9117
NACA TN 2756

TECH LIBRARY KAFB, NM
0065870

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2756

NOISE FROM INTERMITTENT JET ENGINES AND STEADY-FLOW JET ENGINES WITH ROUGH BURNING

By Leslie W. Lassiter

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
August 1952

AFMDC
TECHNICAL LIBRARY
AFL 2811

TECH LIBRARY KAFB, NM

0065870

1G

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2756

NOISE FROM INTERMITTENT JET ENGINES AND STEADY-FLOW JET ENGINES WITH ROUGH BURNING

By Leslie W. Lassiter

SUMMARY

Sound measurements were made on a pulsejet and a subsonic ramjet of the types used for helicopter rotor drive and on a turbojet with afterburner. The pulsejet was found to produce a discrete-frequency spectrum having a single predominant component corresponding to the engine firing frequency. The angular distribution was slightly directional, with the largest sound pressures occurring to the rear of the engine and near its axis. It was found that an estimate of the noise level from a pulsejet could be made by application of resonant-tube theory, if certain of the average flow parameters of the engine are known or can be reasonably approximated.

The small subsonic ramjet and the turbojet with afterburner were both found to produce discrete-frequency noise spectrums. Their spectrums, however, contrasted with that of the pulsejet in that they contained several harmonic components of magnitude comparable with that of the fundamental.

INTRODUCTION

The usefulness of intermittent jet engines may be greatly limited because of the intense noise associated with their operation. They are otherwise very attractive for many applications, because of their simplicity of operation, the small amount of auxiliary equipment necessary, and the high pay loads obtainable as a result of their large thrust-weight ratio. These features make them particularly attractive as a source of rotor power for helicopters.

The shutter type of pulsejet is the most common form of intermittent engines and is designed so that its jet issues from the nozzle in periodic bursts rather than in a continuous stream. In operation of this type of engine, air is drawn into the tube through the flapper type of valves at the forward end and through the tail-pipe orifice and is mixed with fuel

in the combustion chamber. The subsequent combustion raises the chamber pressure sufficiently to force the valves closed and thereby permits the exhaust gases to escape only through the exit nozzle in order to produce thrust. The cycle is repeated at a particular frequency, corresponding to the resonant frequency of the tube-chamber combination.

Very few systematic studies have been made of the noise from pulsejet engines; most of the data currently available were obtained at isolated points in the sound field around partially enclosed engine test cells. These data, however, have indicated that the noise generated by a pulsejet consists principally of discrete-frequency components which correspond to multiples of the engine firing frequency. During rough-burning conditions some types of steady-flow jet engines, such as ramjets and turbojets with afterburners, may also generate noise of a discrete-frequency nature, somewhat similar to that of a pulsejet.

This paper presents noise spectrums and spatial distributions for the pulsejet and ramjet and gives a noise spectrum of a turbojet with afterburner. Experimental results for the pulsejet are compared with calculations by an analysis based on the radiation characteristics of a resonant pipe.

SYMBOLS

E	radiated sound energy per unit time, ergs/sec
ω	angular sound frequency, $2\pi f$, radians/sec
f	sound frequency, cps
r	jet-exit radius, cm
S	jet-exit area, sq cm
ρ	density of ambient air, g/cu cm
ρ'	average density of air at jet exit, g/cu cm
ρ''	density of exit gas at temperature t'', g/cu cm
ρ_i	density of intake air at temperature t_i, g/cu cm
t	ambient temperature, $^{\circ}R$
t_c''	peak combustion-chamber temperature, $^{\circ}R$

t''	peak temperature at jet exit, $^{\circ}R$
t_i	minimum temperature at jet exit during intake, $^{\circ}R$
a	speed of sound in ambient air, cm/sec
a'	average speed of sound at jet exit, cm/sec
a''	sound speed in exit gas at temperature t'', cm/sec
a_i	sound speed at temperature t_i, cm/sec
I	sound intensity, ergs/sec/sq cm
u	root-mean-square value of alternating velocity, cm/sec
u'	average gas velocity at jet exit, cm/sec
p	root-mean-square value of sound pressure, dynes/sq cm $\left(db = 20 \log_{10} \frac{p}{0.0002}\right)$
$\bar{p}$	over-all sound pressure, dynes/sq cm
P	atmospheric pressure, dynes/sq cm
P_c''	peak combustion-chamber pressure, dynes/sq cm
R	universal gas constant, ergs/$^{\circ}$C/mol
h	internal energy of air in combustion chamber, BTU
η	combustion efficiency, percent
H	higher heating value of fuel
F/A	fuel-air ratio
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
k	ratio of specific heats, c_p/c_v
ψ	azimuth angle (referred to 0° on jet axis to rear of jet), deg
Z	distance from point of measurement to jet exit, cm
D	jet-exit diameter, cm

Subscripts:

1 relating to fundamental Fourier component

Z value at distance Z from jet exit

APPARATUS AND METHODS

Sound measurements were made on a pulsejet and a subsonic ramjet of the types (fig. 1) used for helicopter rotor drive and on a turbojet with afterburner. Data were obtained at the 80- and 100-percent-rated-thrust conditions for the pulsejet and at the 100-percent-rated-thrust condition for the turbojet with afterburner. Because of fuel-pump limitations, the 100-percent-rated-thrust condition could not be maintained for the ramjet; therefore, all measurements on the ramjet were made at the 80-percent-rated-thrust condition.

Two test locations were utilized to obtain the data from the pulsejet. The 80-percent-rated-thrust measurements were made with the unit operating on a thrust stand in the vicinity of the Langley helicopter test tower, as shown schematically in figure 2(a). The 100-percent-rated-thrust data were obtained near the Langley 16-foot transonic tunnel, as shown schematically in figure 2(b). All data from the ramjet were obtained at the latter location in order that ram pressure might be obtained from the variable-speed blower and converging nozzle indicated in the figure. This equipment was capable of delivering air at a maximum velocity of 655 feet per second to the ramjet inlet diffuser. It was used with the pulsejet only for starting; once ignited, the engine was allowed to operate statically.

Data from the turbojet afterburner were obtained with the unit functioning in an operational aircraft, which was secured to a concrete base for the tests. No large reflecting surfaces other than the ground were within a radius of approximately 1,000 feet. The sound measurements were made at ground level 50 feet from the jet exit.

The pulsejet and ramjet sound measurements were made $2\frac{1}{2}$ feet above ground level at a distance of 10 feet from the jet exit. Data were obtained at intervals of 15° in azimuth angle ψ from 0° to 90°. At the 80-percent-rated-thrust condition for the pulsejet, this range was extended to 120°.

Data were obtained over the frequency range of 0 to 15,000 cycles per second by means of the two measuring systems shown schematically in figure 3. A Massa Laboratories Model GA-1002 sound-pressure measurement

system was employed in the range of 40 to 15,000 cycles per second and an NACA miniature electrical pressure gage and low-pass filter unit were used in the range of 0 to 40 cycles per second. Output of the Massa system was recorded on a Type PT-6 Magnecorder tape recorder to provide a permanent record for later analysis. Similarly, the output of the miniature gage system was recorded on a Brush pen recorder. Total sound-pressure levels in each frequency band were obtained from electronic voltmeter readings at the output of each measuring system.

Frequency spectrums for each unit at the various azimuth angles were obtained by playback of the recordings into a Panoramic Sonic Analyzer, which presents graphically on its viewing screen a plot of intensity against frequency for the frequency range of 40 to 20,000 cycles per second. The magnecorder records were played directly into the analyzer, as indicated in the lower right-hand portion of figure 3. Playback of the tape recordings was also made into a conventional cathode-ray oscillograph to obtain total-pressure wave forms of the noise.

ANALYSIS

Since the pulsejet operating cycle is an acoustic-resonance phenomenon, it is of interest to compare the experimental noise data with results of an approximate analysis based on the assumption that pulsejet noise-radiation properties are comparable with those of a resonant pipe. For simplification of the analytical procedure, only the fundamental Fourier component is considered.

The sound energy per unit time E radiated from a tube subject to sinusoidal excitation has been derived from references 1 and 2 as

$$E = \frac{1}{2} S u_1^2 \rho' a' \left(\frac{\omega r}{a}\right)^2 \tag{1}$$

where the primed quantities are average values at the tube exit when the medium inside the tube is at a different temperature from that of the ambient air. This energy is dispersed in accordance with the radiation characteristic of the tube, which, in keeping with the pipe analogy, is assumed to be identical in all directions when the wave length of sound is large relative to the tube diameter. Hence the sound power per unit area, or intensity, at the distance Z is obtained by dividing equation (1) by the area of a sphere of radius Z. Thus,

$$I_{1_Z} = \frac{1}{2} S u_1^2 \rho' a' \left(\frac{\omega r}{a}\right)^2 \frac{1}{4\pi Z^2} \tag{2}$$

and since

$$I_{1_Z} = \frac{p_{1_Z}^2}{\rho a}$$

the sound pressure is given as

$$p_{1_Z} = \frac{\omega S u_1}{2\pi Z}\left(\frac{\rho\rho' a'}{a}\right)^{1/2} \tag{3}$$

In order to calculate the magnitude of the fundamental sound pressure at distance Z the parameters ρ', a', and u_1 must be evaluated. The following approximate thermodynamic analysis, based on the treatment of reference 3 and on the assumption of a constant-volume combustion process, may be used for that purpose.

If the work done by the intake ram is neglected, the initial conditions of density, temperature, and pressure in the pulsejet combustion chamber are essentially the same as those in the ambient medium. Combustion of the fuel produces an increase in the internal energy of the air mass of magnitude

$$\Delta h = \eta H \frac{F}{A}$$

This increase leads to an elevation of the combustion-chamber temperature to the new value

$$t_c'' = t + \frac{\Delta h}{c_v}$$

and results in an increased pressure of

$$P_c'' = P \frac{t_c''}{t}$$

If this pressure is greater than 1.89P, as is usually the case, choking occurs at the tube exit and the peak pressure at that point is

limited to $0.528P_c''$. The corresponding peak temperature t'' at the tube exit is then

$$t'' = t_c''(0.528)^{\frac{k-1}{k}}$$

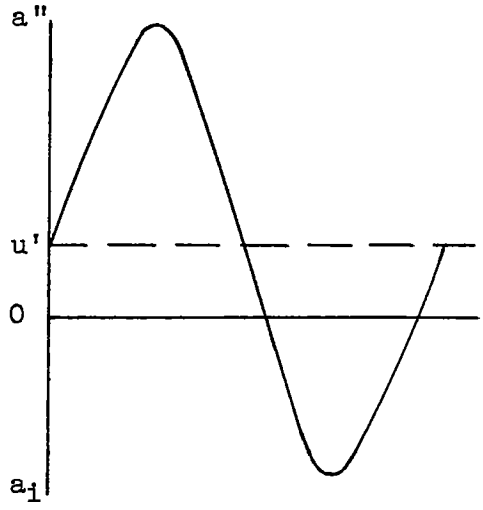
and results in a sound speed at that temperature of

$$a'' = \left(\frac{0.528P_c''r}{\rho''}\right)^{1/2}$$

where the density ρ'' is expressed as

$$\rho'' = \frac{0.528P_c''}{Rt''}$$

Hence, as shown in the accompanying diagram, the peak exit velocity is a''.



On the intake half-cycle, the peak velocity approaches a limit which is the speed of sound under the conditions existing after an adiabatic expansion from atmospheric pressure to a pressure of 0.528P. By assuming

that the engine operates near this limit on intake, the negative peak velocity may be approximated by

$$a_i = \frac{0.528Pr}{\rho_i}$$

where

$$\rho_i = \frac{0.528P}{0.84t}$$

Thus the assumption that the velocity wave form is approximated by a sine wave alternating about some average value requires that these amplitudes, positive and negative, define the double amplitude of the sine wave. Its root-mean-square value is then

$$u_1 = \frac{a'' + a_i}{2\sqrt{2}}$$

The average density ρ' and sound speed a' to be substituted into equation (3) are obtained from

$$\rho' = \rho - \frac{\rho_i - \rho''}{\pi}$$

and

$$a' = a + \frac{a'' - a_i}{\pi}$$

The sound pressure calculated by substituting these values into equation (3) is that in a free field. When the engine is operated near ground level, the pressures may be expected to approach a value twice that calculated, since conditions then approximate a source radiating into a semi-infinite medium.

RESULTS AND DISCUSSION

Pulsejet

Over-all angular distribution.- The angular distribution of over-all sound pressure from the pulsejet is shown in the polar diagram of figure 4 for the 80- and 100-percent-rated-thrust conditions. The curves

shown were plotted from the data obtained only in the range of 40 to 15,000 cycles per second, since pressures in the range of 0 to 40 cycles per second were of the order of 50 decibels below that of the pulsejet fundamental and were masked by the higher-frequency noise which came through the low-pass filter. Since the 80- and 100-percent-rated-thrust data were obtained at different locations, an attempt has been made to adjust the latter on the basis of a correction factor indicated by a comparison of a set of check data at an azimuth angle of 30° and 100-percent-rated-thrust condition from both locations. The curves indicate that pulsejet noise has a distribution which is only slightly directional in the region rearward of the jet exit for both the 80- and 100-percent-rated-thrust conditions but which drops off rather quickly at angles near 90°. The increase in thrust results in a magnitude change in the over-all level of approximately 3 to 6 decibels for the azimuth angles measured. The greatest increases occur at small azimuth angles, where the level is increased from approximately 138.5 to 144 decibels.

Frequency spectrums.- The frequency content of pulsejet noise is illustrated by the spectrums and wave forms shown in figure 5. The graphs at the left of the figure are panoramic frequency analyses at three azimuth angles, and the wave forms at the right-hand side are the corresponding records of total pressure against time, shown above a reference sine wave of 100 cycles per second. The unequal spacing of intensity grid lines in the spectrum plots is a characteristic of the design of the analyzer, which ordinarily indicates in decibels above and below an arbitrary reference level coinciding with midscale deflection. For the present tests, the analyzer was calibrated to indicate absolute values of sound pressure. The spectrums indicate that, at all azimuth angles, the over-all noise is composed chiefly of a single tone of approximately 100 cycles per second. Several harmonics of this frequency are present also, but their magnitudes relative to that of the fundamental are such that they do not contribute much to the over-all level. This fact can also be seen from the wave forms, since they do not generally depart greatly from sinusoids. The predominant noise frequency of 100 cycles per second corresponds to the firing frequency of the unit, which is determined by the resonant frequency of the configuration and is hence a function of tube length, combustion-chamber volume, and operating temperature.

A comparison of the measured fundamental distribution with that calculated from equation (3) on the assumption of sinusoidal operation is shown in figure 6. Values of the parameters used in the computation are as follows:

$$\frac{F}{A} = 0.0717 \qquad \eta = 0.20$$

$$r = 7.6 \text{ cm} \qquad t = 540^\circ \text{ R}$$

$$\omega = 628 \text{ radians/sec}$$

The two curves indicate good agreement at azimuth angles up to approximately 45°; at larger angles the measured values are lower than those calculated from the simple-resonant-tube theory. It appears that refinement of the present simplified analysis is necessary in order to resolve this distribution discrepancy. The observed tendency for the analysis to overestimate the pressure levels at reduced engine thrust is considered to be further evidence that some refinement is necessary.

Noise reduction.- The predominance of the fundamental component of pulsejet noise and the fact that its wave length is large relative to the engine exit diameter suggest that out-of-phase operation of dual-engine installations in close proximity might prove beneficial in reducing the noise levels. Several proposed means of obtaining out-of-phase operation of dual units have been illustrated in a paper (not generally available) by K. Staiger and W. I. E. Kamm, which deals with the operating characteristics of pulsejet engines.

Steady-Flow Jet Engines With Rough Burning

When either internal appurtenances or an unsteady-flow state lead to a condition of rough burning, certain steady-flow jet engines such as ramjets and some turbojet afterburners generate noise which, in some respects, is similar to that from a pulsejet. Although these engines do not, in general, function in an intermittent manner, they do produce a discrete-frequency spectrum rather than the random spectrum usually associated with steady-flow jet engines (ref. 4). Data from the subsonic ramjet and a turbojet with afterburner are therefore included in the present paper.

Over-all distribution for small ramjet.- The angular distributions of over-all noise for the small ramjet in the frequency ranges of 0 to 40 cycles per second and 40 to 15,000 cycles per second are illustrated in figure 7 for the 80-percent-rated-thrust condition at a ram velocity of 655 feet per second. Like that of the pulsejet, ramjet noise appears to be slightly directional rearward of the engine for the frequency range of 40 to 15,000 cycles per second. The maximum sound pressures occur near 15° azimuth; pressures at the 90° azimuth are somewhat less than those measured at smaller angles. A rather sharp directional pattern is associated with the noise in the range of 0 to 40 cycles per second which produces a lobe in the axial direction rearward of the engine.

Frequency spectrum of small ramjet.- Figure 8 illustrates the type of spectrums obtained at two different azimuth angles from measurements on the subsonic ramjet at 80 percent rated thrust. The spectrums indicate that the ramjet noise contains several discrete-frequency components near the low end of the frequency scale. The magnitudes of these

components were found to be of a similar order at both azimuth angles, as was true for the pulsejet noise. In addition to these components, it is to be expected that the ram blower will contribute a random noise of the type usually associated with continuous jets; however, a series of measurements taken with the engine in position, but inoperative, indicates that, in the frequency range of the discrete components, the random noise of the blower is of the order of 25 decibels lower than the levels of the periodic components.

Turbojet with afterburner.- In some cases the afterburner method of turbojet thrust augmentation produces a periodic noise somewhat like that of the subsonic ramjet. An illustration of afterburner noise of this type is given in figure 9, which presents the frequency spectrum of noise from a turbojet engine during afterburner operation. The figure indicates that several predominant discrete-frequency components are present in addition to the random noise. These discrete components appear to bear a harmonic relation to each other, as was true for both the ramjet and pulsejet. Hence, under certain conditions of rough burning, the nature of afterburner noise during static operation may be somewhat like that of a subsonic ramjet and a pulsejet.

CONCLUSIONS

Sound measurements on a pulsejet, a subsonic ramjet, and a turbojet with afterburner indicated the following conclusions:

1. Pulsejet noise is composed principally of a few discrete-frequency components which bear a harmonic relation to each other. The fundamental frequency corresponds to the engine firing frequency and is generally of greater amplitude than its harmonics.

2. The spatial distribution of the pulsejet sound field is slightly directional in the region rearward of the jet exit and appears to drop off rather sharply at angles near 90°.

3. Comparison of experimental and calculated values of fundamental sound pressure of the pulsejet indicate good agreement at azimuth angles up to approximately 45°; at larger angles the measured values are lower than those calculated from simple resonant-tube theory.

4. Under conditions of rough burning, ramjets and some turbojet afterburner units may generate noise spectrums which contain several discrete-frequency components near the low end of the frequency scale.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., June 2, 1952

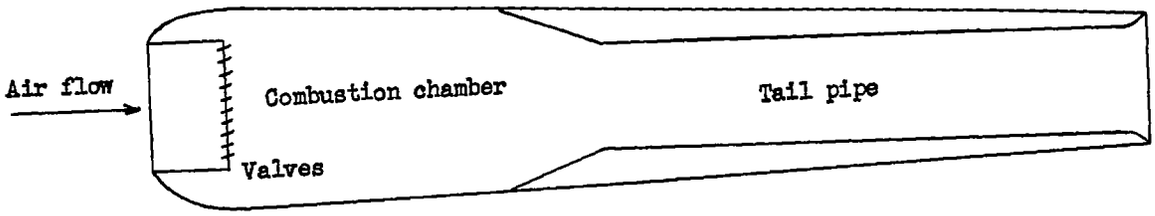
REFERENCES

1. Richardson, E. G.: Sound. Edward Arnold & Co. (London), Fourth ed., 1947, pp. 239-240.

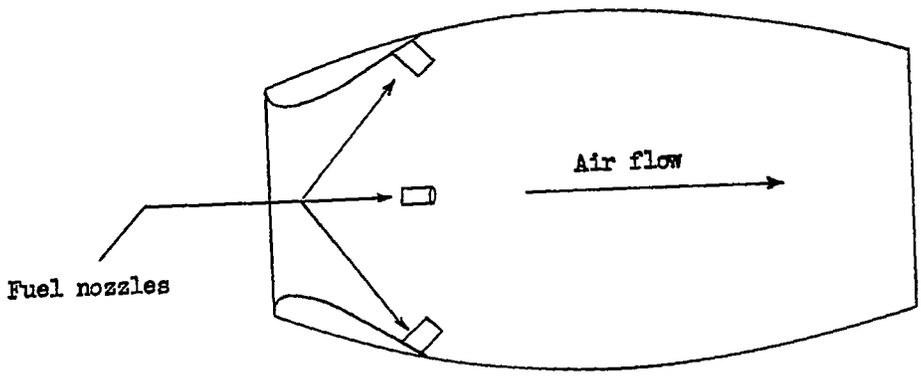
2. Stewart, George Walter, and Lindsay, Robert Bruce: Acoustics. D. Van Nostrand Co., Inc., 1930, p. 130.

3. Katz, Israel: Principles of Aircraft Propulsion Machinery. Pitman Pub. Corp., 1949, pp. 111-119.

4. Eldredge, Donald H., Jr., and Parrack, Horace O.: Jet Engine Sound Spectra. AF TR No. 5827, ATI 57639, Air Materiel Command, U. S. Air Force, June 1949.

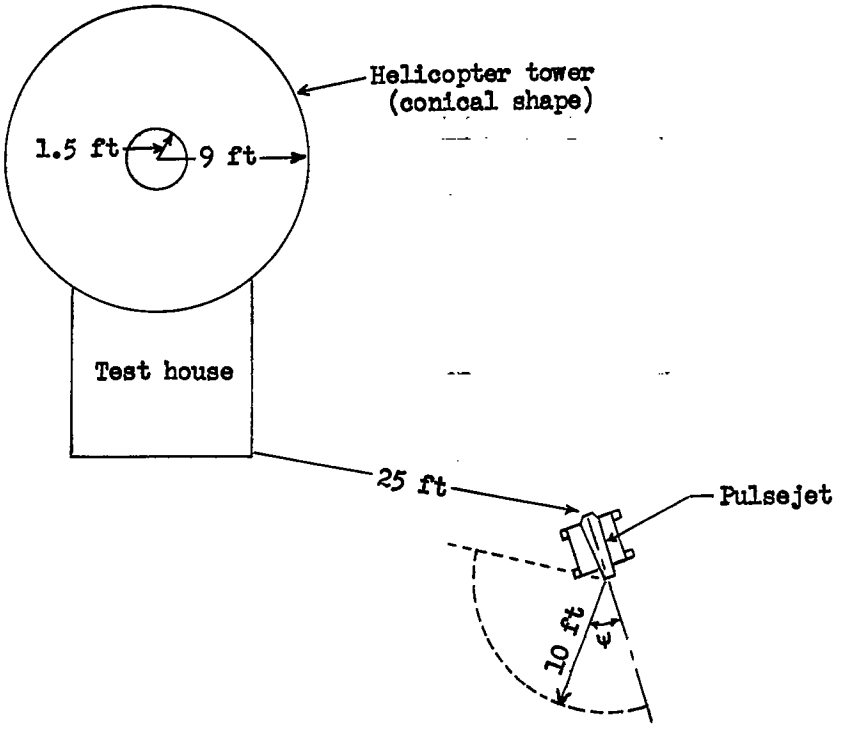


(a) Pulsejet.

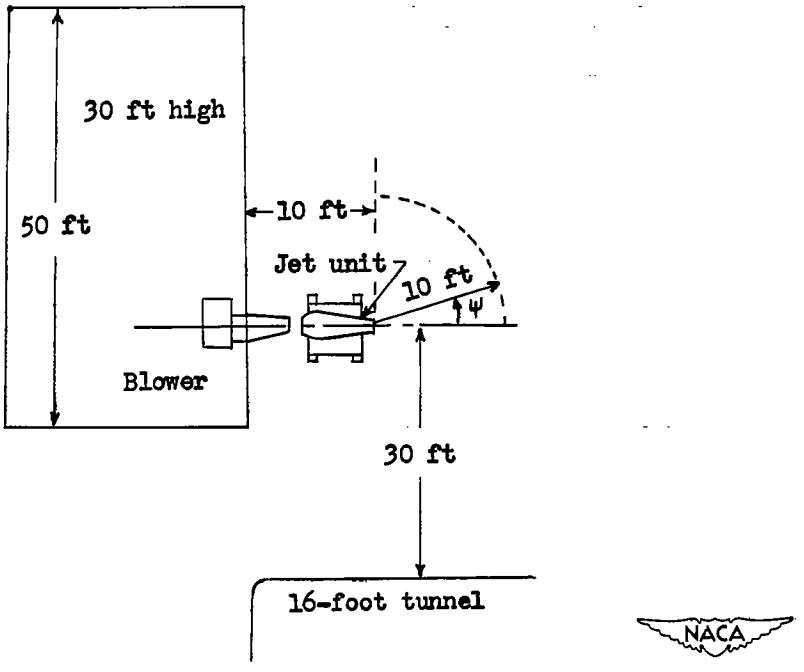


(b) Subsonic ramjet.

Figure 1.- Schematic drawings of typical pulsejet and subsonic ramjet used for helicopter rotor drive.



(a) Vicinity of Langley helicopter test tower.



(b) Vicinity of Langley 16-foot transonic tunnel.

Figure 2.- Test areas for pulsejet and ramjet noise measurements.

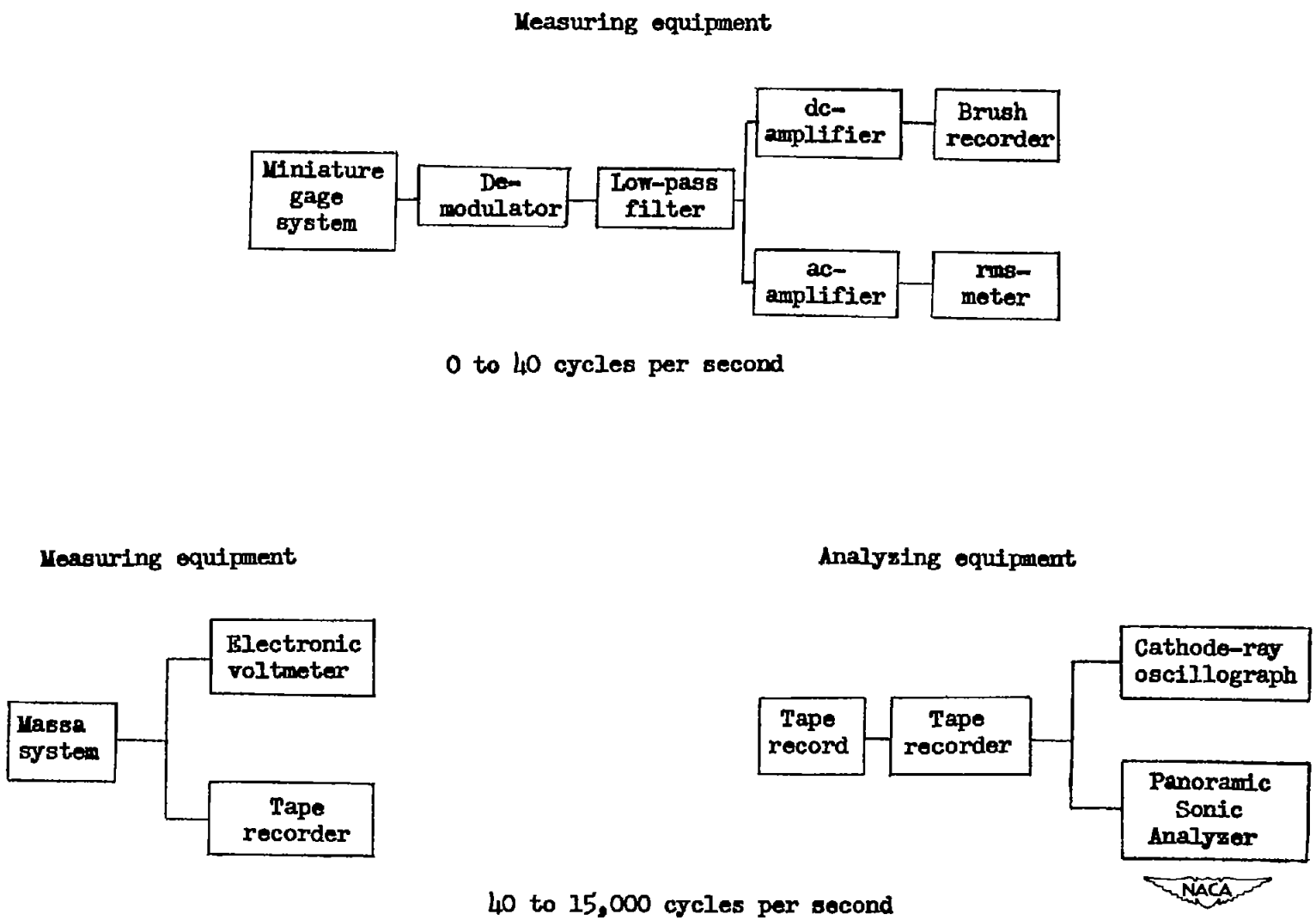


Figure 3.- Block diagram of instrumentation for noise tests of intermittent jets.

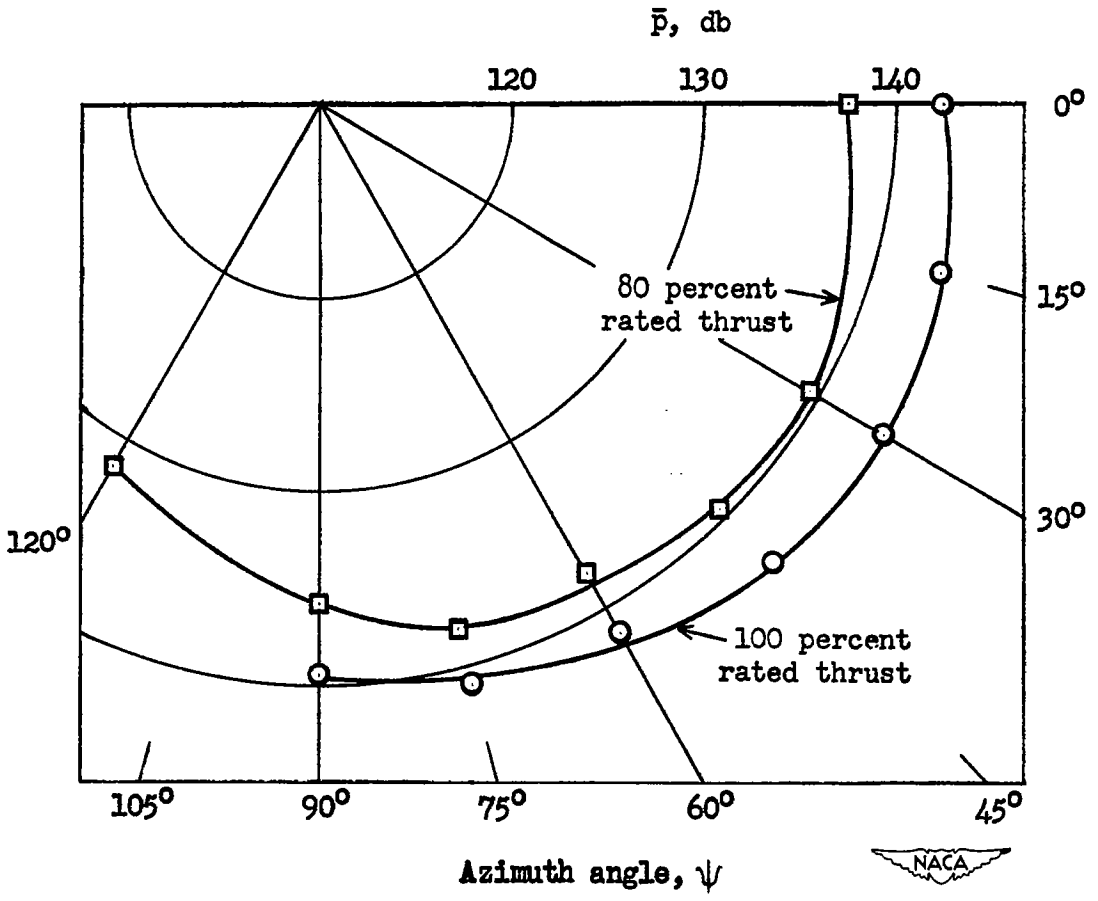


Figure 4.- Angular distribution of over-all sound pressure from pulsejet. $\frac{Z}{D} = 20$.

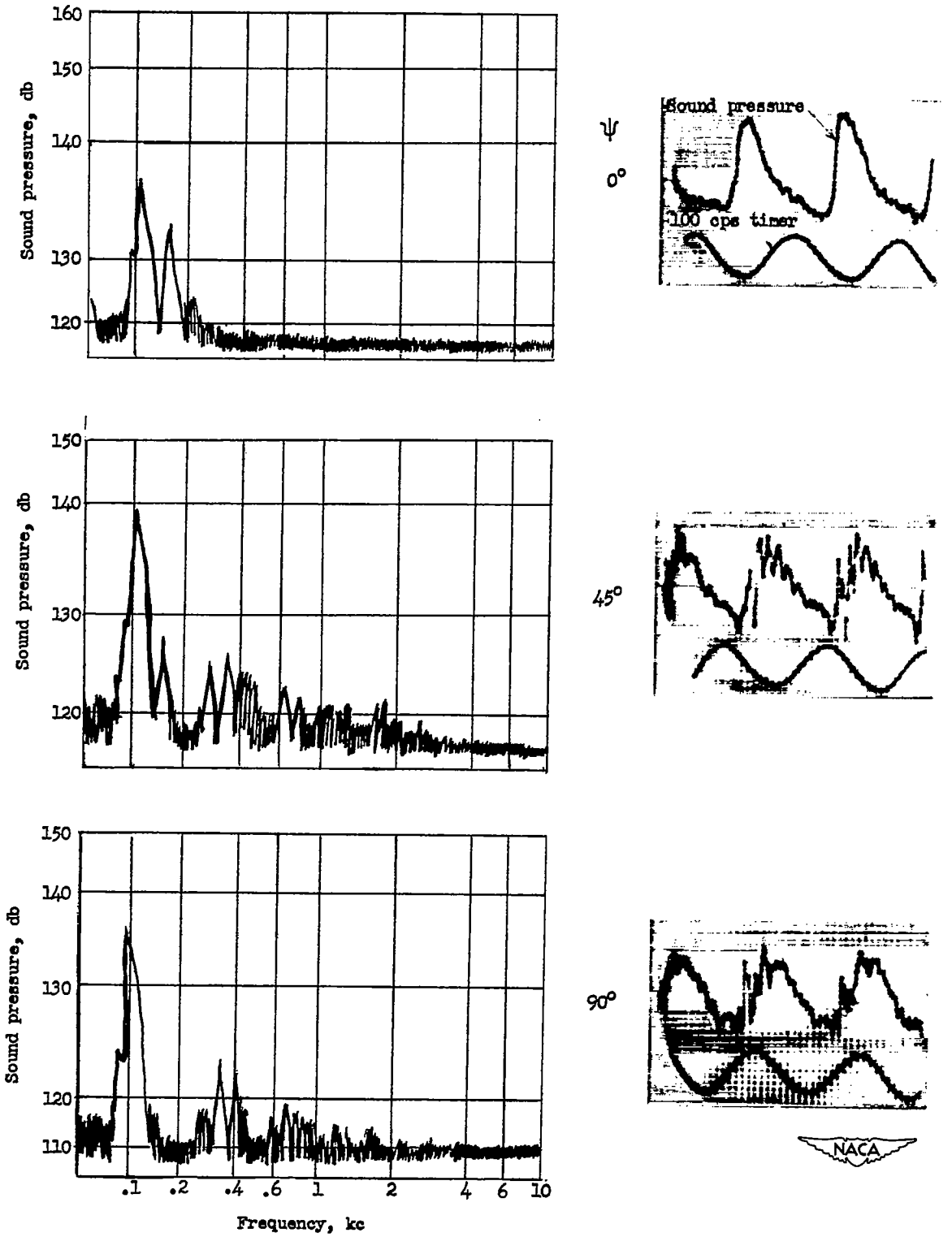


Figure 5.- Pulsejet noise spectrums and wave forms. 80 percent rated thrust (72 lb); $\frac{Z}{D} = 20$.

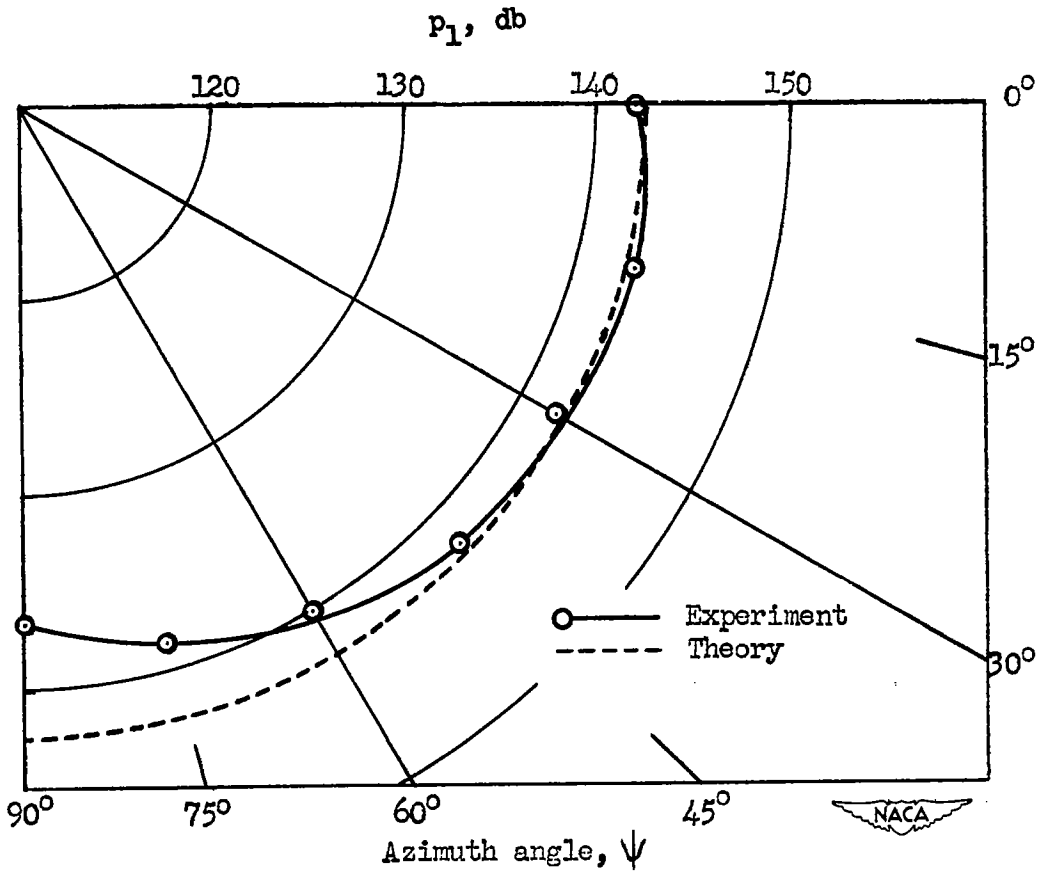


Figure 6.- Angular distribution of pulsejet fundamental. 100 percent rated thrust (90 lb); $\frac{Z}{D} = 20$.

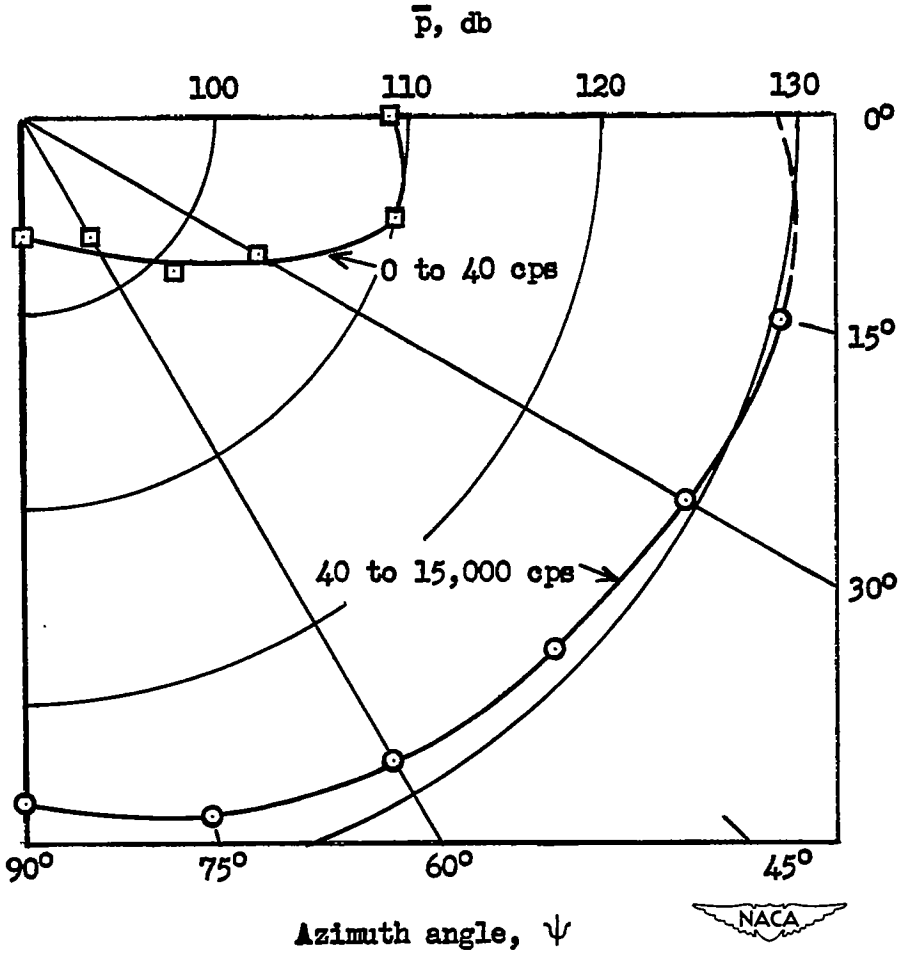
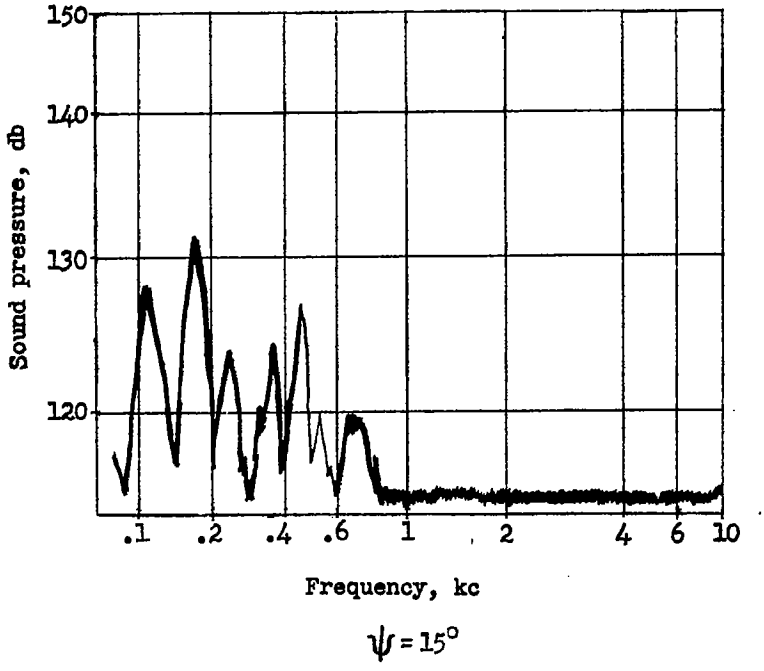


Figure 7.- Angular distribution of over-all sound pressure from ramjet with rough burning. 80 percent rated thrust (22.4 lb); $\frac{Z}{D} = 26.7$.



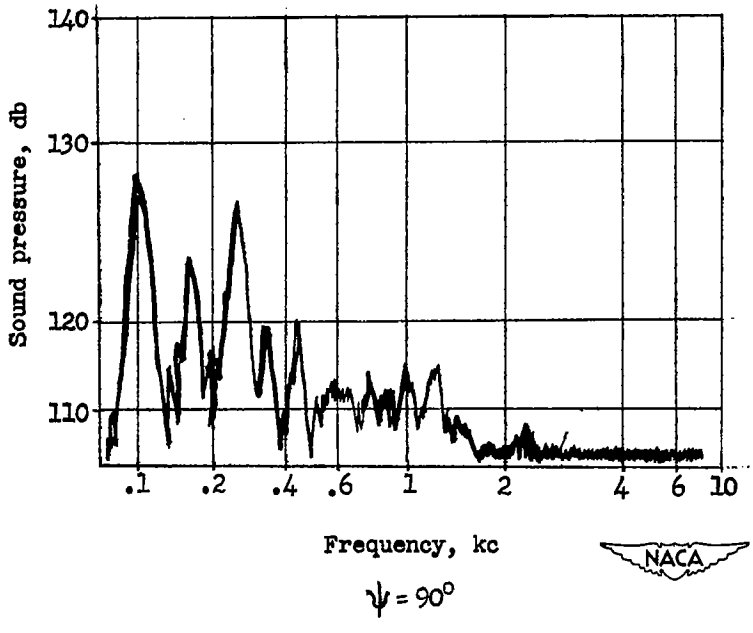


Figure 8.- Ramjet noise spectrums. 80 percent rated thrust (22.4 lb); $\frac{Z}{D} = 26.7$.

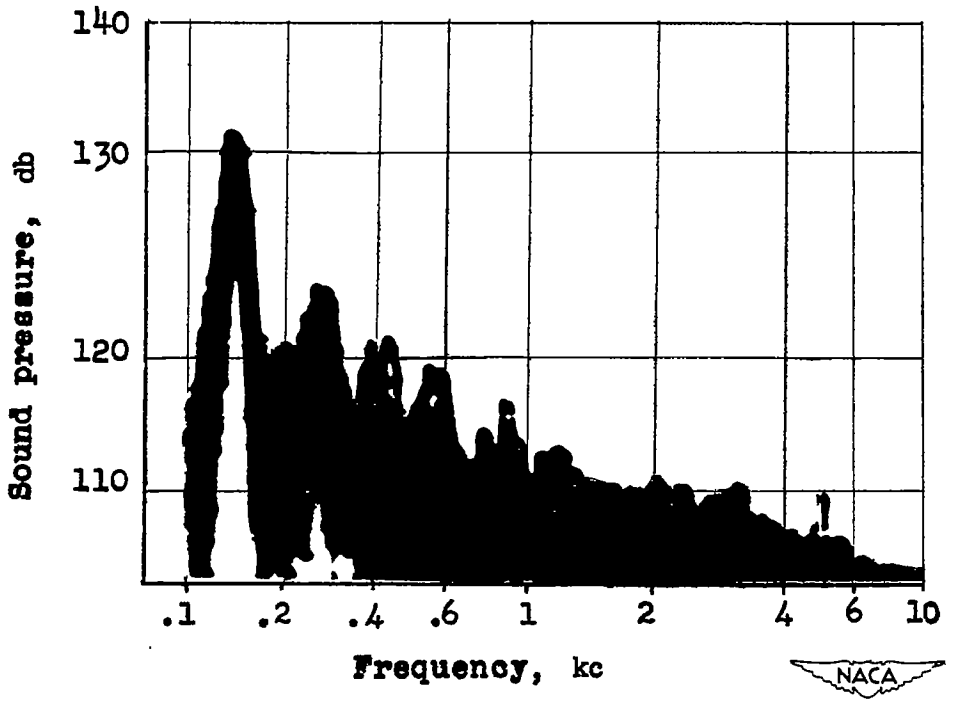


Figure 9.- Noise spectrum of turbojet with afterburner. $\psi = 120^{\circ}$; $\frac{Z}{D} = 33$.