

FR-3266

AUDIBLE P-80 JET AIRCRAFT NOISE

Weiant Wathen-Dunn

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Distribution Unlimited

Approved for
Public Release

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ABSTRACT

The polar distribution, in a horizontal plane, of the acoustic energy generated in the 100-cycle to 10-kilocycle band by a P-80 jet fighter, running at full throttle on the ground, has been measured and analyzed on a constant-bandwidth basis. The data have been used to compute the octave-band levels in the same frequency range, and from these, in turn, overall levels have been computed which check, to within 2 db in all cases, the overall levels actually measured. The formulas and the methods used are discussed in greater detail in appendices.

PROBLEM STATUS

This is an interim report on one phase of Problem No. S30-01. Work is continuing.

AUTHORIZATION

NRL Problem No. S30-01.

AUDIBLE P-80 JET AIRCRAFT NOISE

PROBLEM

The present problem is to measure and analyze the sonic and ultrasonic noise generated by a P-80 on the ground. This report presents the overall levels, at certain points around the plane, and their analyses to approximately 10 kc. Further analyses to 25 kc will be made and reported when the necessary equipment can be assembled and calibrated and, what is more important, if a plane can be made available.

The present work is part of the larger problem of measuring and analyzing sonic and ultrasonic noise (1) in jet planes during flight, (2) around jet planes on the ground, and (3) in the vicinity of jet-engine test stands. The results of such measurements are of particular interest because of the deleterious effects which are today rather generally supposed to result from exposing personnel to such noise for any length of time. The Naval Research Laboratory is cooperating with the Naval Medical Research Institute in determining whether or not such effects exist and, if they do, the frequencies and levels necessary to produce them. When the results of this research are known and the analyses have been completed, the effects of jet noise on human beings can be evaluated.

EQUIPMENT AND METHOD OF MEASUREMENT

All measurements were made, using a battered P-80, at Patuxent River, Md., through the cooperation of the Physiological Test Section of the Tactical Test Division, Naval Air Test Center.

The measuring and analyzing equipment is diagrammed in Figure 1 and pictured, with the exception of the microphone and "insert-resistor", in Figure 2. The remaining units are shown in Figure 3. The complete apparatus is divided into two sections: (1) the measuring, analyzing, and recording system; and (2) the calibrating system. The former consists of a Western Electric 630-A dynamic microphone connected to an Erpi RA-277-F sound-level meter and analyzer. The analyzer is of the heterodyne type and has a constant bandwidth--in this case 50 cps. The output of the Erpi is recorded by a Sound Apparatus FR recorder with an rms rectifier circuit. The calibrating system consists of an oscillator for producing a 1-kc signal; a vacuum-tube voltmeter, calibrated at one specific point, for measuring the signal; and an attenuation box for controlling the level of the voltage appearing in series with the microphone.

The two sections are joined by the common insert-resistor.¹ The circuit arrangement is such that a measurement of the voltage at the input to the attenuation box is sufficient to

¹ See circuit diagram, Figure 1. The insert-resistor is marked R_1 .

determine the "inserted" series voltage.

A general description of the method of calibrating the microphone and of the method of determining the response of the measuring, analyzing, and recording system, to both single tones and noise, is given in Appendices I and II.

The source of sound for the experiments was the plane shown in Figure 4. Figure 5 pictures the measuring location, which was flat and relatively free of reflecting objects. The measuring positions were limited to those indicated by the filled circles in Figure 6. These points occur every 45° in azimuth, beginning at 22.5° , and are referred to an arbitrary center half-way between the plane's air intake and its jet outlet. In addition, measurements were made directly behind and directly in front of the plane, as well as in the cockpit without the canopy.

The distances of the measuring positions from the center of the circle were dictated by a desire to have a maximum signal-to-noise ratio without overloading the microphone. They were determined on the basis of a preliminary survey made with a General Radio portable sound-level meter. The overload point for the microphone was taken, arbitrarily but with some reason, as 130 db, and in each case the microphone was placed as near the plane as possible without exceeding this value for the overall sound-pressure level.

Considerable variations in wind conditions were encountered during the work, and it was necessary to change the true heading of the plane so as to keep it pointing into the wind. A summary of the

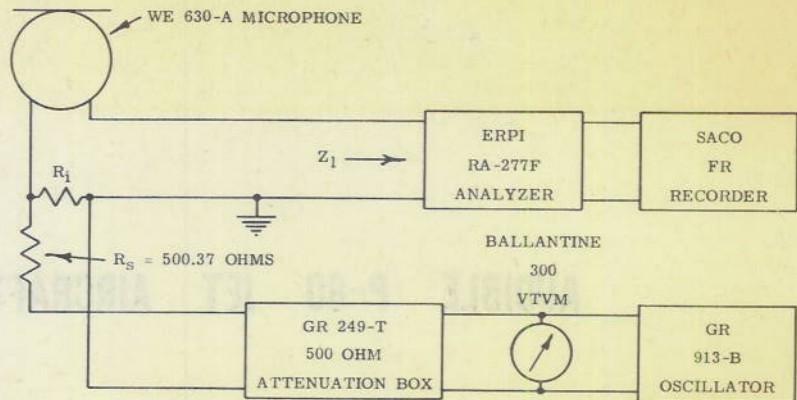


Fig. 1 - Arrangement of Apparatus for Field Use

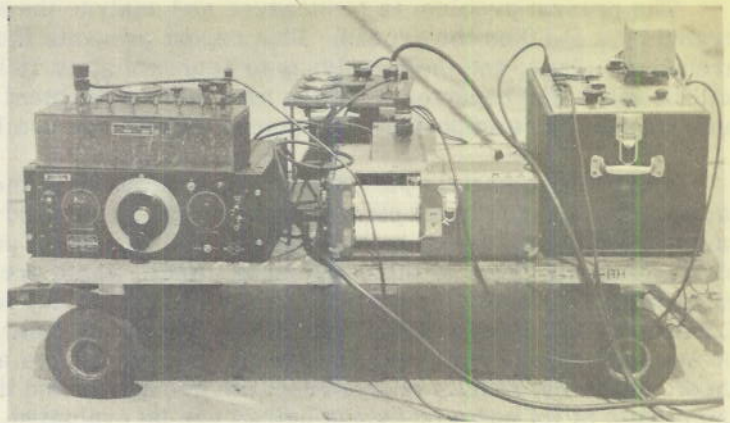


Fig. 2 - Apparatus in the Field



Fig. 3 - Microphone and Insert-Resistor on Field Stand Ready for Use

measuring conditions is given in Table 1 (cf. page 12). All microphone positions are given relative to the plane, but the plane headings are true compass readings.

Each measurement and analysis was obtained at full throttle (11,500 rpm). Under favorable conditions all measurements at a single microphone position were made in three consecutive runs, each followed by a calibration. The first run measured the overall level; the second analyzed the low-frequency range from 100 to 1000 cps; and the third analyzed the high-frequency range from 500 cps to 10 kc. For the first run a 1-kc calibration signal was applied with the analyzer out of the circuit, but in the second and third cases the analyzer was in the circuit and tuned, in the proper range, to the calibrating signal.

Two sample tapes are shown in Figures 7 and 8. The square-topped or step-shaped traces associated with each run are the calibrations. The sharp dips during the analysis are frequency markers, obtained by shorting the recorder with a telegraph key when round-number dial marks passed the index line on the analyzer. Unfortunately, the analyzer dial marks are inaccurate, and it was necessary to translate them into true frequencies, with results which may be noted in Figure 7.

The sound-pressure level corresponding to the calibration line for each run was determined by a method outlined in Appendix II. The sound-pressure level scale was then calculated by noting the relation of the calibration line to the lines printed on the tape.



Fig. 4 - Picture of P-80 Measured



Fig. 5 - Area Where Measurements Were Made

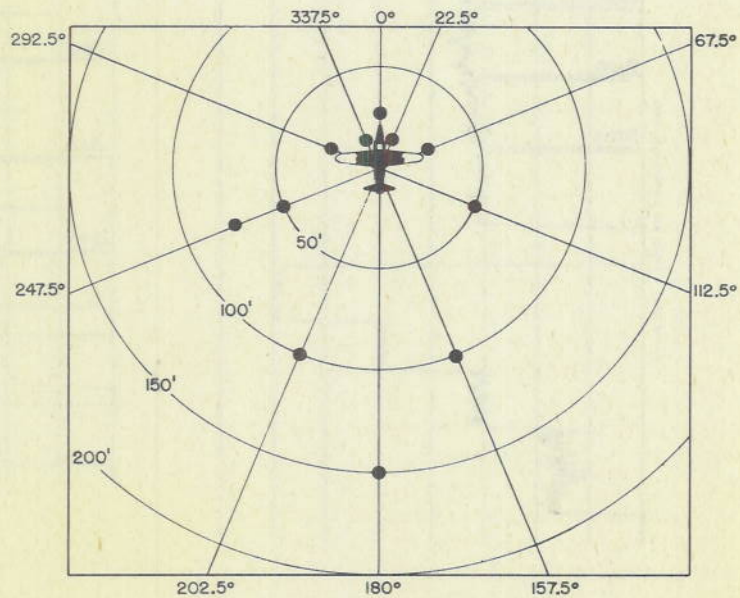


Fig. 6 - Measuring Positions

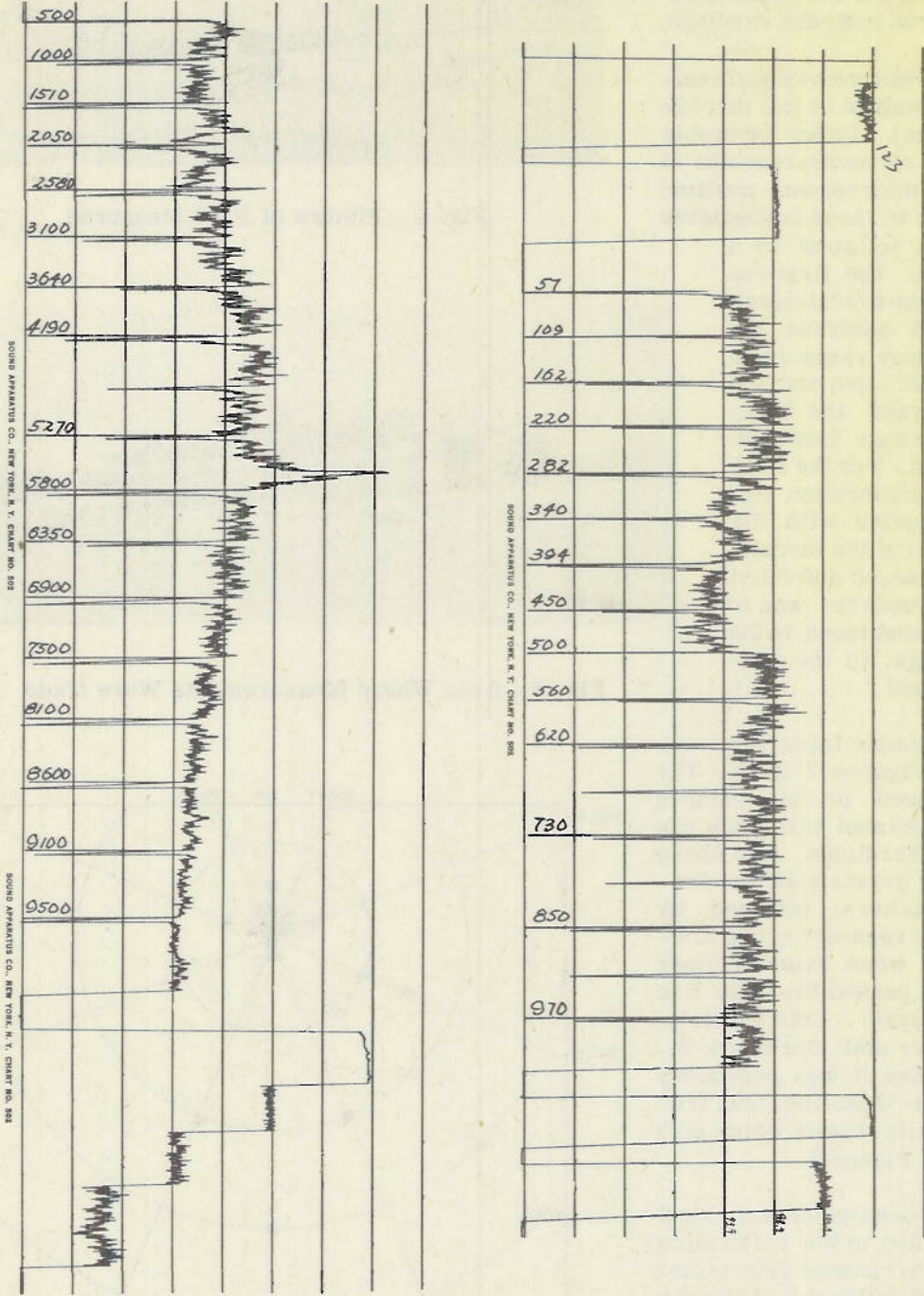


Fig. 7 - Sample Recorder Tape; Forward Position

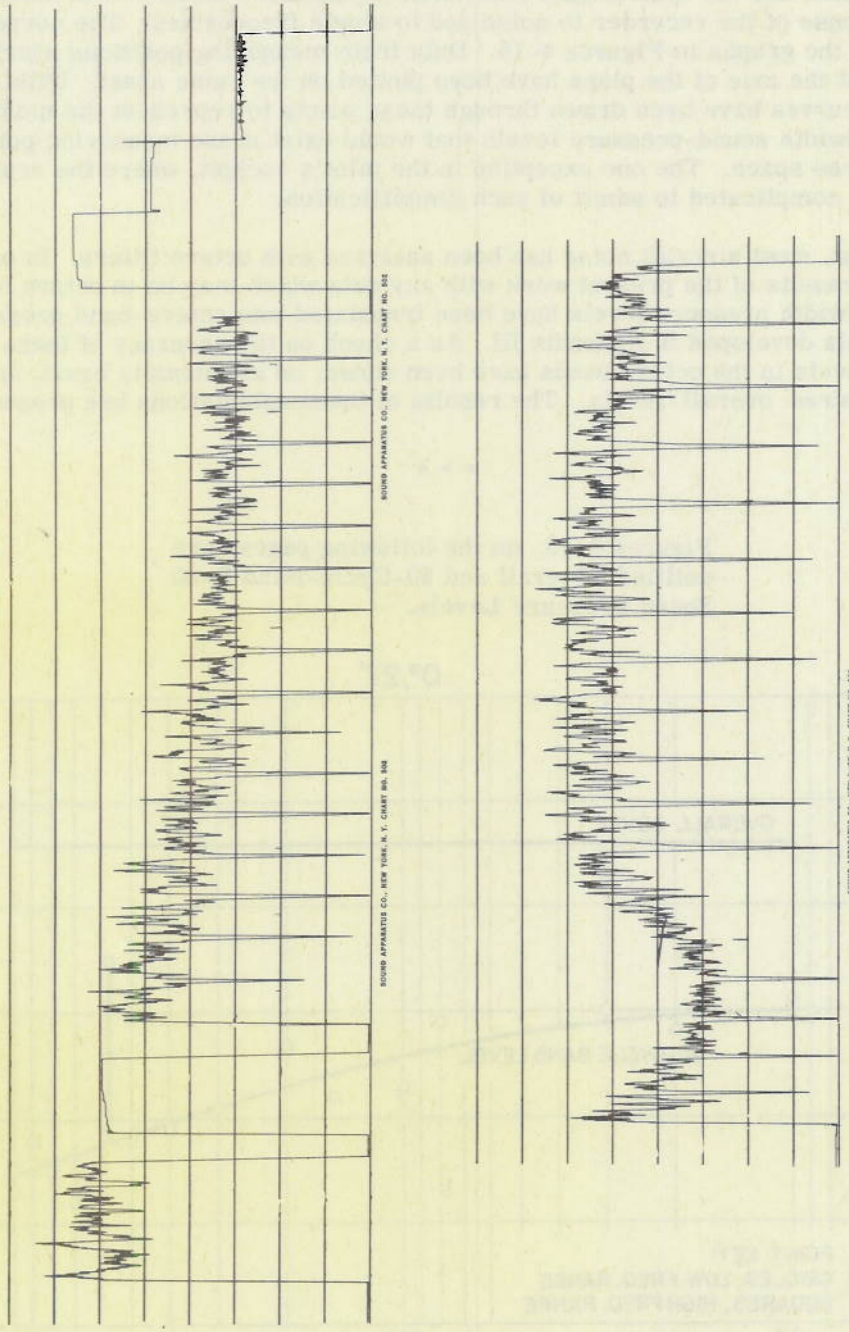


Fig. 8 - Sample Recorder Tape; Jet Wake

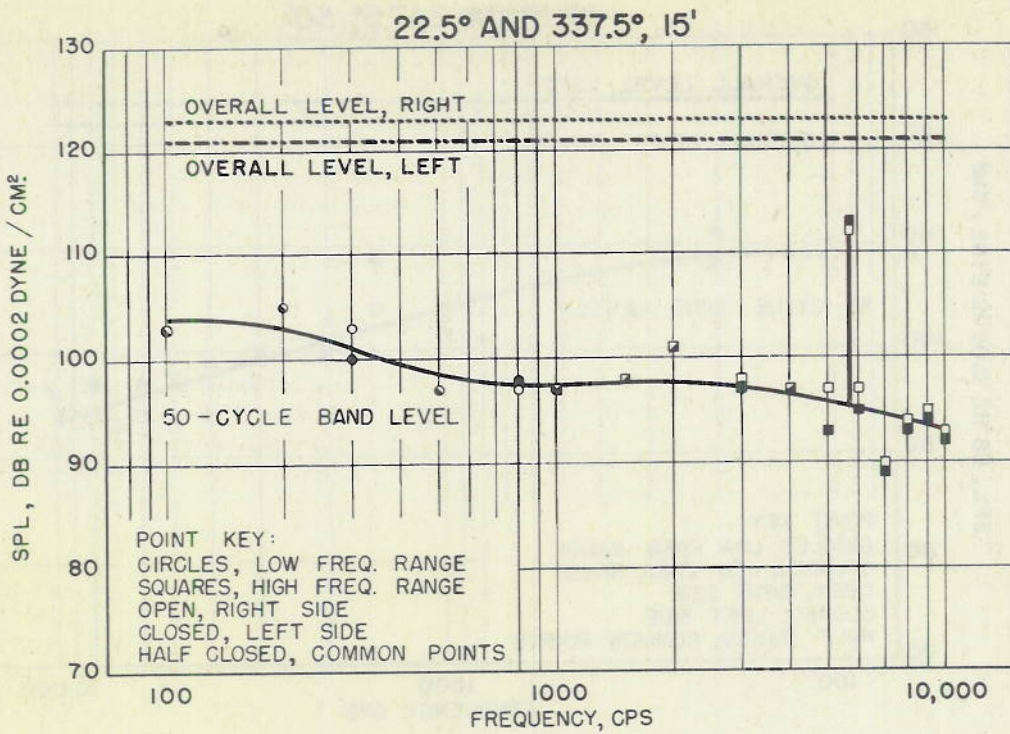


Figure 10

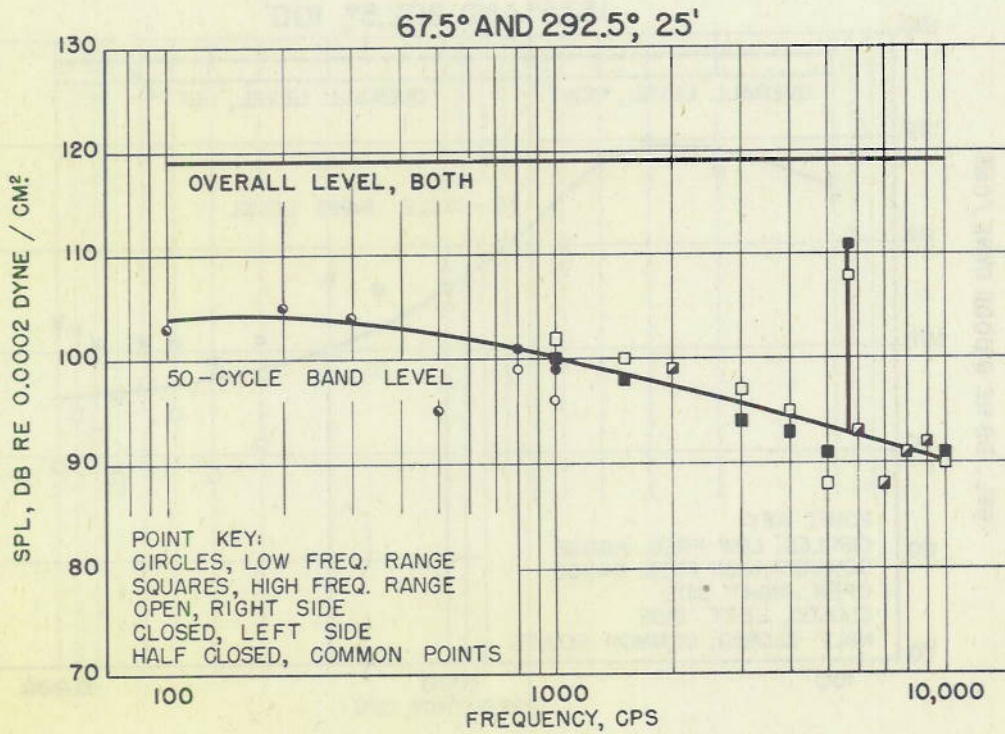


Figure 11

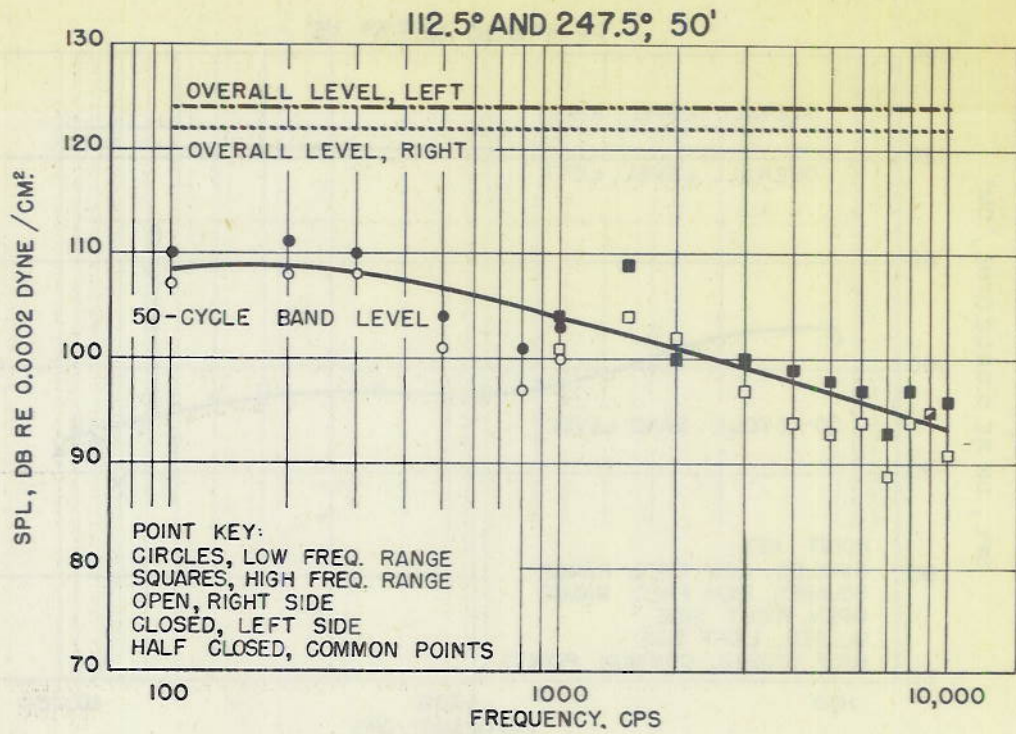


Figure 12

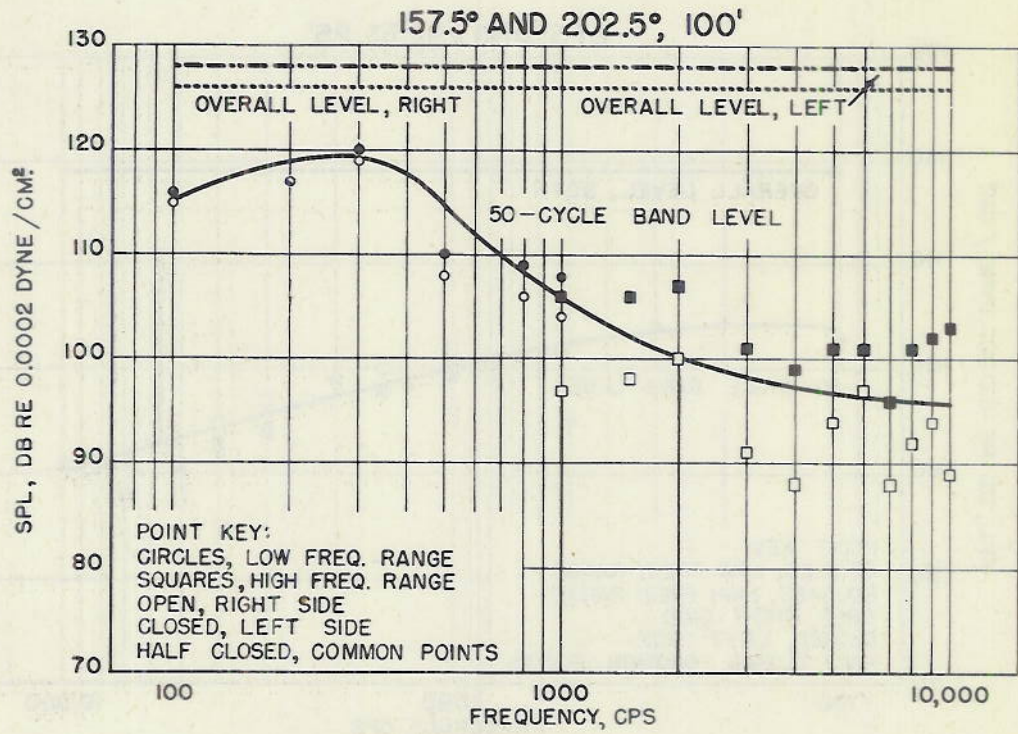


Figure 13

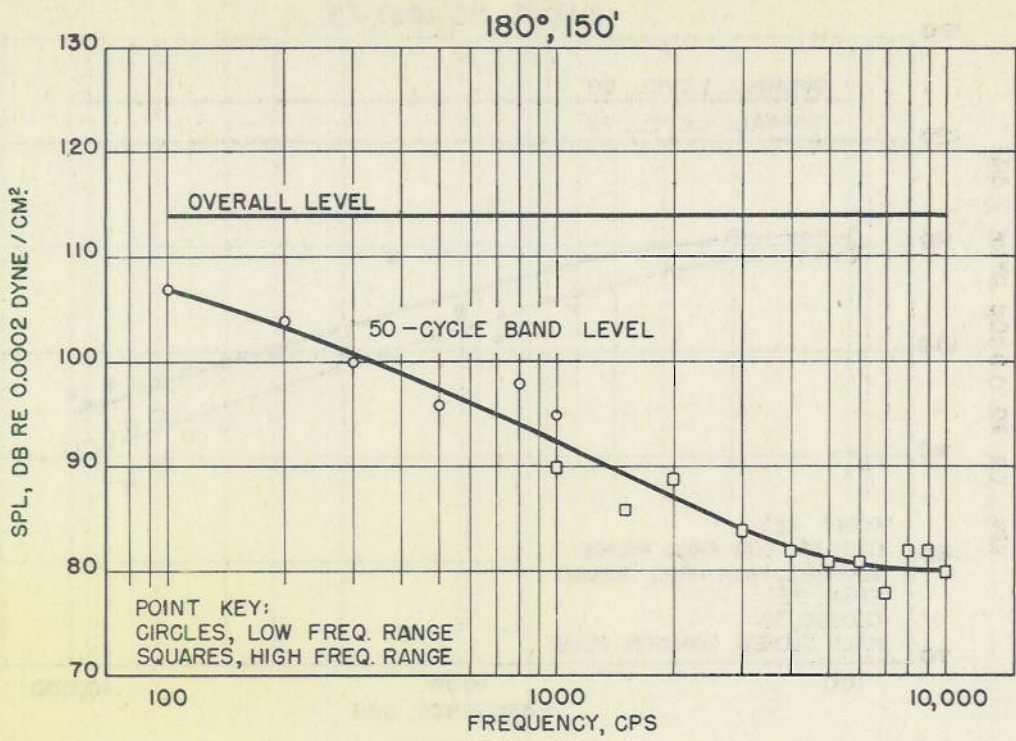


Figure 14



Figure 15

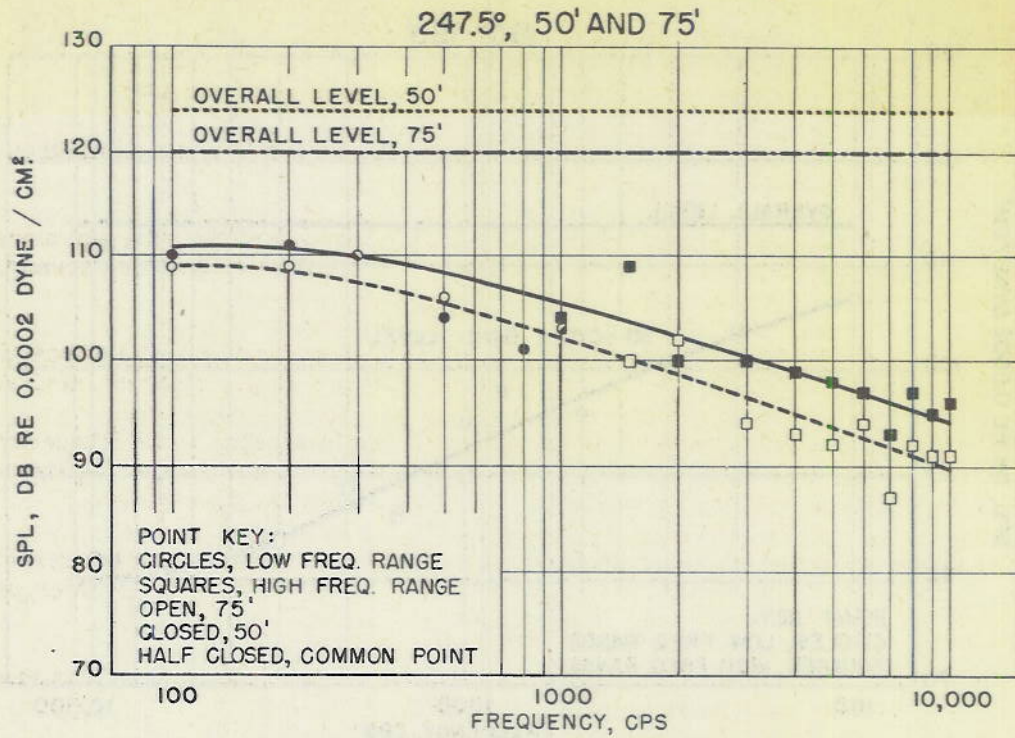
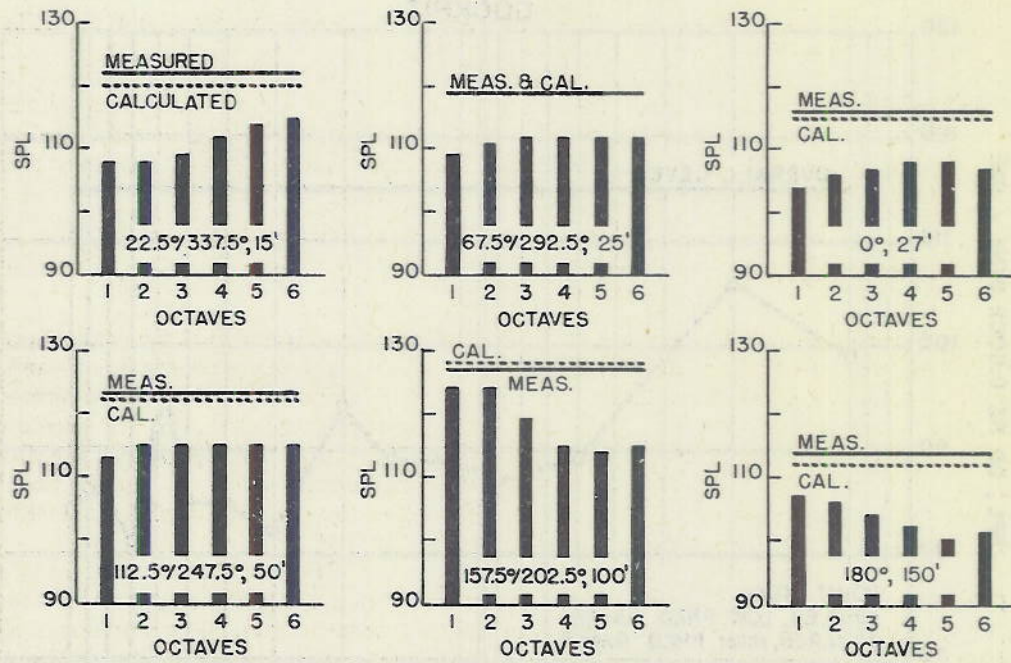


Fig. 16 - Variation in P-80 Sound Pressure Level with Distance



(NOTE: THE SIX OCTAVES COVER THE FREQUENCY RANGE 150-9600 CPS)

Fig. 17 - P-80 Octave-Band Sound Pressure Levels

RESULTS

From the data in Figures 9-17 certain generalizations may be made:

- (a) The overall levels are much higher toward the rear of the plane than they are toward the front.
- (b) The noise is steadier and more reproducible forward of the wing and more erratic to the rear, especially in the jet wake, where very heterogeneous sound transmission conditions exist.
- (c) The 4-db difference in level between the 50-ft position and the 75-ft position at 247.5° indicates an attenuation of approximately 6 db per distance doubled.
- (d) All the constant-bandwidth sound-pressure levels decrease with frequency in the region above 1 kc. In all cases but one they do so monotonically, and in the majority of cases they drop at a rate of approximately 3 db per octave.
- (e) Forward of the wing, the whine of the compressor impeller is predominant. It shows up in the analyses for the forward positions but becomes submerged in the louder jet noise toward the rear.
- (f) The impeller whine is not so predominant in the pilot's cockpit as it is at points just outside the fuselage.
- (g) When the calculated octave-band levels are arranged in order of increasing distance from the plane (as they are in Figure 17), it becomes apparent that the higher frequencies fall in relation to the lower frequencies as the distance is increased. This is not all due, however, to absorption increasing with frequency, as will be noted in the discussion.
- (h) The calculated overall levels check the average of the actually measured overall levels to within 2 db in all cases. In every case but one, the calculated level is below or equal to the measured level, and this is to be expected since the calculated levels are not based on all of the actual pass band.

DISCUSSION OF RESULTS

Irregularities in the measured points fall into two categories. The peaks and dips caused by the interference pattern constitute the first. These reinforcements and cancellations correlate rather well with the geometry of the experiment² and shed some light on the effective sources of sound. For the most forward positions, the air intake is the effective source, but the jet outlet which is more potent appears to become the effective source for all other positions. The situation is complicated, however, by the fact that the after measuring positions are at large distances from the plane, which causes the patterns from the several possible sources to merge.

In the second category is the random scattering at the higher frequencies due to irregular measuring conditions and irregular sound transmission. The worst example of this is found at angles of 157.5° and 202.5° , which are very near the edge of the normal

² The hard concrete apron was the only reflecting surface considered.

jet wake, with the result that the measuring positions may be either in or out of the wake, depending on slight variations in the wind direction.

The more rapid decrease in level of the higher frequencies as distance increases appears to be due only in part to the higher attenuation of these frequencies in the medium. An aural check indicates that, as the observer moves to the rear of the plane, the quality of the sound changes, and there are less high frequencies in the sound itself. The angles associated with the greatest distances are those where the original high-frequency content was lowest.

Lastly, it is interesting to note that the frequency of the impeller whine, 5700 cps, checks very well with the rpm of the motor and the number of blades on the impeller. The engine speed was 11,500 rpm, and the impeller has 30 blades. If each blade is responsible for one sound impulse per revolution the frequency thus generated is very nearly 5700 cps.

* * *

TABLE I
MEASURING CONDITIONS

Relative Microphone Angle, ° Bearing	Microphone Distance, Feet	True Plane Heading, ° Bearing	Wind		Microphone Height or Position, Inches	I-40 Engine	Date
			True Heading, ° Bearing	Velocity, Knots			
0	27	190	220 ± 10	0- 3	58	Original Repaired	11 July
22½	15	190	0	0	"	Original Repaired	11 July
67½	25	120	lo.* 140 ± 10 hi. 125 ± 10	9-11 10-13	"	Original Repaired	10 July
112½	50	120	lo. 120 ± 10 hi. 130 ± 10	8 8-10	"	Original Repaired	10 July
157½	100	180	lo. 180 ± 10 >6 kc. 130 ± 10	3- 5 8-10	"	Original Repaired	10 July
180	150	235	235 ± 5	8-10	"	New	31 July
202½	100	315	0 ± 10	5- 8	"	Original	19 June
247½	75	315	160 ± 50	3- 7	"	Original	17 June
247½	50	315	0 ± 10	5- 8	"	Original	19 June
292½	25	190	220 ± 10	0- 3	"	Original Repaired	11 July
337½	15	190	220 ± 10	0- 3	"	Original Repaired	11 July
Cockpit		298	lo. 300 ± 5 hi. 315 ± 5	5- 7 8-10	†	New	31 July

* lo. and hi. refer to low and high frequency ranges on analyzer.

† 9" in front of armor plate, 2" to right of center line, 3" above level defined by sides of cockpit.

APPENDIX I

MICROPHONE CALIBRATION

The Western Electric 630-A dynamic microphone, serial no. 2127, was calibrated by a substitution method at the National Bureau of Standards. Two views of the microphone and the insert-resistor housing are given in Figures 18 and 19. The standard of comparison was a Western Electric 640-A condenser microphone, serial no. 102, for which the pressure calibration, the free-field correction, and the temperature coefficient were known. A block diagram of the calibrating system is given in Figure 20.

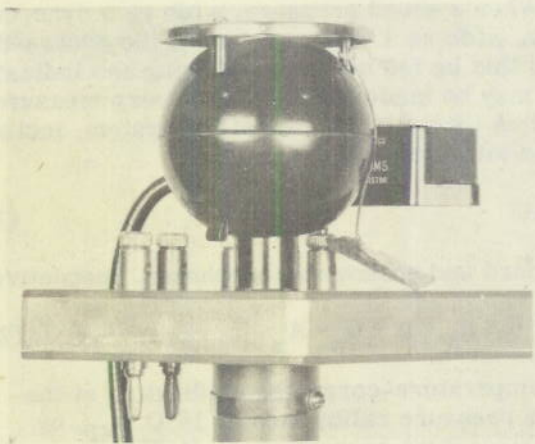


Fig. 18 - Microphone and Insert-Resistor Housing Viewed from Direction of Incident Sound Wave

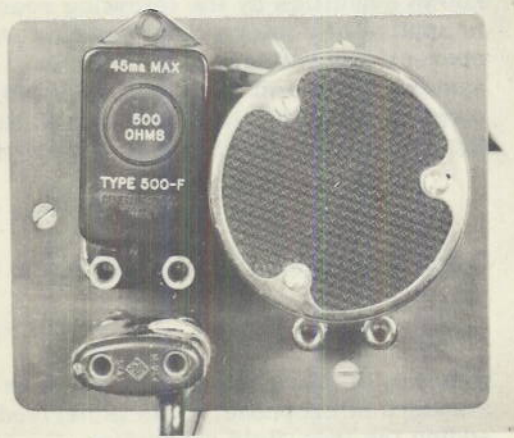


Fig. 19 - Microphone and Insert-Resistor Housing, Plan View. Sound Always Incident from Upper Right

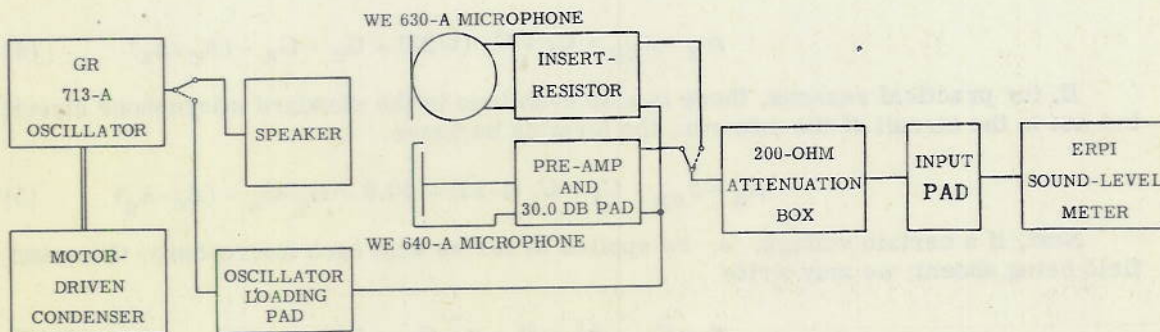


Fig. 20 - Block Diagram of Arrangement of Apparatus for Microphone Calibration

The method was as follows. The standard microphone was placed in a free field about 1 meter from, and on the axis of, the source loudspeaker. The oscillator energized the speaker, and the output of the standard microphone was fed into the indicating system, which consisted essentially of an Erpi sound-level meter. The attenuation box was adjusted so that the reading on the Erpi was within 1 db of some arbitrary point on the meter scale. The attenuation in the box and the difference between the actual meter reading and the arbitrary scale point were combined to give an attenuation figure, A_c .

The unknown microphone was then substituted for the standard, and the indicating system connected to its output. The orientation of the insert-resistor housing was such that the whole assembly appeared to the incident sound wave as shown in Figure 18. The attenuation reading for the same sound field was noted and designated by A_x . The oscillator was then connected to the loading pad, and the two microphone circuits were actuated by the voltage developed across a 1-ohm resistor in the pad. The attenuation readings for the two microphones were noted in the same way as before and were designated by A'_c and A'_x , respectively. The entire process was repeated for each of the calibration frequencies. Above 500 cps the signal was warbled ± 50 cps.

The calibration of the unknown microphone may be obtained from the measured and known quantities by the following reasoning. When a sound pressure, p (db re 1 dyne/cm²), is applied to a microphone having a sensitivity, ρ (db re 1 volt/dyne/cm²), the generated open-circuit voltage is $\rho + p$ (db re 1 volt). If this be fed into an amplifying and indicating system, the result is a reading, R (db), which may be made the same for every measurement by adjusting the attenuation in the circuit, A (db). If the gain of the system, including the coupling losses, be designated by G (db) the following relation holds.

$$R = \rho + p + G - A \quad (1)$$

Using subscripts c and x to designate the standard and unknown microphones, respectively

$$\rho_c + p + G_c - A_c = R = \rho_x + p + G_x - A_x \quad (2)$$

where ρ_c is used to designate the free-field, temperature-corrected calibration of the standard microphone. This is derived from its pressure calibration at 25°C, ρ_{cp} , by adding the free-field correction, C_f , and the temperature correction, $C_t(t-25)$, where C_t is the temperature coefficient in db/°C, and t is the temperature in °C. Thus

$$\rho_c = \rho_{cp} + C_f + C_t(t-25) \quad (3)$$

and, from (2)

$$\rho_x = \rho_{cp} + C_f + C_t(t-25) + G_c - G_x - (A_c - A_x) \quad (4)$$

If, for practical reasons, there is a 30.0-db loss in the standard microphone circuit but not in the circuit of the unknown, the formula becomes

$$\rho_x = \rho_{cp} + C_f + C_t(t-25) - 30.0 + G_c - G_x - (A_c - A_x) \quad (5)$$

Next, if a certain voltage, e , be applied in series with each microphone, the sound field being absent, we may write

$$e + G_c - A'_c = R = e + G_x - A'_x \quad (6)$$

whence

$$G_c - G_x = A'_c - A'_x \equiv \Delta A' \quad (7)$$

Using the same symbolizm, $A_c - A_x \equiv \Delta A$, the complete equation becomes

$$\rho_x = \rho_{cp} + C_f + C_t (t - 25) - 30.0 + \Delta A' - \Delta A \quad (8)$$

The calibration thus obtained is given by the solid line in Figure 21. For comparison, the dotted line in the same figure is an average 630-A calibration scaled from advertising data published by the Western Electric Co. In general, the agreement is considered good, but the 4-, 5-, 7-, and 10-kc values are above the average and are probably due to resonances caused by the insert-resistor housing. Since, however, all measurements here reported were made with the housing in the same relative position as when the calibration was made, the curve is considered sufficiently valid. For future measurements the housing will be entirely disassociated from the microphone.

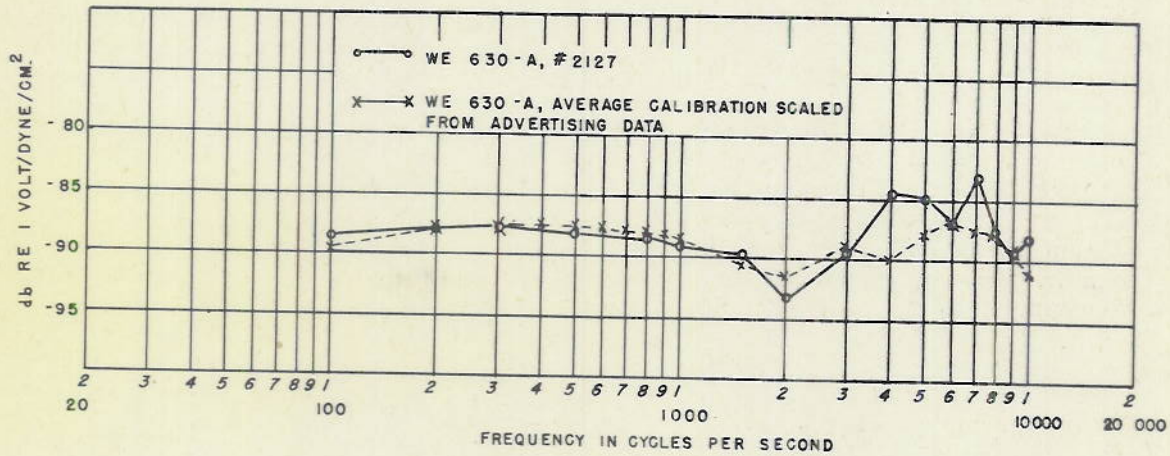


Fig. 21 - Calibration of Western Electric 630-A Microphone, Serial No. 2127

APPENDIX II

SYSTEM CALIBRATION AND DATA CORRECTION

The calibration schedule for the present work was based on the assumption that the gain of the measuring system was the only characteristic not stable over long periods of time. In other words, the absolute response-frequency characteristic of the microphone, the relative response-frequency characteristic of the amplifying and recording system³, and the relative response of the latter to noise impulses and to single frequencies were assumed to be stable enough so that no more than one calibration was needed over a period of several months. As a consequence of these assumptions, it was necessary to know the gain at only one frequency after each measurement in the field. The frequency used was 1 kc.

The calibrating signal was introduced in series with the microphone, having first been attenuated 71.0 db from an original level of 21.7 db re 1 volt (the calibrated point on the voltmeter) by a matching L-pad. The circuit is shown in Figure 1. When necessary, the signal level was lowered still further by adjusting the attenuation box, and the actual insert-voltage was equal to $21.7 - 71.0 - A$, where A was the attenuation in the box.

Such an insert-voltage is equal to that open-circuit voltage from the microphone which would cause the same reading on the indicating system, provided R_i is kept relatively small and provided the microphone has the same acoustic termination as it had when measuring the sound. Consequently, since the microphone calibration was known, the insert-voltage corresponded to a certain sound-pressure level, which was determined in the following manner.

The difference between the insert-voltage and the microphone calibration for 1 kc (-89.2 db re 1 volt/dyne/cm²) gave the corresponding sound pressure in db re 1 dyne/cm². This was translated into sound-pressure level by adding 74.0 db, and the complete equation for the level became

$$L = 21.7 - 71.0 - A + 89.2 + 74.0 \text{ db}$$

This was the level associated with the calibration line on the recorder tape.

The resulting sound-pressure scale is applicable, strictly speaking, only to the data at 1 kc. In general, at any other frequency a correction must be applied to the narrow-band data, and a correction is necessary for the wide-band, or "overall", reading as well. The corrections for the narrow-band case are easily found. First, the difference between the single-frequency response at 1 kc and the single-frequency response at the other frequency is determined for each part of the system. Then the difference between the single-frequency response of the recorder and its narrow-band noise-impulse response is measured at the same frequency. The required correction may be obtained from the algebraic sum of these differences.

³ These will remain constant provided no changes are made in the cabling between the various units. In the work here reported changes were made, and two conditions obtain: (1) "short" cabling, and (2) "long" cabling.

An equally accurate correction for the wide-band case is not so simple to obtain. Fortunately, in the present instance the various parts of the system are relatively "flat", and it is sufficient to average the single-frequency response of each part of the system over the frequency region where the narrow-band components contribute most to the overall level and to use the difference between this average response and the 1 kc value to compute the correction. The difference between the single-frequency response at 1 kc and the wide-band noise-impulse response can be used to calculate the noise-impulse correction.

As indicated above, the final corrections are compounded from the corrections obtained from the following data: (1) the microphone calibration; (2) the relative analyzer and recorder response-frequency characteristic, including the cabling; and (3) the relative response of the recorder to noise impulses as compared to its response to single frequencies. These will now be discussed in order, and in each case both the narrow-band corrections, for analyzed data, and the wide-band correction, for overall data, will be considered.

Microphone Calibration

The microphone calibration is given in Figure 21. Corrections for the analyzed readings were determined from the differences between the microphone calibration values at the various frequencies and the value at 1 kc. The corrections are these differences, with proper attention to sign. They are given in column 1 of Table II.

With regard to the wide-band correction, the microphone calibration is flat in the low-frequency region where most of the jet noise energy lies, and the average response between 100 cps and 1 kc was used in calculating the correction shown at the bottom of column 1, Table II.

TABLE II
CORRECTIONS FOR TAPE READING

Frequency cps	Microphone Corrections, db	Short Cable Gain Corrections, db	Long Cable Gain Corrections, db	Noise Corrections, db	Combined Short Cable Corrections, db	Combined Long Cable Corrections, db
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
100	-0.6	+0.4	-0.1	+2.4	+2.2 = +22	+1.7 = +22
200	-1.4	+0.4	-0.2	+2.5	+1.5 = +22	+0.9 = +11
300	-1.5	+0.4	+0.4	+1.6	+0.5 = +11	+0.5 = +11
500	-1.1	+1.0	0	+0.4	+0.3 = 00	-0.7 = -11
800	-0.8	+0.5	0	+1.6	+1.3 = +11	+0.8 = +11
1000	0	0	0	+1.2	+1.2 = +11	+1.2 = +11
1500	+0.5	-0.2	0	+1.4	+1.7 = +22	+1.9 = +22
2000	+4.0	-0.4	0	+0.7	+4.3 = +44	+4.7 = +55
3000	+0.3	-1.4	-0.4	+0.4	-0.7 = -11	+0.3 = 00
4000	-4.5	-1.7	-1.0	+1.1	-5.1 = -55	-4.4 = -44
5000	-4.3	-2.1	-1.4	+1.1	-5.3 = -55	-4.6 = -55
6000	-2.4	-2.4	-1.7	-0.1	-4.9 = -55	-4.2 = -44
7000	-6.6	-1.9	-1.7	-0.8	-9.3 = -99	-9.1 = -99
8000	-1.6	-1.1	-1.0	-0.1	-2.8 = -33	-2.7 = -33
9000	+0.2	-0.6	-0.2	-0.2	-0.6 = -11	-0.2 = 00
10000	-1.1	+1.2	+0.4	-0.4	-0.3 = 00	-1.1 = -11
OVERALL	-0.9	0	0	+0.8	-0.1 = 00	-0.1 = 00

Combined Relative Analyzer and Recorder Response

The combined relative response-frequency characteristic of the amplifying, analyzing, and recording system was measured by inserting into it, at each frequency, the same known voltage, and noting the results on the recorder tape. The set-up is shown in Figure 22. The frequencies were limited to those for which the microphone calibration was known. For the narrow-band corrections, the analyzer was tuned to the signal frequency, while the wide-band response-frequency characteristic was determined with the Erpi in the "overall" position. This latter response, for both cabling conditions, is sufficiently flat at the low end so that the average of the responses between 100 cps and 1 kc is no different from the 1 kc value, which results in a zero correction. The analyzed-data corrections are listed in column 2 of Table II for the "short cable" condition, and in column 3 of the same table for the "long cable" condition.

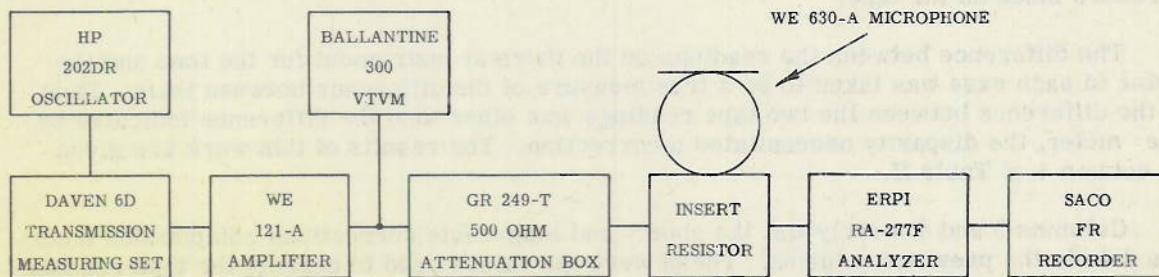


Fig. 22 - Arrangement of Apparatus for Measuring Relative Response-Frequency Characteristic of Analyzing and Recording System

Relative Response of Recorder to Noise and Single Frequencies

The response of the recorder to noise impulses is different from its response to a single tone, both in the wide- and narrow-band cases. It is necessary to measure the difference between these two responses, since, after all, while it is noise that is measured in the field, the system itself is calibrated with single tones. The measurement of this difference requires an instrument that indicates true rms values, regardless of the wave form. An instrument actuated by a thermocouple satisfies this requirement, and a thermomilliammeter was used as shown in Figure 23. The GR 714-A amplifier had an input impedance sufficiently high to allow its use as a bridging amplifier across the recorder and a gain great enough to give a reading on the meter in series with the 100,000-ohm resistor loading its output.

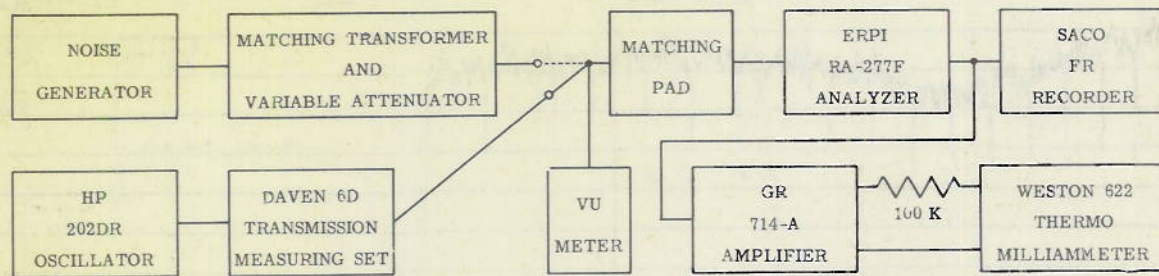


Fig. 23 - Arrangement of Apparatus for Comparing Noise and Single-Frequency Response of Recorder

APPENDIX III ⁴

CALCULATION OF OCTAVE-BAND LEVELS

There has been a general tendency in this country, particularly in the field of underwater sound, to report the results of noise analyses in terms of "spectrum level". The spectrum level is the pressure level, L_f , at frequency, f , given by

$$L_f = 20 \log \left[\frac{p_f}{p_0} \right] \quad (1)$$

where p_0 is the reference pressure and p_f is the rms pressure in a 1-cycle band centered on f . In consequence of the definition of p_f the following relation holds

$$I_f = \frac{p_f^2}{\rho c} \quad (2)$$

where I_f is the intensity in the single-cycle band. Furthermore, L_f is seen to be the pressure level per unit bandwidth. It is a quantity which cannot, for practical reasons, be measured directly. It must be computed from data taken with a measuring system having an effective bandwidth sufficiently narrow so that, over this bandwidth, the pressure is essentially uniformly distributed in frequency. If W be this effective bandwidth, then the intensity in a 1-cycle band is $1/W$ of the total intensity, and the spectrum level is

$$L_f = L_m - 10 \log W \quad (3)$$

where L_m is the measured pressure level.

The concept of spectrum level is useful in converting from constant-bandwidth sound-pressure levels to octave sound-pressure levels. In the present instance, since $\gamma = 50$ cps, the spectrum levels may be obtained by dropping the curves shown in Figures 9 - 14 inclusive, by 17 db. Each of the resulting curves can be approximated by a series of short, straight lines, connected together as shown in Figure 25. Naturally, the degree of approximation is determined by the length of the lines. For the present purpose, it will be sufficiently accurate for each line to cover a complete octave in the series beginning at 150 cps.

Each of these lines, then, is a short segment of an infinitely long line given, in general, by

$$A 20 \log \left[\frac{p_f}{p_0} \right] = m B \log \left[\frac{f}{f_0} \right] + C \quad (4)$$

A and B are scale factors relating decibels and the logarithm of the frequency ratio to the unit of measurement used in the particular graph where the slope, m , is measured. p_0 and f_0 are, of course, the reference pressure and frequency, respectively, while C is a constant necessary only to the equation in this form. It will be eliminated immediately.

⁴ The material in this appendix is adapted from a Bureau of Ordnance report, A.A.R. No. 24, by Sidney K. Shear, entitled, "Relationships between Spectrum Level and Octave Level".

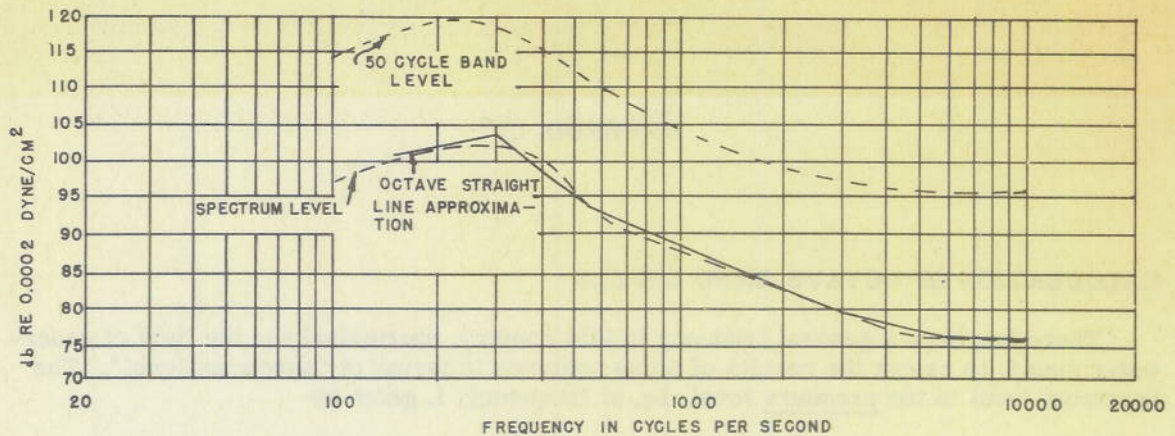


Fig. 25 - Sample Straight-Line Approximation of Spectrum Level, 150 cps to 9600 cps

At any particular frequency, f_1 , (4) becomes

$$A 20 \log \left[\frac{p_1}{p_0} \right] = m B \log \left[\frac{f_1}{f_0} \right] + C \quad (5)$$

and by subtracting (5) from (4),

$$A 20 \log \left[\frac{p_f}{p_1} \right] = m B \log \left[\frac{f}{f_1} \right] \quad (6)$$

whence

$$p_f = p_1 \left[\frac{f}{f_1} \right]^{mB/20A} \quad (7)$$

The cumbersome slope-and-scale-factor exponent may be eliminated by substituting n , the number of decibels decrease per octave, which causes (7) to become

$$p_f = p_1 \left[\frac{f}{f_1} \right]^{-n/6} = \frac{p_1 f_1^{n/6}}{f^{n/6}} \quad (8)$$

This, it will be noted, is a continuous function which must yield the proper values of p_f at integral values of f . In other words, a continuous function has been substituted for the function which assigns a specific rms pressure to each integral value of f and no other.

Next, consider the following relation

$$I_{\text{oct}} = \frac{p_{\text{oct}}^2}{\rho c} \quad (9)$$

where I_{oct} is the intensity in the octave from f_1 to $2f_1$ and p_{oct} is defined as follows,

$$\begin{aligned} p_{\text{oct}} &= \sqrt{\rho c I_{\text{oct}}} = \sqrt{\rho c} \cdot \sqrt{I_{f_1+1} + I_{f_1+2} + I_{f_1+3} + \dots + I_{2f_1}} \\ &= \sqrt{\rho c} \cdot \sqrt{\frac{p_{f_1+1}^2}{\rho c} + \frac{p_{f_1+2}^2}{\rho c} + \frac{p_{f_1+3}^2}{\rho c} + \dots + \frac{p_{2f_1}^2}{\rho c}} \\ &= \sqrt{p_{f_1+1}^2 + p_{f_1+2}^2 + p_{f_1+3}^2 + \dots + p_{2f_1}^2} \end{aligned} \quad (10)$$

Thus p_{oct} is seen to be the square root of the sum of the squares of the single-cycle-band rms pressures.

Since I_f is, by definition, the intensity per unit bandwidth, the intensity in a band df wide is $I_f df$, and the intensity in an octave is

$$I_{\text{oct}} = \int_{f_1}^{2f_1} I_f df = \int_{f_1}^{2f_1} \frac{p_f^2}{\rho c} \cdot df = \frac{p_1^2 f_1^{n/3}}{\rho c} \int_{f_1}^{2f_1} \frac{df}{f^{n/3}} \quad (11)$$

When $n \neq 3$

$$I_{\text{oct}} = \frac{p_1^2 f_1}{\rho c} \left[\frac{2^{1-n/3} - 1}{1 - n/3} \right] \quad (12)$$

When $n = 3$

$$I_{\text{oct}} = \frac{p_1^2 f_1}{\rho c} (0.693) \quad (13)$$

which can be shown to equal

$$\frac{p_1^2 f_1}{\rho c} = \lim_{n \rightarrow 3} \left[\frac{2^{1-n/3} - 1}{1 - n/3} \right] \quad (14)$$

(12) may thus be considered as the general solution, and, by (9), it becomes

$$\frac{p_{\text{oct}}^2}{\rho c} = \frac{p_1^2 f_1}{\rho c} \left[\frac{2^{1-n/3} - 1}{1 - n/3} \right] \quad (15)$$

Eliminating ρc and dividing each side by the square of the reference pressure, p_o^2 , yields

$$\frac{p_{\text{oct}}^2}{p_o^2} = \frac{p_1^2 f_1}{p_o^2} \left[\frac{2^{1-n/3} - 1}{1 - n/3} \right] \quad (16)$$

Whence, by taking 10 times the logarithm of each side

$$20 \log \left[\frac{p_{\text{oct}}}{p_o} \right] = 20 \log \left[\frac{p_1}{p_o} \right] + 10 \log f_1 + 10 \log \left[\frac{2^{1-n/3} - 1}{1 - n/3} \right] \quad (17)$$

The left hand side is the octave pressure level in the octave from f_1 to $2f_1$, while the right hand side is the sum of the spectrum level at f_1 , 10 times the logarithm of f_1 , and 10 times the logarithm of

$$\frac{2^{1-n/3} - 1}{1 - n/3}$$

where n is the number of decibels decrease per octave. n may, of course, be negative.

Using the straight line approximations of the spectrum level curves, L_{f_1} and n were determined to the nearest db in each case. Substitution in (17) yielded the octave levels given in Plate 17.

Lastly, given a number of octave pressure levels, they may be treated as intensity levels and added together to give the overall intensity, I_{oa} . Thus

$$I_{oa} = I_1 + I_2 + I_3 + \dots \quad (18)$$

If I_0 be the reference intensity, then

$$\frac{I_{oa}}{I_0} = \frac{I_1}{I_0} + \frac{I_2}{I_0} + \frac{I_3}{I_0} + \dots \quad (19)$$

Now, quite generally,

$$10 \log \frac{I}{I_0} = 20 \log \frac{p}{p_0} = L \quad (20)$$

whence

$$\frac{I}{I_0} = 10^{L/10} \quad (21)$$

Specifically, substitution of (21) in (19) yields

$$10^{L_{oa}/10} = 10^{L_1/10} + 10^{L_2/10} + 10^{L_3/10} + \dots \quad (22)$$

And

$$L_{oa} = 10 \log \left[10^{L_1/10} + 10^{L_2/10} + 10^{L_3/10} + \dots \right] \quad (23)$$

The overall levels were computed from (23), and, in each case, these were within 2 db of the level actually measured in the field.

* * *

TABLE I
MEASURING CONDITIONS

Relative Microphone Angle, ° Bearing	Microphone Distance, Feet	True Plane Heading, ° Bearing	Wind		Microphone Height or Position, Inches	I-40 Engine	Date
			True Heading, ° Bearing	Velocity, Knots			
0	27	190	220 ±10	0- 3	58	Original Repaired	11 July
22½	15	190	0	0	"	Original Repaired	11 July
67½	25	120	lo.* 140 ±10 hi. 125 ±10	9-11 10-13	"	Original Repaired	10 July
112½	50	120	lo. 120 ±10 hi. 130 ±10	8 8-10	"	Original Repaired	10 July
157½	100	180	lo. 180 ±10 >6 kc. 130 ±10	3- 5 8-10	"	Original Repaired	10 July
180	150	235	235 ± 5	8-10	"	New	31 July
202½	100	315	0 ±10	5- 8	"	Original	19 June
247½	75	315	160 ±50	3- 7	"	Original	17 June
247½	50	315	0 ±10	5- 8	"	Original	19 June
292½	25	190	220 ±10	0- 3	"	Original Repaired	11 July
337½	15	190	220 ±10	0- 3	"	Original Repaired	11 July
Cockpit		298	lo. 300 ± 5 hi. 315 ± 5	5- 7 8-10	†	New	31 July

lo. and hi. refer to low and high frequency ranges on analyzer.

9" in front of armor plate, 2" to right of center line, 3" above level defined by sides of cockpit.

TABLE II
CORRECTIONS FOR TAPE READING

Frequency cps	Microphone Corrections, db	Short Cable Gain Corrections, db	Long Cable Gain Corrections, db	Noise Corrections, db	Combined Short Cable Corrections, db	Combined Long Cable Corrections, db
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
100	-0.6	+0.4	-0.1	+2.4	+2.2 = +22	+1.7 = +22
200	-1.4	+0.4	-0.2	+2.5	+1.5 = +22	+0.9 = +11
300	-1.5	+0.4	+0.4	+1.6	+0.5 = +11	+0.5 = +11
500	-1.1	+1.0	0	+0.4	+0.3 = 00	-0.7 = -11
800	-0.8	+0.5	0	+1.6	+1.3 = +11	+0.8 = +11
1000	0	0	0	+1.2	+1.2 = +11	+1.2 = +11
1500	+0.5	-0.2	0	+1.4	+1.7 = +22	+1.9 = +22
2000	+4.0	-0.4	0	+0.7	+4.3 = +44	+4.7 = +55
3000	+0.3	-1.4	-0.4	+0.4	-0.7 = -11	+0.3 = 00
4000	-4.5	-1.7	-1.0	+1.1	-5.1 = -55	-4.4 = -44
5000	-4.3	-2.1	-1.4	+1.1	-5.3 = -55	-4.6 = -55
6000	-2.4	-2.4	-1.7	-0.1	-4.9 = -55	-4.2 = -4
7000	-6.6	-1.9	-1.7	-0.8	-9.3 = -9	-9.1 = -9
8000	-1.6	-1.1	-1.0	-0.1	-2.8 = -3	-2.7 = -3
9000	+0.2	-0.6	-0.2	-0.2	-0.6 = -1	-0.2 = 0
10000	-1.1	+1.2	+0.4	-0.4	-0.3 = 0	-1.1 = -1
OVERALL	-0.9	0	0	+0.8	-0.1 = 0	-0.1 = 0