NAVY DEPARTMENT

THE DAVID W. TAYLOR MODEL BASIN

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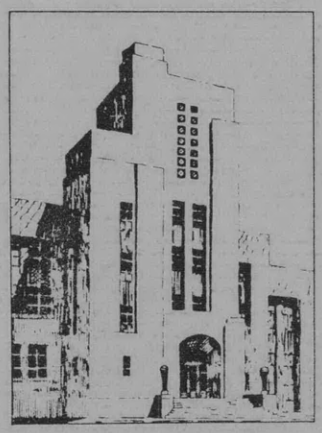
FREE FIELD MEASUREMENTS OF SOUND RADIATED BY SUBSONIC AIR JETS

by

Robert Lee



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ABSTRACT

Measurements are reported of the sound radiated by small air jets at subsonic velocities. The measurements were made in a free acoustic field to obtain the directional pattern of the radiation in half-octave frequency bands covering the range 38 to 13,600 cps.

The directional patterns show an angle of maximum intensity at the higher frequencies. As the frequency decreases, this angle moves toward the jet axis, finally ceasing to exist for the lower frequencies and for the wide-band measurements.

The directional patterns and the total sound power radiated in all directions are compared with other available data. Certain differences are attributed to the effect of the length-diameter ratio of the nozzle.

INTRODUCTION

The David Taylor Model Basin has been engaged in a continuing investigation of the characteristics of sound generated by flowing fluids under a program entitled, "Hydrodynamic Noise Research."[1] As part of this program, measurements have been made of the acoustic noise associated with turbulent flow, more specifically, of the noise radiated by a turbulent air jet at subsonic jet velocities.

The first Model Basin measurements of the noise from a turbulent jet have already been reported.[2] These measurements were made in a reverberant chamber, thus providing an automatic integration of the sound power radiated in all directions regardless of the directionality of the sound source. The results were in substantial agreement with Lighthill's theory of turbulence noise[3] which predicted that the acoustic efficiency, i.e., the ratio of radiated acoustic power to the pneumatic power dissipated by the jet, was proportional to the fifth power of the Mach number.

The measurements to be presented in the present report were made in a free acoustic field rather than in a reverberant chamber. This extension of the previous work had three objectives: first, to obtain the directional characteristics of the radiated jet noise; second, to check the results of the previous measurements made in the reverberant chamber; and third, to compare the present results with experimental findings of other workers which have become available since the work at the Taylor Model Basin was last reported.

In the present experiment, fully developed turbulent air jets issuing from long tubes of diameters of 1/2 inch and 5/8 inch, both having lengths of 100 diameters, were studied.

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[1]References are listed on page 13.

The complete directional radiation characteristics of each jet, its total sound power output, and its frequency spectrum were determined for a large range of subsonic speeds.

APPARATUS AND PROCEDURES

The measurements were carried out on open ground outside the Flow Facility Building of the Taylor Model Basin. The essential air flow system is shown in Figure 1. The air jet was located about 5 feet above the grass-covered ground with the closest building about 50 feet behind the jet. For distances less than 3 feet from the sound source, the contributions due to reflections from ground and building wall were found to be negligible so that a free field condition may be considered to be satisfactorily met. As discussed subsequently, this was verified by the fact that the variation of sound intensity with distance followed the inverse square law.

Air flow was initiated by filling the reservoir tank under pressure, and then allowing air to flow through the long 3-inch diameter copper pipe into a small calming tank subsequently to discharge as a jet into the atmosphere through the small tube under test. During the flow, the reservoir pressure was maintained at about 35 psi absolute by feeding in air from an air supply. Constant reservoir pressure was desirable to provide a better pressure regulation for the second pressure-reducing valve. A pressure-reducing valve located in the main 3-inch line was employed to give constant controllable outlet pressure and consequently controllable jet velocity. Velocities up to 1000 ft/sec were employed.

Velocity measurements were made with a hypodermic total-head tube placed at the center opening of the issuing jet. Constant jet temperature corresponding to that of the ambient temperature was assumed. For nearly fully-developed turbulent pipe flow, the velocity profile across the jet opening depends only slightly on the Reynolds number. Accordingly, using the values obtained by Deissler[4] for the ratio of axial velocity at the jet opening to mean jet velocity for various Reynolds numbers, all the velocities measured by the total-head tube were converted to mean jet velocities.

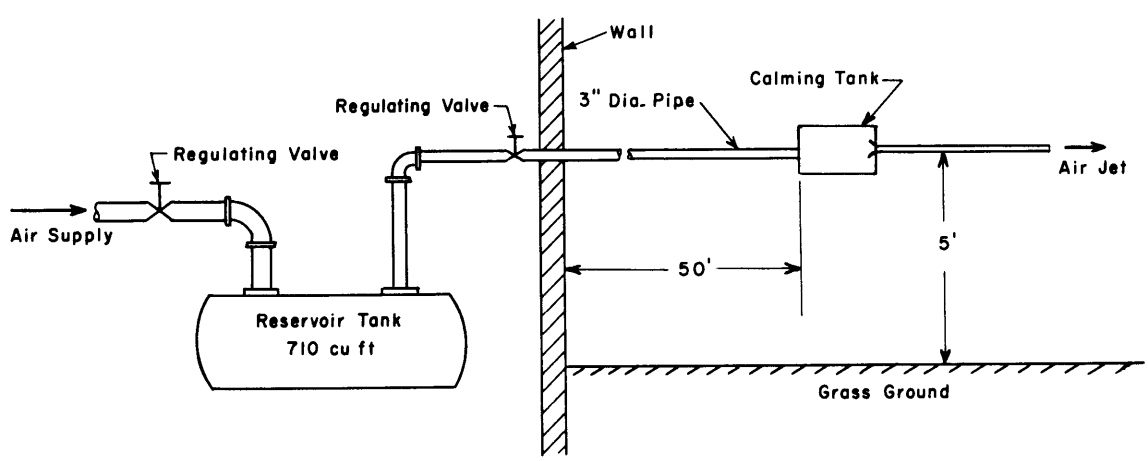

Figure 1 - Schematic Diagram of Air Flow System

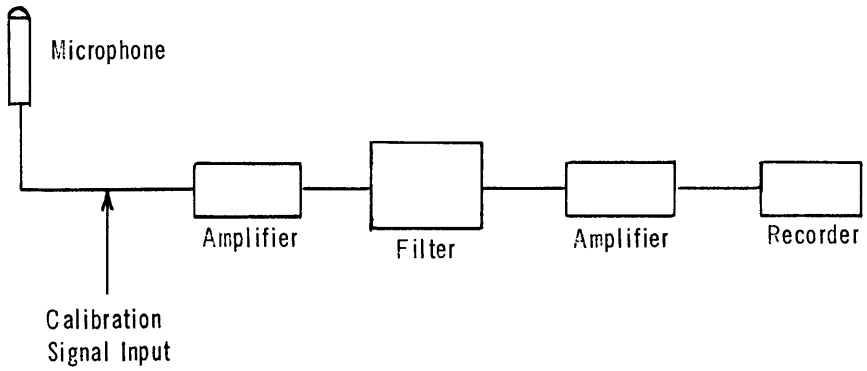

Figure 2 - Block Diagram of Electrical System

The noise radiated by the jet was measured by conventional instruments indicated schematically in Figure 2. The dynamic microphone is an Electro-Voice Model 655 A. A Gertsch Products Company BP-1 filter set was used for measurement in half-octave bands with center frequencies from 250 to 11,400 cps. Two Instrument Electronics amplifiers and a Sound Apparatus Company Type FR level recorder, with its rectifier modified to respond to mean-square voltage, completed the necessary acoustic instruments. The microphone sensitivity had been obtained previously by laboratory calibration.[5] From the sensitivity calibration curve, sound pressure levels in each half-octave band were corrected for the microphone sensitivity by using the average sensitivity in the corresponding band. The microphone was sensitive up to 13,000 cps, though flat response was by no means achieved. In fact, a rapid drop in sensitivity of nearly 10 db from 7000 to 13,000 cps leads to the possibility that the experimental error due to the microphone is relatively larger at the higher frequencies. Calculation of the absolute sound pressure was facilitated by making a calibration of the electrical system before each run.

In addition to the half-octave measurements, it is of interest to determine the wide-band sound power over all frequencies. The wide-band power can be calculated by adding the power in the individual half-octave bands. However, it is simpler to make a measurement in a wide band, and this was done by setting the filters to cover the range 38 to 13,600 cps. To compute the absolute value of the sound power from this wide-band measurement, some average sensitivity must be assumed for the system, since the actual sensitivity of the microphone varies considerably over the frequency range. The average sensitivity was determined by first calculating, for some particular measurement condition, the sum of the powers in the individual half-octave bands. The wide-band sensitivity is equal to the measured electrical power in the wide band divided by the calculated power. This average sensitivity may

vary with the spectrum of the sound being measured. However, in the present case, the sensitivity calculated for two of the most extreme spectra (25 and 150 deg azimuth at 640 ft/sec) differed by only 1 db.

Directivity patterns were obtained by placing the microphone facing the jet opening at the end of a rotating arm. Rotation of the arm was such that the microphone head was always in the same horizontal plane as the jet axis and was equidistant from the jet mouth for all angles. After the pressure-reducing valve was adjusted to produce a desired constant jet velocity, and the band-pass filter set at a desired frequency band, the arm was slowly rotated about the jet, and continuous sound measurements were thus taken for all angles. The procedure was repeated for all frequency bands. Measurements designed to determine the effect of velocity were taken with the microphone fixed at one position, while the velocity was varied.

The measurements were made on days when the outdoor temperature varied from 40 to 70 degrees F. The effects of these variations in temperature, and also of variations in moisture content, if any, were not considered.

RESULTS AND DISCUSSION

VARIATION OF SOUND PRESSURE WITH DISTANCE

The effect of distance from the nozzle mouth on the sound pressure was determined for various frequencies and azimuth angles. The results indicated that, at distances of at least 1 wavelength and at least 20 nozzle-mouth diameters, the sound pressure follows the inverse distance law, $p \propto 1/r$, sufficiently well for all frequencies. Closer to the mouth, some data indicate that the sound pressure variation with distance deviates from the inverse distance law, depending on the frequency and the azimuth angle. This is probably due to the fact that the effective acoustic center of the jet is not at the jet mouth, and that the jet consists of multipole sources such as dipoles or quadripoles, rather than simple sources.

DIRECTIVITY PATTERN OF RADIATED JET NOISE

Figure 3 shows the directivity patterns of the sound pressure in the wide band and various half-octave bands for the jets with 1/2-inch and 5/8-inch diameters. Results indicate the existence of an angle θ_{max} at which the maximum sound pressure occurs. θ_{max} appears to move away from the jet axis with increase in frequency. In general, a change in jet velocity or jet size also influences the directivity pattern. It will be shown later that the smaller the azimuth angle, the faster the sound pressure increases with an increase in jet velocity. This has the effect of displacing θ_{max} closer to the jet axis at higher velocities. Some measurements of the National Advisory Committee for Aeronautics (NACA)[6] have shown further that for a given velocity and frequency, an increase in jet diameter tends to broaden the directivity pattern, thus shifting the maximum radiation angle away from the jet.

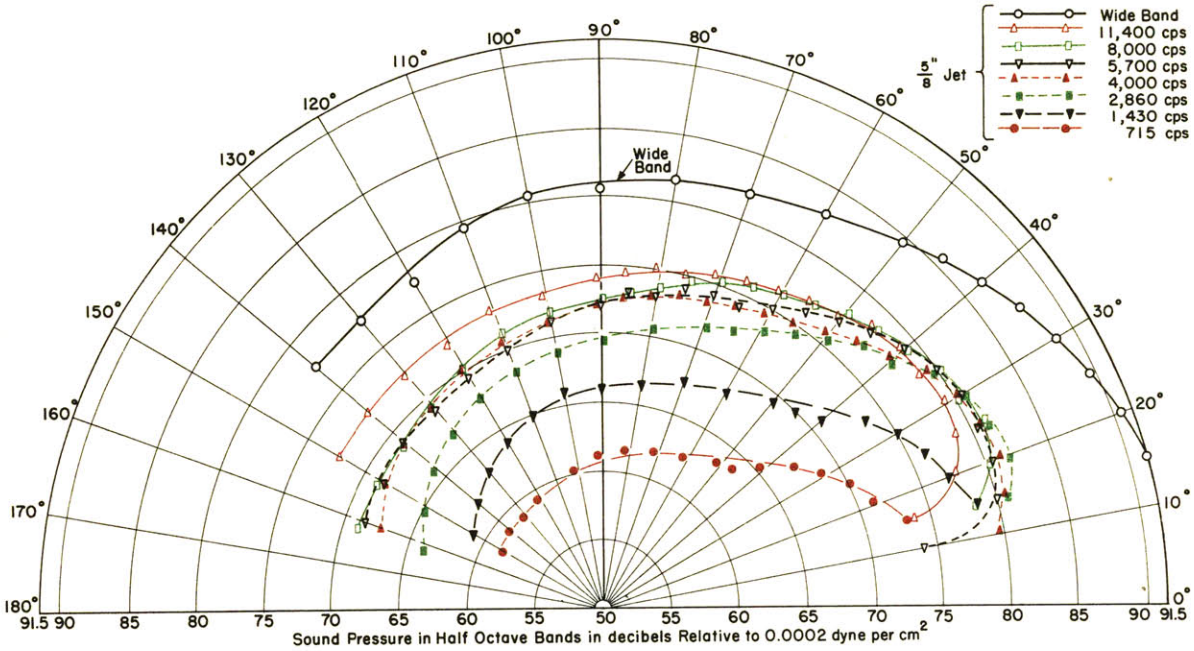

Figure 3a - 5/8-Inch Air Jet

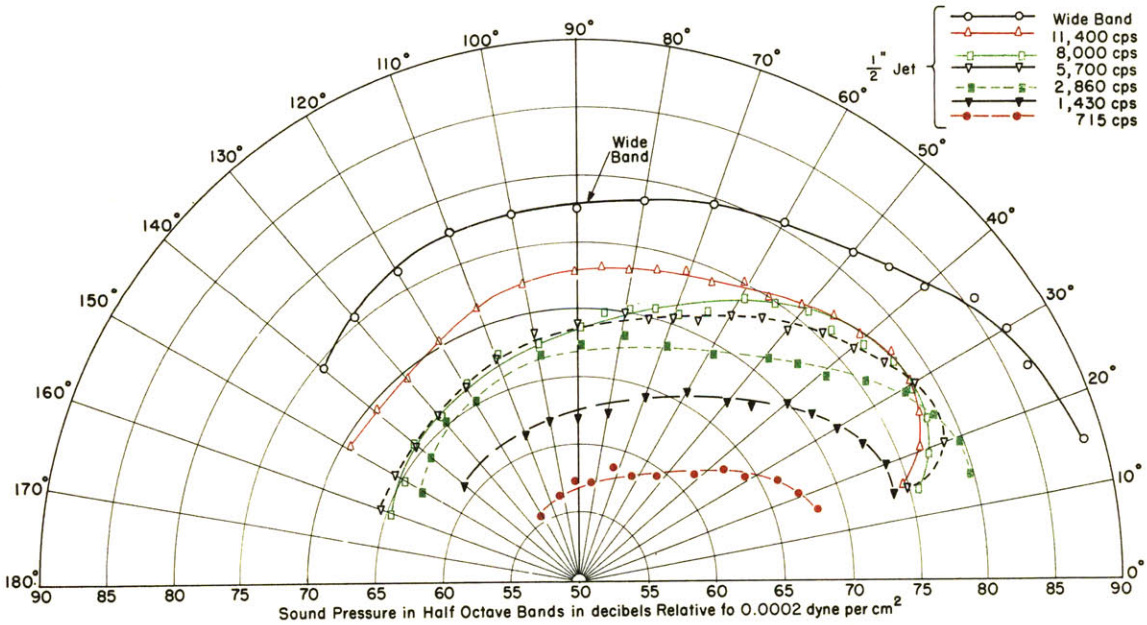

Figure 3b - 1/2-Inch Air Jet

Figure 3 - Directional Patterns of Noise Radiated by Air Jets at Various Frequencies at a Distance of 3.0 Feet

The levels are for half-octave bands centered at the frequencies shown on the curves, except for the wide band (36 - 13,600 cps). Downstream corresponds to 0 degrees.

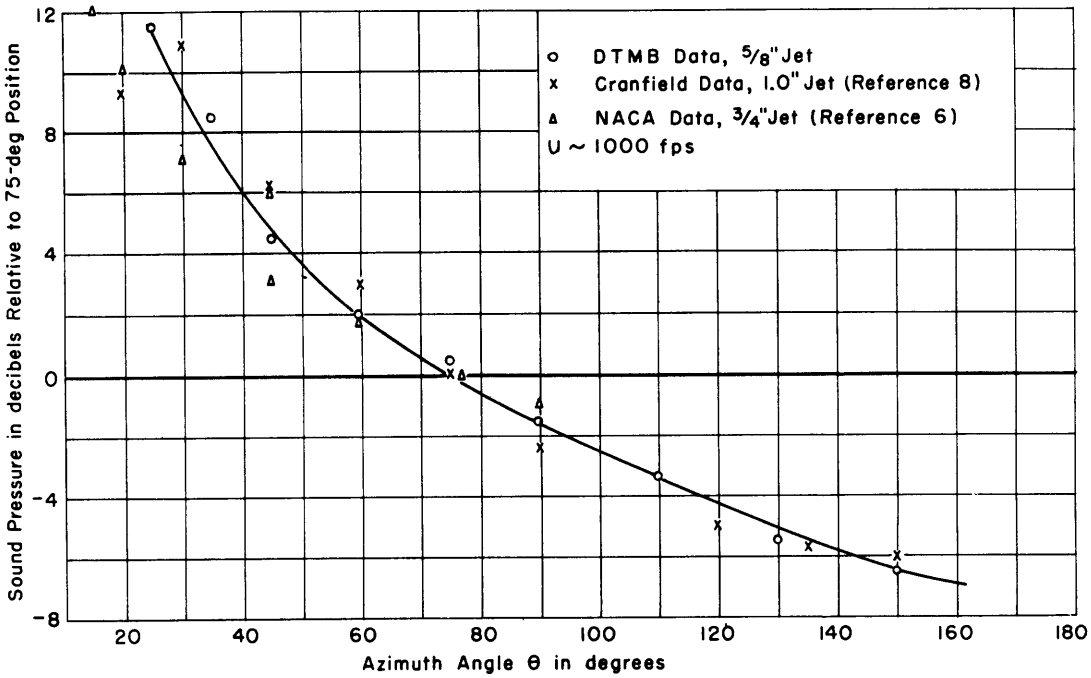

Figure 4 - Wide-Band Sound Pressure As a Function of Azimuth Angle Obtained by Three Independent Measurements

All these observations indicate the dependence of the directivity pattern of the radiated jet noise on three quantities: frequency, velocity, and jet size.

A comparison of the directivity pattern for a wide frequency band obtained in the present experiment with those reported by the NACA[6] and the Cranfield College[7] for a comparable velocity and jet size is shown in Figure 4.

SOUND SPECTRA

The results indicate that the sound pressure spectra depend on both the jet velocity and the azimuth angle. For a given azimuth angle, the spectra have rather flat maxima, which shift slightly toward higher frequencies with increase in jet velocity. Sample spectra for various jet speeds, at an azimuth angle of 25 degrees are shown in Figure 5. The peak frequency, as noted, shifts from the vicinity of 3200 cps at 250 ft/sec to about 5000 cps at 840 ft/sec, thus indicating again what has previously been reported,[2] that the peak frequency of the sound produced by a jet is slightly dependent upon jet velocity.

For a jet velocity of 620 fps, sound pressure spectra for various azimuth angles are shown in Figure 6. It may be observed that with increase in azimuth angle, the contribution of higher frequency components to the wide-band noise is greater. At large azimuth angles, the spectra exhibit no peaks within the frequency range covered by the measurements. It is to be expected, however, that spectrum peaks will be reached at some higher frequency for these angles. It should be noted that the location of spectrum peaks shown applies only to

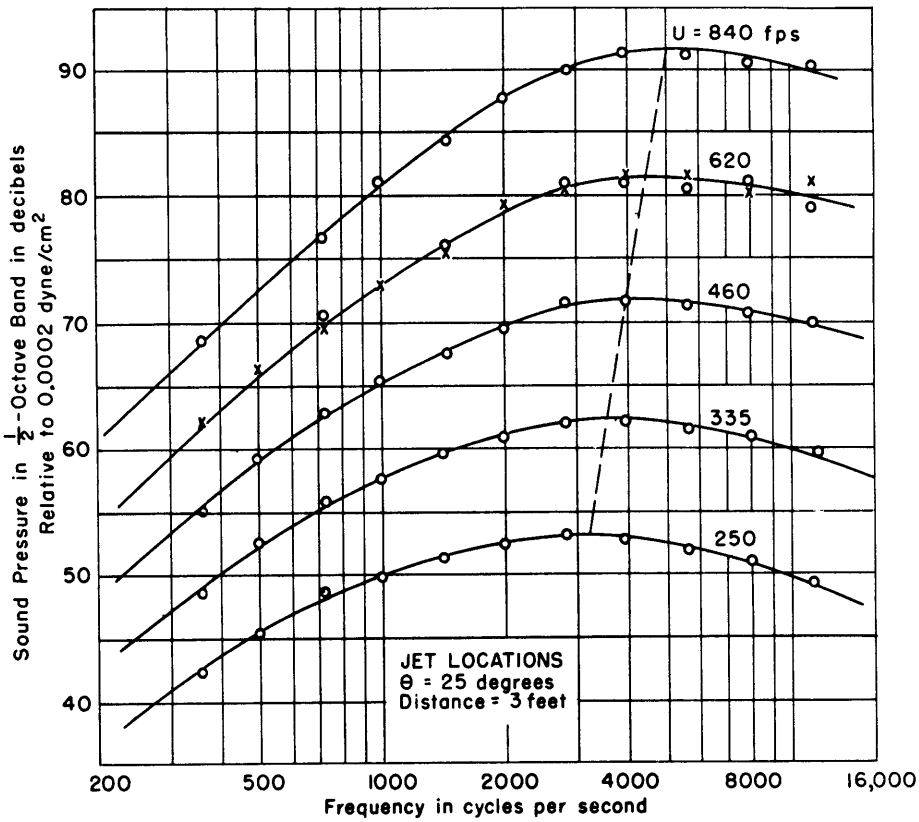

Figure 5 - Sound Pressure Radiated by 5/8-Inch Diameter Air Jet at an Angle of 25 Degrees As a Function of Frequency and Velocity

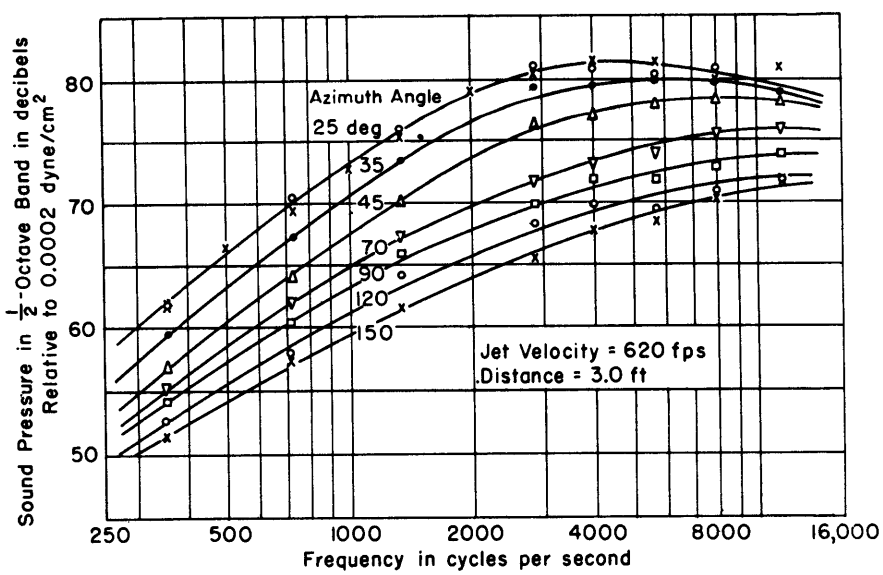

Figure 6 - Sound Pressure Radiated by 5/8-Inch Diameter Air Jet at a Velocity of 620 Feet/Second As a Function of Frequency and Azimuth Angle

the sizes of jets employed in the present experiment; larger size jets would have peaks at lower frequencies. The general upward shift of the spectrum to higher frequencies with increase in velocity and azimuth angle observed has also been reported by Powell.[8]

TOTAL ACOUSTIC POWER SPECTRUM OF THE SOUND SOURCE

Because of the change of the directivity pattern with frequency, a frequency analysis at one point in the sound field does not indicate the spectrum of the total power radiated by the jet. Assuming the directivity pattern of the jet noise to be axially symmetric, the total acoustic power output in some frequency band may be obtained by numerical integration of the directivity pattern obtained in the horizontal plane.

The distributions in frequency of the total sound power radiated by the 1/2-inch and 5/8-inch jets obtained by integration of the directivity patterns are plotted in Figure 7. In the frequency range where experimental data are available, the total power spectra exhibit no distinct peaks, but rather show a gradual rise at the higher frequencies. The previously reported Model Basin data[2] did show broad peaks, the frequency of the peak increasing in terms of the dimensionless frequency parameter fD/C from 0.15 to 0.3 with increasing Reynolds number. In the present case, a peak must occur above 10,000 cps, corresponding to a frequency parameter of greater than 0.35, at a Reynolds number somewhat smaller than the lowest value of the previous data. This disagreement as to the peak frequency may be due to the fact that the nozzles used for producing the previously tested jets were shorter than those used in the present experiment.

When comparing the shape of the spectra reported by different experimenters, it should be noted that the general shape of a spectrum varies with the quantity used to indicate the

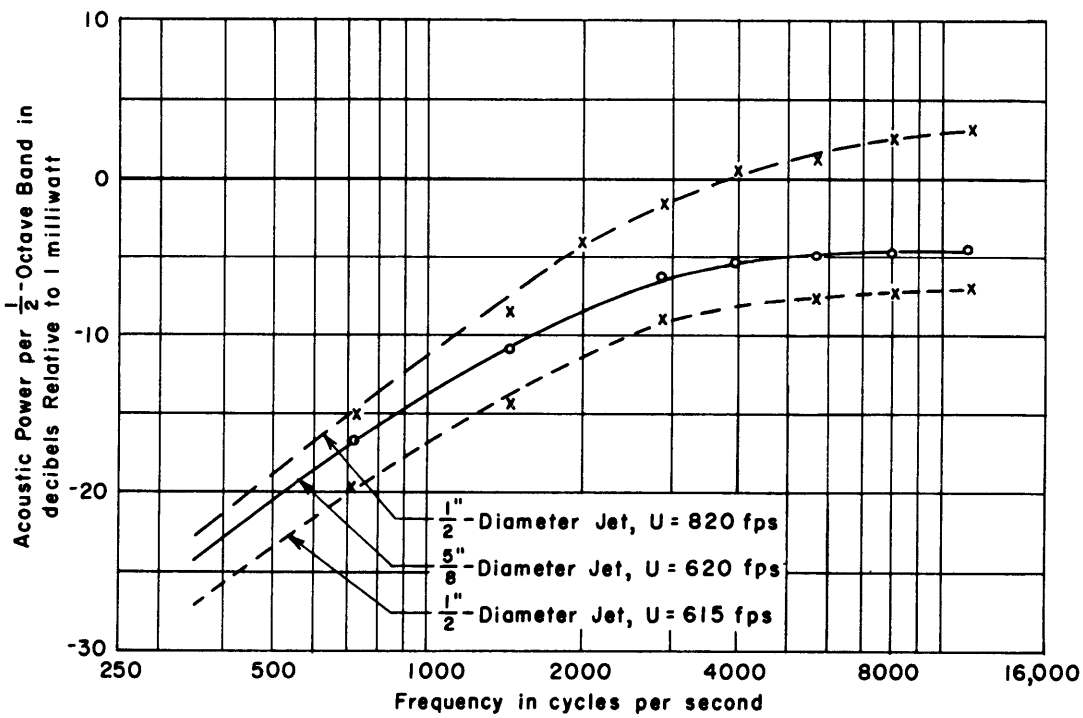

Figure 7 - Spectrum of the Total Acoustic Power Radiated in All Directions by the 1/2-Inch and 5/8-Inch Diameter Air Jets

amplitude of the spectrum. In the present case the amplitude is given in terms of the power per half-octave band. If the amplitudes were given instead in terms of the spectral density, or power per cps, the entire spectrum would have its slope made more negative by 3 db per octave, so that a maximum in the spectrum would exist if plotted on this basis.

EFFECT OF JET VELOCITY ON SOUND PRESSURE

The sound pressure variation as a function of jet velocity for a given frequency band was found by fixing the microphone at one position while varying the jet velocity. The observed variation of sound pressure with velocity can be fitted to a simple power law of the form $p \propto U^b$. The exponent b was found to vary depending upon the frequency and azimuth angle. In general, values of the exponent seem to increase with increase in frequency and decrease in azimuth angle. Figures 8 and 9 show part of the experimental data in support of the establishment of the velocity power law as a function of frequency and azimuth angle. Table 1 summarizes the values of b calculated from the pressure versus velocity data. The range of values for b from 2.1 to 3.9 agrees well with those reported by the Cranfield College.[7]

The knowledge of the velocity power law at various angles and frequencies enables one to calculate the sound pressure at any fixed point in the noise field for the particular jet size employed in this experiment; but, of course, it does not provide one with the whole

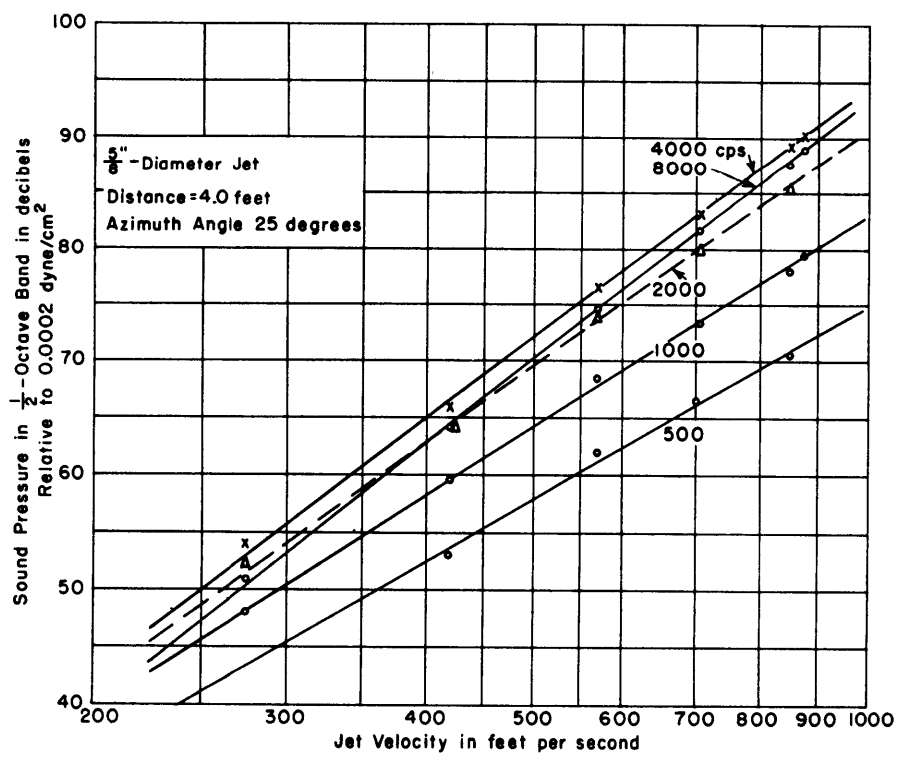

Figure 8 - Sound Pressure in Half-Octave Bands As a Function of Jet Velocity for Various Frequencies

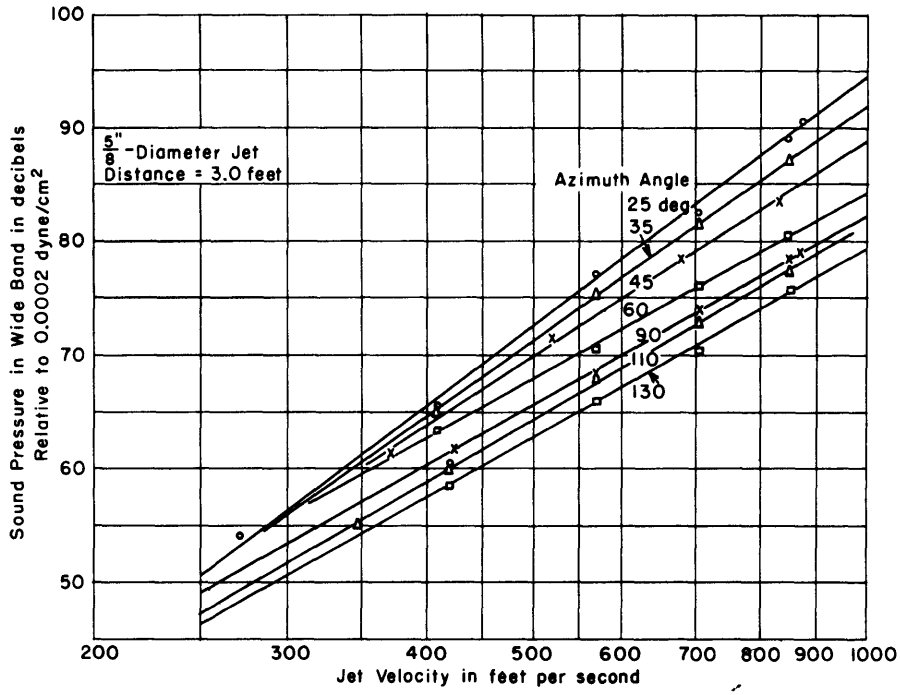

Figure 9 - Effect of Velocity and Azimuth Angle on Sound Pressure in a Wide Band (36 - 13,600 cps)

TABLE 1

Values of b as Functions of Frequency and Azimuth Angle Where b is Defined by the Velocity Power Law $p \propto U^b$

Angle deg \ Frequency cps	360	500	715	1000	1430	2000	2860	4000	5700	8000	11400	Wide Band
25	2.6	2.6	2.7	3.1	3.2	3.4	3.6	3.7	3.7	3.7	3.9	3.7
35	2.3	2.5	2.4	2.6	2.7	3.0	3.2	3.3	3.5	3.6	3.8	3.4
45	-	-	-	2.3	2.4	2.6	2.9	2.9	2.9	3.1	3.2	3.1
60		2.4	2.4	2.3	2.4	2.3	2.4	2.8	2.7	2.9	2.8	2.8
75		2.4	2.4	2.4	2.6	2.6	2.6	2.9	2.8	2.9	2.9	3.1
90		-	-	2.4	2.4	2.4	2.4	2.4	2.8	2.9	2.9	2.7
110		2.3	2.1	2.2	2.2	2.3	2.3	2.5	2.5	2.6	2.9	2.9
130		2.3	2.2	2.1	2.2	2.3	2.2	2.4	2.2	2.5	2.7	2.5
150		-	-	2.0	2.0	2.2	2.1	2.1	2.3	2.5	2.6	2.6

picture of the general directional characteristic of jet noise. Furthermore, if the effective noise center of the sound source of the jet is dependent upon the velocity, as is suspected by workers in Cranfield College, then the values of b when determined close to the jet would be dependent also upon the distance between the microphone location and the jet exit.

EFFECT OF JET VELOCITY ON TOTAL ACOUSTIC POWER RADIATED BY A JET

Lighthill suggested in his theory that the total acoustic power output of a turbulent jet may be expected to vary with the eighth power of the jet velocity. This was verified by the previously reported Model Basin data. Computation of the total wide-band acoustic power radiated by the jet for the present data are plotted in Figure 10. The acoustic power in the wide band covering 36 to 13,600 cps varies approximately as the 6.4th power of the velocity rather than as the 8th power. This apparent disagreement as to the dependence of the total acoustic power on the velocity between the two experiments can perhaps be attributed to the following. The acoustic power measured in the wide band in the present experiment is only a fraction, possibly as small as one-third, of the total acoustic power actually radiated by the jet at all frequencies, since the microphone was not sensitive at the higher frequencies. If this fraction of the total acoustic power is dependent upon velocity, as might be expected because of the shift of the spectrum to higher frequencies with increase in velocity, then the actual dependence of the total acoustic power on the velocity would be greater than the 6.4th power. To speculate a little further, if the shift in the spectrum with velocity is such that the fraction of the acoustic power measured in the wide band is only one-third of the actual

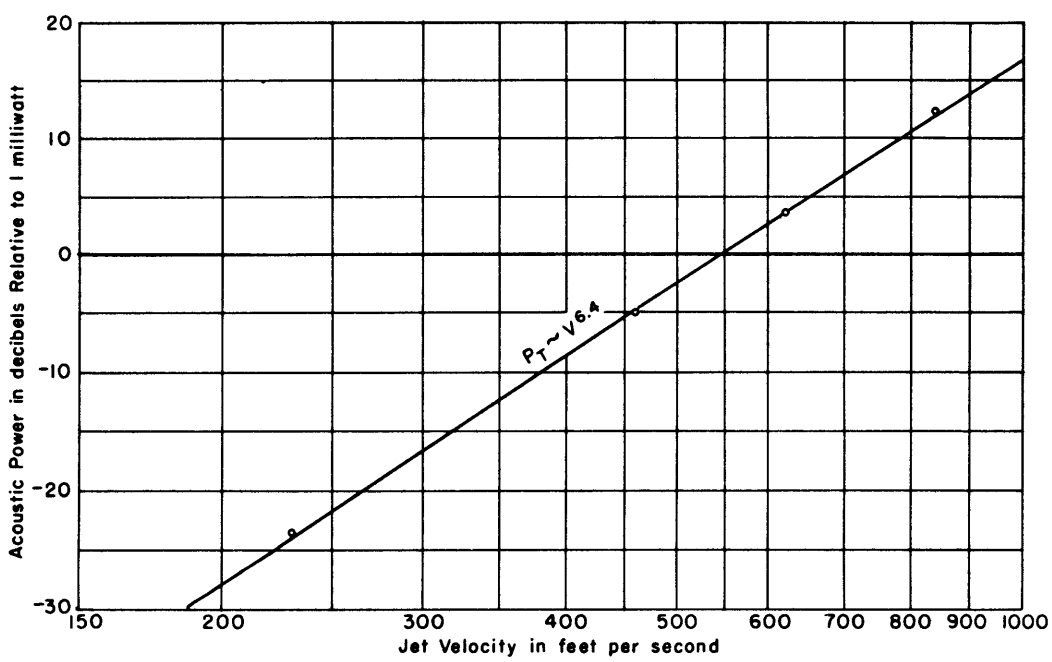

Figure 10 - Acoustic Power Radiated in Wide Band (36 - 13,600 cps) by 5/8-Inch Air Jet As a Function of Velocity

total radiated acoustic power at the velocity of 1000 fps, and one-half at the velocity of 250 fps, then the correction needed to apply to the present measurement would indeed bring about the 8th power law. This amount of power spectrum shift required would be consistent with the frequency shift in the spectra shown in Figure 5.

COMPARISON OF TOTAL POWER SPECTRA

It is of interest to compare the power spectra obtained from the present measurements with those previously reported.[2] To find a basis for comparison of spectra from jets of different diameters, use is made of the conclusions drawn in the previous report, namely, that at a given Mach number, frequency bands should be compared on the basis of a dimensionless frequency parameter fD/c, and that the total acoustic power in any such dimensionless frequency band is approximately proportional to the jet area. Accordingly, a comparison can be made by plotting the acoustic power per unit jet area against the dimensionless frequency parameter for some particular value of Mach number.

Such a comparison is shown on Figure 11 for a jet velocity of 620 ft/sec (corresponding to Mach number 0.57). As can be seen, the previous data obtained for two jet sizes in

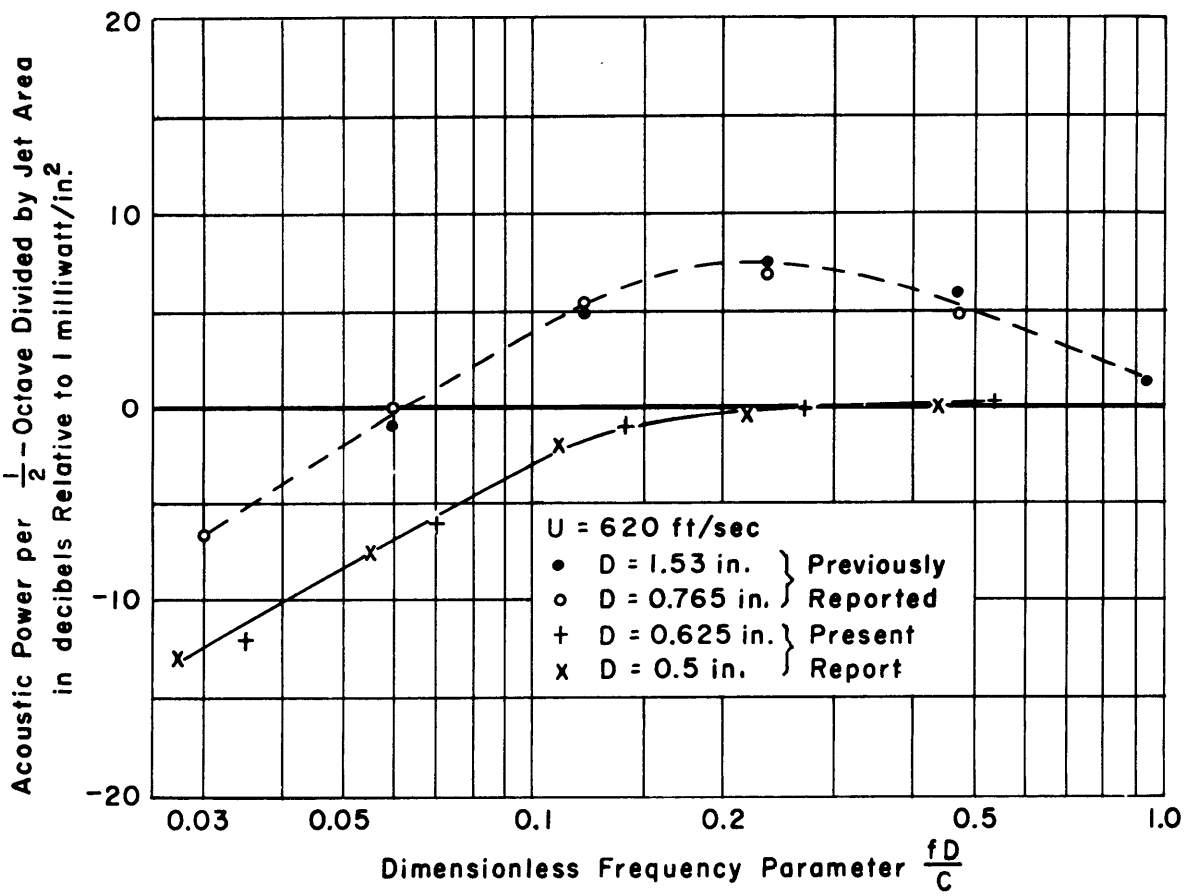

Figure 11 - Comparison of Total Power Spectra for Four Jet Diameters

The previously reported data were obtained from Reference 2 by interpolation between two velocities.

a reverberant chamber are self-consistent, and the present data obtained for two jet sizes in a free field are also self-consistent, but the two sets of data are not in good agreement with each other. The previous data indicate some six decibels (four times) more power, and also show a distinct peak in the spectra in contrast with the rather flat plateau of the present data.

In view of the self-consistency of each set of data, the differences cannot be attributed to random errors. Although errors in microphone calibration could account for three decibels difference, it is doubtful whether six decibels could be attributed to this cause. The most likely explanation, at this writing, seems to be the fact that the previous data were obtained with short nozzles having length-diameter ratios of about 5, whereas the present measurements involved length-diameter ratios of 100. Lighthill's theory indicates that greater sound output is to be expected where the shear is concentrated in a thinner layer, as would be the case for the jets issuing from the shorter nozzles.

SUMMARY AND CONCLUSIONS

The measurements of the sound radiated by an air jet indicate that the directivity patterns of the sound depend on the frequency. The angle of maximum sound pressure increases, relative to the direction of flow, with increasing frequency.

The sound pressure spectrum at any point in the noise field is dependent upon the jet velocity and azimuth angle; the entire spectrum shifts towards higher frequencies with increase in velocity and azimuth angle.

The present measurements indicate somewhat smaller values of total acoustic power than were previously reported. The power spectra are flatter than those previously reported. These differences may be due to the fact that the present nozzles are longer than those tested previously.

Comparison of the present results with those obtained by other workers show general agreement with respect to the directional characteristics of the radiated jet noise.

It is suggested that future investigations on noise radiated by jets include in the program an independent variation of the Reynolds number and Mach number. The effect of length-diameter ratio of the nozzle also requires investigation. A larger range of jet sizes, with varying degree of turbulence development, should be employed. As an additional check on Lighthill's theory, measurement of the pressure fluctuations inside the jet itself should be made.

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2	Head, Aero Dept, Royal Aircraft Establishment, Farnborough Hants, England
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9	BJSM (Navy Staff)

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Measurements are reported of the sound radiated by small air jets at subsonic velocities. The measurements were made in a free acoustic field to obtain the directional pattern of the radiation in half-octave frequency bands covering the range 38 to 13,600 cps.

The directional patterns show an angle of maximum intensity at higher frequencies. As the frequency decreases, this angle moves toward the jet axis, finally ceasing to exist for the lower frequencies and for the wide-band measurements.

The directional patterns and the total sound power radiated in

1. Noise - Measurement
2. Air Jets - Noise
I. Lee, Robert
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