P_{m\mu} \operatorname{Cos}\left[(m-\Omega t)\right] e^{-\frac{m}{r_o}\sqrt{k^2 - M_m{}^2}\, X} \tag{2}$$

where $P_{m\mu}$ is the pressure amplitude for m circumferential lobes and μ radial modes; r_o is the radius of the outerwall of the duct.

Computations of the critical Mach number by Tyler and Sofrin have shown that, when the rotor speed is below critical so that the $\mu = 0$ mode is decaying, the higher radial modes decay more rapidly and become insignificant. The rate of decay for the $\mu = 0$ radial mode is given by

$$\frac{\Delta \mathrm{db}}{\Delta X / r_o} = 8.69\, m \sqrt{M^*_m{}^2 - M_m{}^2}$$

For any given rotor and stator blade interaction, Tyler and Sofrin have shown that not all modes are propagated. The propagated order of the circumferential mode m is given by

$$m = nB + rV$$

where B is the number of rotor blades

n is the order of harmonic

V is the number of stator blades and v can take any positive or negative integer values.

Furthermore, larger values of m give rise to rapidly decaying higher modes, so that only one or two values of m are significant in determining the actual duct radiation characteristics.

In the present model fan, with 18 rotor blades and 11 stators, the lowest order of m generating noise at the fundamental blade-passing frequency is m = -3 (-ve sign indicates the pressure pattern rotating in a direction opposite to that of the shaft because of rotor and stator blade interaction).

The following Table gives the decay rate per outer radius of the duct wall for the different tip Mach numbers of the recorded spectra.

RPM	Tip Mach Number	Decay Rate in db/Outer Radius
13125	0.62	28.3
9750	0.45	30.4
7500	0.35	36.9

5.3 Broadband Noise

The problem of predicting or estimating the broadband noise is more complicated. The present measurements indicate a relatively high intensity of broadband noise extending over a wide range of frequencies (1000 - 15,000 c/s).

Based on the accumulated data on the measurements of jet noise, the spectrum of the noise from the efflux may be approximately located between 100 c/s - 2000 c/s. In this frequency range, the figures indicate a relatively low noise level.

Experiments of Sharland1) suggest that a substantial contribution to the generation of broadband noise comes from the presence of turbulence ahead of the rotor blades. However, further measurements of the spectra of free stream turbulence at the inlet are necessary in order to assess the relative magnitude of the generation of broadband noise by each source.

6.0 CONCLUSIONS

Preliminary measurements of the noise from a ducted fan-in-wing show the peak at blade-passing frequency, with a wide band noise extending from 1000 c/s to 15,000 c/s.

There are no appreciable peaks at the harmonics of the blade-passing frequencies.

Based on the experimental results by a number of workers (Lowson2), the discrete tone may be attributed to rotor and stator blade interaction effects.

Analysis of spinning modes in the duct reveals high decay rates along the inlet duct for the discrete tones at the harmonics of blade-passing frequencies.

7.0 FUTURE WORK

The following projects on the noise from the fan-in-wing configuration are recommended for future work.

1) Accurate measurements of the far field noise and spectra in an anechoic room, covering a wide range of angles from the fan axis.
2) Estimation of the sources of noise generation by studying the aerodynamics of the fan, namely, by probing rotor wakes between the rotor and stator blade rows and decay of the rotor wakes axially and circumferentially.
3) Studies concerning the effect on noise of different fan blade loadings.
4) Sensitivity of noise measurements to inflow distortion.

8.0 REFERENCES

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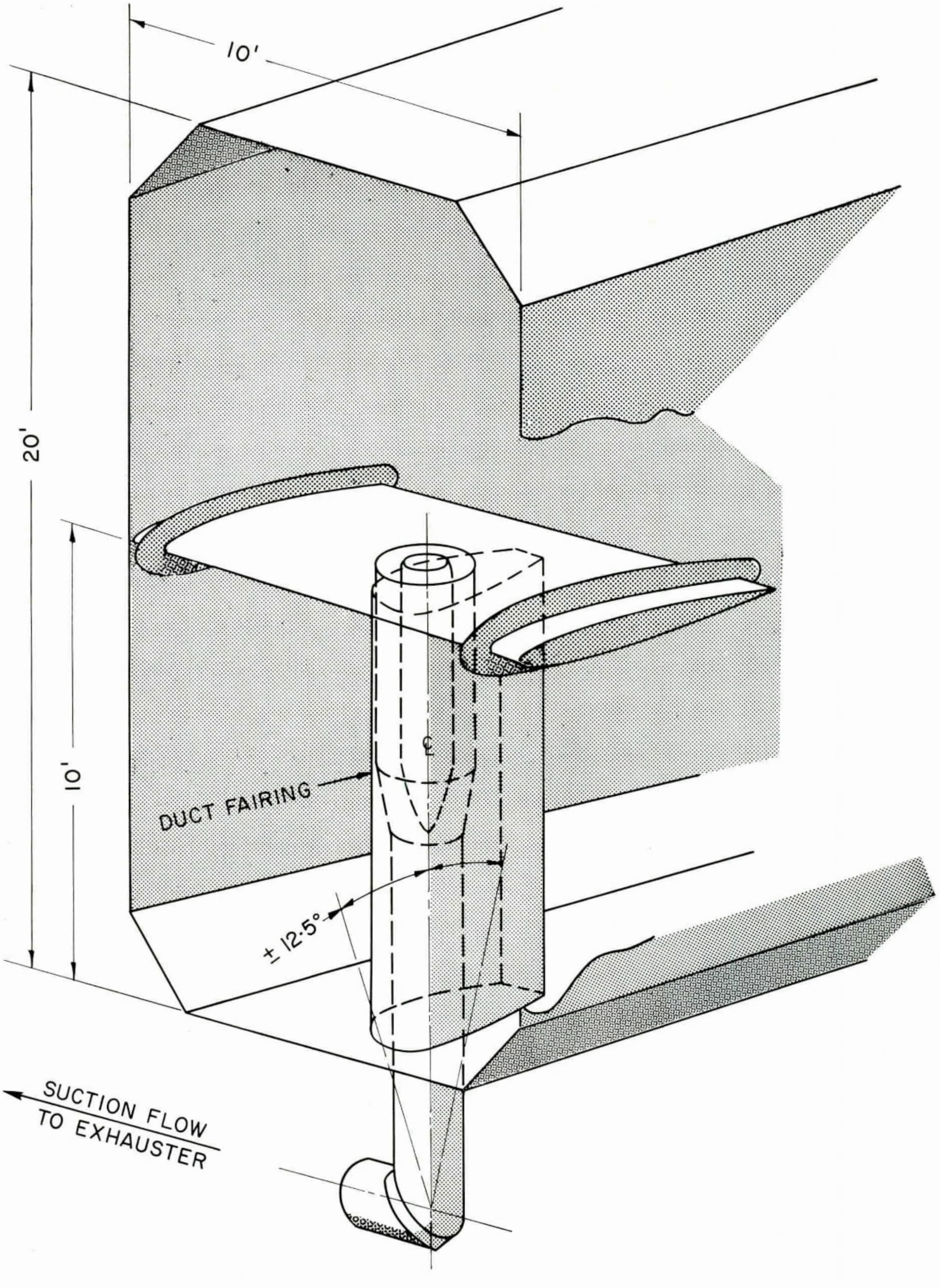

FIG. I : EXPERIMENTAL ARRANGEMENT

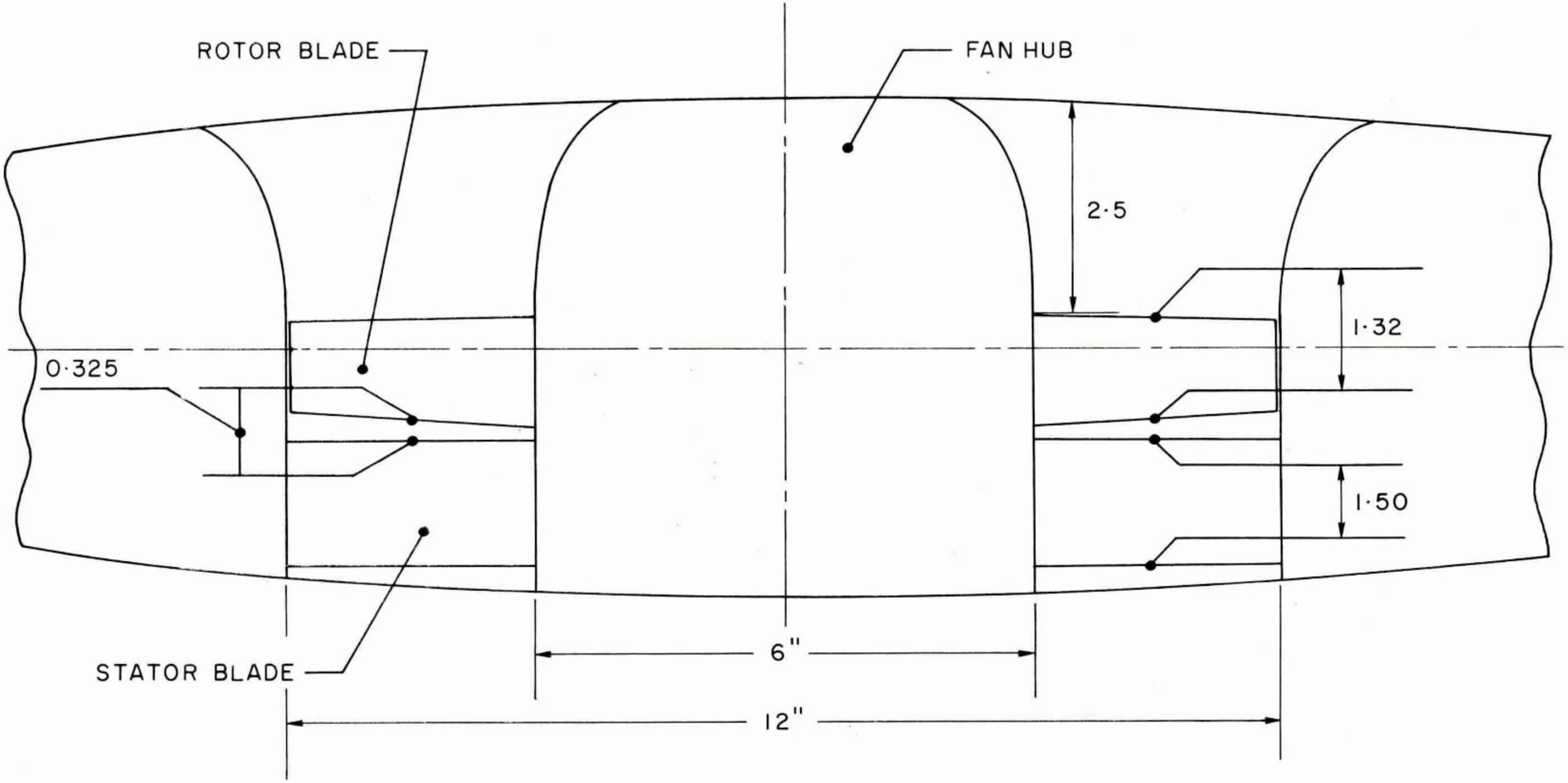

FIG. 2 : FAN-IN-WING CROSS SECTION

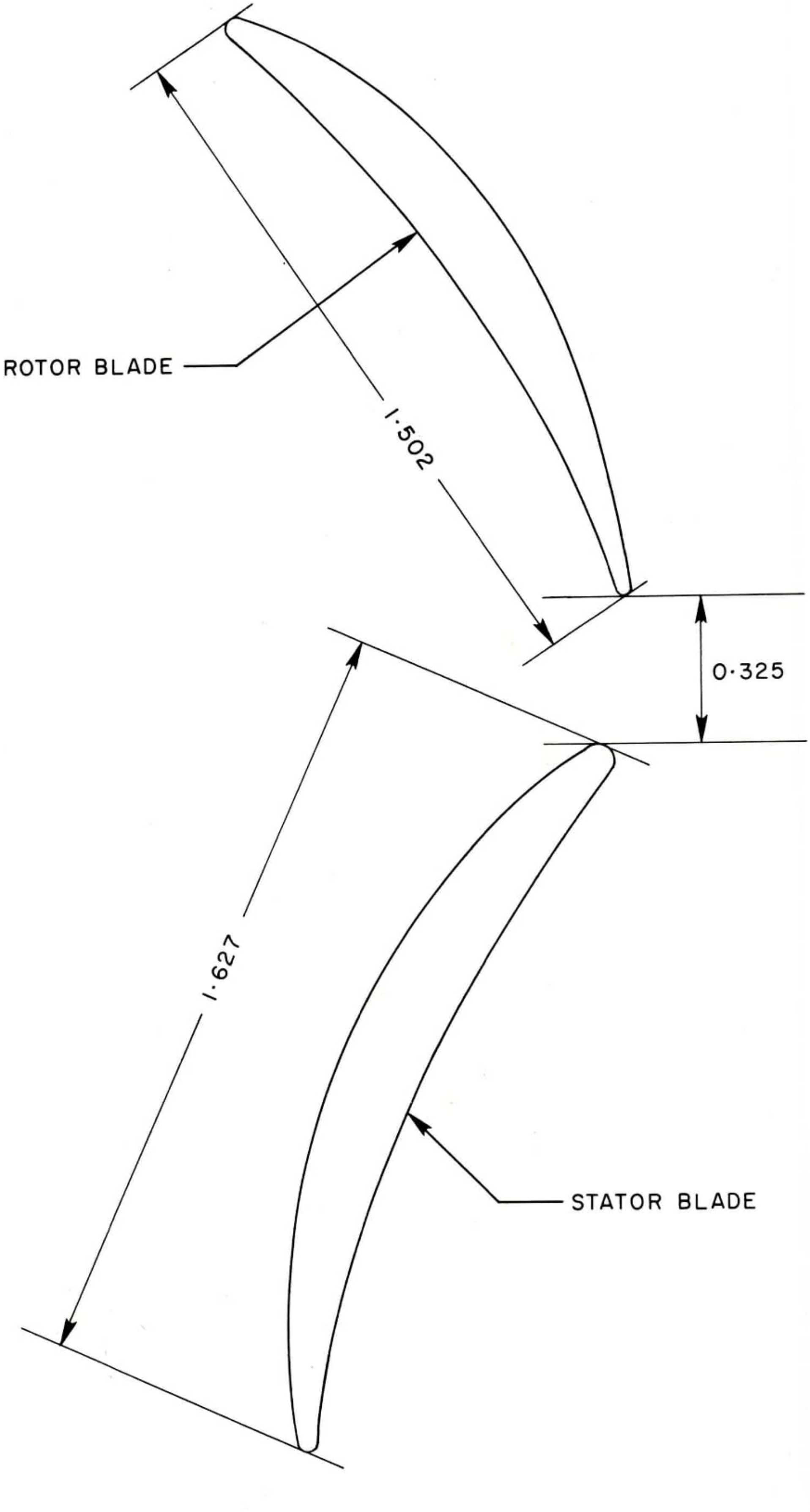

FIG. 3 : FAN BLADE CONFIGURATION AT MID SPAN

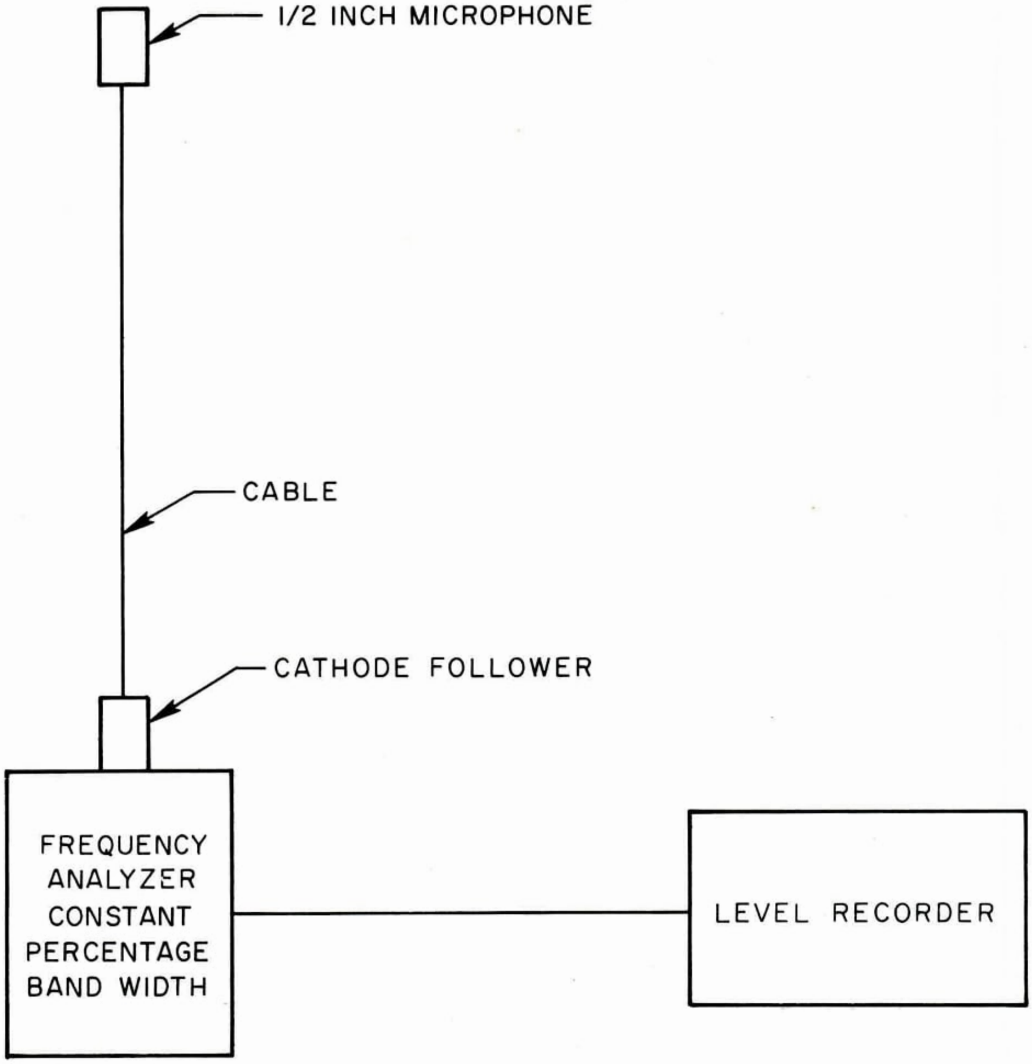

FIG. 4: BLOCK DIAGRAM OF THE INSTRUMENTATION

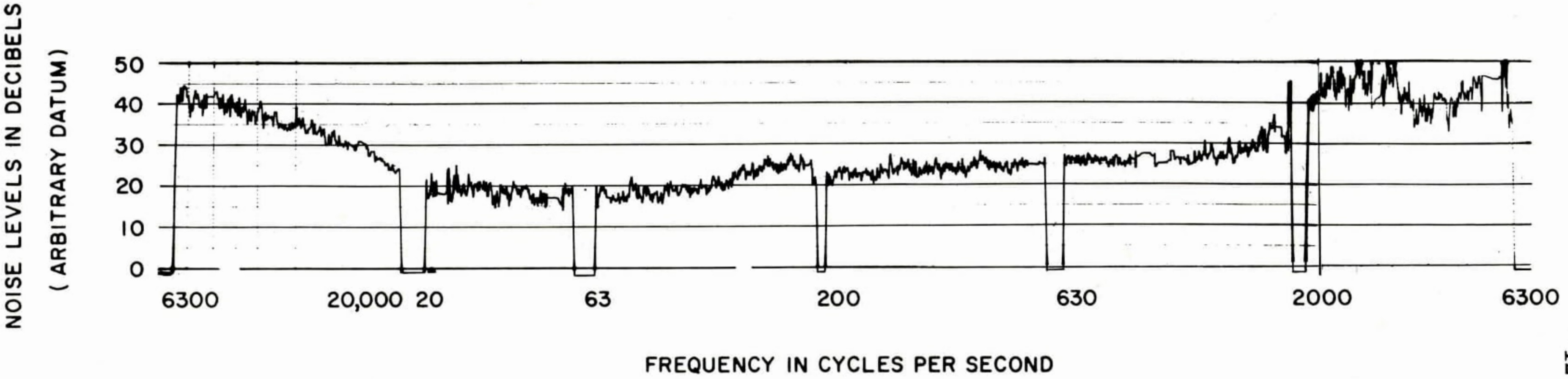

FIG. 5 : SPECTRUM OF NOISE FOR A FAN SPEED OF 7,500 RPM

(MICROPHONE POSITION 5 FT FROM THE INLET, 20° TO THE AXIS OF THE FAN)

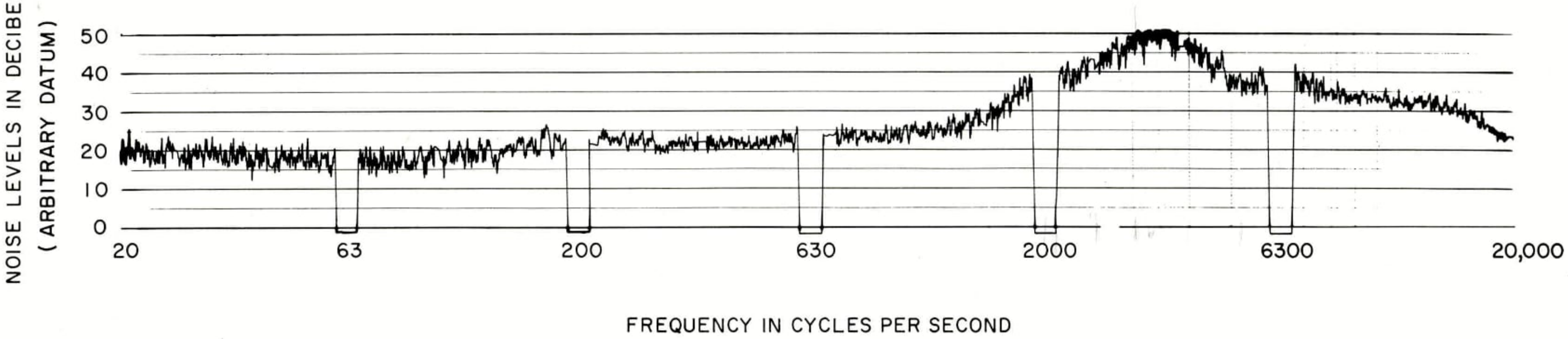

FIG. 6 : SPECTRUM OF NOISE FOR A FAN SPEED OF 9,750 RPM

(MICROPHONE POSITION 5 FT FROM THE INLET, 20° TO THE AXIS OF THE FAN)

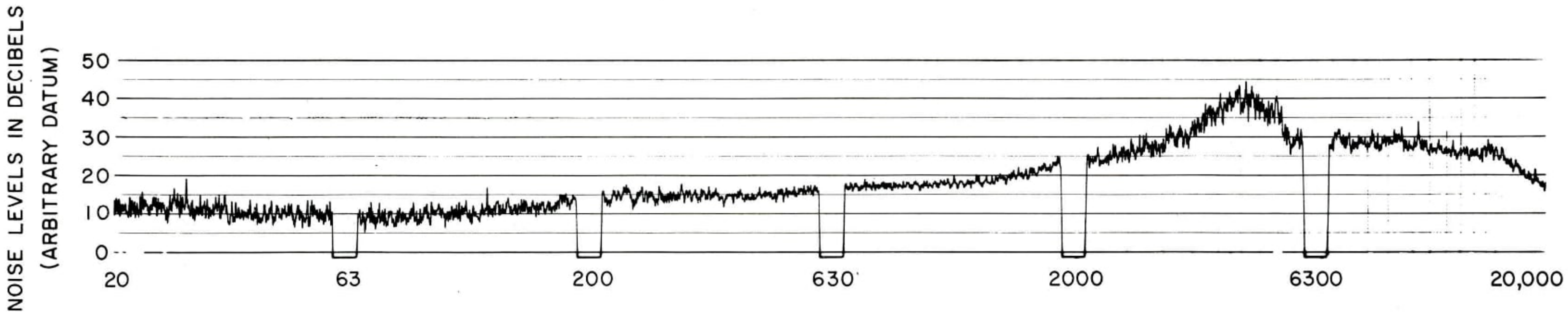

FIG. 7 : SPECTRUM OF NOISE FOR A FAN SPEED OF 13,125 RPM

(MICROPHONE POSITION 5 FT FROM THE INLET, 20° TO THE AXIS OF THE FAN)

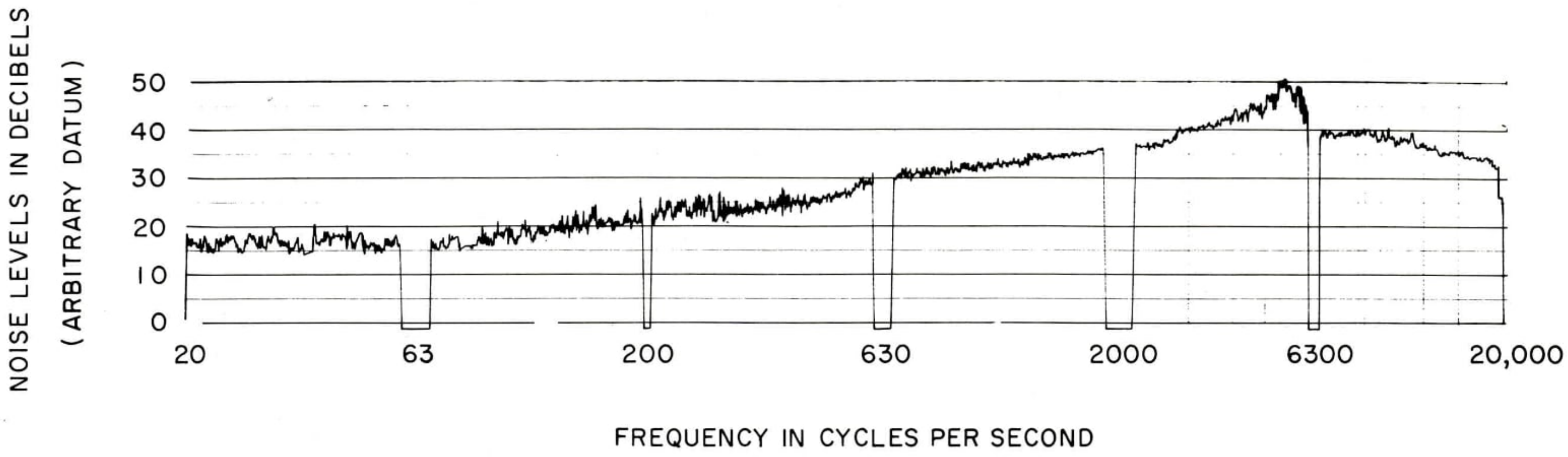

FIG. 8 : SPECTRUM OF NOISE FOR A FAN SPEED OF 13,125 RPM

(MICROPHONE POSITION 5 FEET FROM THE OUTLET, 20° TO THE AXIS OF THE FAN)

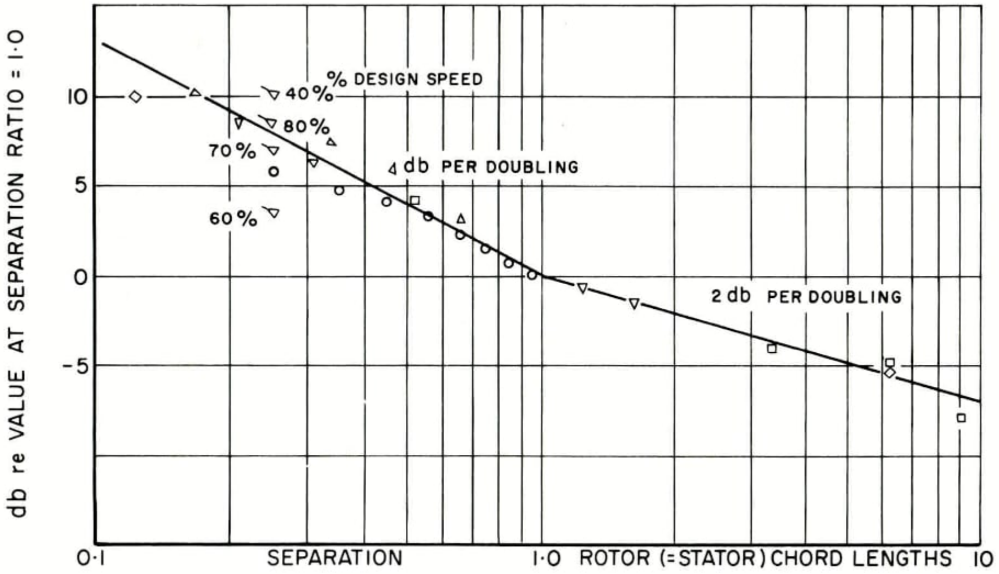

FIG. 9 : EFFECT OF ROTOR AND STATOR BLADE SPACING

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1. Ducted fans
2. Rotor noise
3. Noise - Measurement

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