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JET ENGINE SOUND SPECTRA

UNITED STATES AIR FORCE
AIR MATERIEL COMMAND
Wright-Patterson Air Force Base
Dayton, Ohio

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JET ENGINE SOUND SPECTRA

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ABSTRACT

Sound fields produced by the J-33, J-34 and J-35 turbo-jet engines in test cells have been measured and analyzed into their component frequencies. Crystal microphones calibrated up to 100,000 cps have been used to measure both audible and ultrasonic frequency components. Analysis of the sound frequencies has been accomplished by using the microphones in various combinations with a Hewlett Packard harmonic wave analyzer, and a special Aero Medical Laboratory panoramic sound frequency analyzer. Overall sound pressures of 127 to 147 decibels above 0.0002 dynes per square centimeter have been recorded from these engines under various test conditions. Such high sound pressures were confined to the audible frequency range. In contrast to the sound spectrum produced by conventional aircraft engines, these high sound pressures were found at frequencies as high as 10,000 cps. Above 20,000 cps sound pressures were less than 120 decibels above 0.0002 dynes per square centimeter.

PUBLICATION APPROVAL

For the Commanding General:

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FOREWORD

This report was prepared as part of the work being accomplished at the Aero Medical Laboratory, Engineering Division, Air Materiel Command, under the research and development project identified by Expenditure Order No. 695-63. Study of the sound produced by the J-34 turbo-jet engine in the test cell at the Civil Aeronautics Technical Development Laboratories, Indianapolis, Indiana were conducted jointly with the Civil Aeronautics Administration. Arrangements for study of the J-35 turbo-jet engine in the sound treated test cells at Plant 5, Allison Division of General Motors Corporation, Indianapolis, Indiana, were made by the Civil Aeronautics Administration. Permission to use some of the data obtained in this joint study was granted by Dr. Barry G. King, Chief, Aeromedical Design and Materiel Division, Medical Service, Civil Aeronautics Administration.

INTRODUCTION

Even casual observation apprises one that intense sound fields and mechanical vibrations of appreciable amplitude are generated in the operation of aircraft and aircraft components both in the air and on the ground. Do these sounds and vibrations constitute a hazard to United States Air Force personnel? To answer this question it is necessary to know the nature of the sounds and vibrations to which personnel may be exposed. The sound field around a jet engine is of particular interest because of its high intensity and because of the increasing number of men who are exposed to these sound fields.

A complex sound field generated by a jet engine consists of a very large number of component frequencies, at various pressure levels. Such a complex sound may be described in physical terms. The dimensions are the frequency and the intensity of each frequency component in the medium through which the sound is propagated. Should there in general be any hazard to personnel in or from a complex sound field, it will be obvious that it is impossible to know whether to ascribe this hazard to the complex sound field as a whole, or to one or more of its components.

An answer to this question may be obtained by exposing men to single frequency components or to a small group of frequency components under controlled conditions and known sound intensities. If any ill effects exhibited by man in the complex sound field are observed to exist only in the presence of certain frequency components or only at certain intensities of the various components and do not occur otherwise, it can be concluded that only these components are responsible for the hazard of the total complex sound field. It would be possible to study the effects on man of an essentially unlimited number of sound frequencies, each over a wide range of sound intensities. Then these same sound components should also be studied when combined in an infinite number of smaller and larger groups. Practically, it is better to limit such studies to the frequency and intensity ranges actually encountered by Air Force personnel. The purpose of the work described in this report is to establish such limits by analyzing existing complex sound fields into their various components.

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There has been much speculation concerning the nature of sound fields generated by jet engines. This speculation has been mainly concerned with the presence of sound frequencies above man's audible frequency range (15-15,000 cycles per second) and with the ill effects such frequencies might have on man. This speculation is the direct result of the almost complete lack of information concerning the ultrasonic frequencies that are present. The present study was initiated to determine as completely as possible the presence and intensity of all the frequencies in the complex sound field around jet engines. This information is necessary in planning a program which will study the effect on man of sound, both in the audible and the ultrasonic frequency ranges.

SECTION I

INSTRUMENTATION

Four microphones and three sound frequency analyzers in four combinations have been used in this study.

The first combination used was a sound pressure system including the Massa model M-101 microphone, model M-103 preamplifier and model M-104 amplifier(1). The electrical output of this system was led to a Hewlett Packard Model 300 A Harmonic Wave Analyzer. The frequency response of the amplifier system is flat within ±0.5 db from 20 to 20,000 cycles per second. The free field sensitivity of the microphone(2) (normal incidence) is 92 db below one volt per dyne per square centimeter up to 5500 cps. At about 6000 cps the sensitivity suddenly rises to 85 db below one volt per dyne per square centimeter and then falls at about 7000 cps to 100 db below one volt per dyne per square centimeter. From about 7500 cps to 20,000 cps the sensitivity slowly increases with frequency from 92 to 83 db below one volt per dyne per square centimeter. Except for the frequency range 5500 to 7500 cps where the error may be ±7.5 db, the system can be accurately calibrated to within ±2 db.

The technique used in measuring the sound field with these instruments was to take readings on the vacuum tube voltmeter of the harmonic wave analyzer which was tuned to a thirty (30) cycle per second half band width. R.M.S. voltages were recorded as a function of frequency from 10 to 16,000 cps at frequencies which showed the highest voltages, the lowest voltages, and "plateaus" of constant voltage over a wide frequency range. The data thus obtained was plotted by connecting the measured peaks, dips and "plateaus".

The second sound pressure system included the Massa Model M-106 microphone, Model M-107 preamplifier and Model M-108 amplifier. The electrical output of this system was led to the Aero Medical Laboratory panoramic sound frequency analyzer(3). The frequency response of the amplifier system is flat within ±0.5 db from 2000 to 60,000 cps. At 1000 cps the frequency response is down 2.5 db. Below 1000 cps the frequency response drops rapidly until it is down 15 db at 200 cps. The free field sensitivity of the microphone(2) (normal incidence) is 92 db below one volt per dyne per square centimeter from 1000 to 5000 cps and increases gradually to 80 db below one volt per dyne per square centimeter at 35,000 cps. Above 35,000 cps the microphone sensitivity is so erratic that the microphone cannot be used with any certainty. Below 1000 cps the amplifier system is the limiting factor and was so designed to minimize any pick-up from mechanical vibrations.

The Aero Medical Laboratory panoramic sound frequency analyzer is an adaptation to sound frequencies of the panoramic analyzer used for radio frequencies during World War II. The analyzer will display on a cathode ray tube the voltage output of a microphone system as a function of frequency. The basic filter pass band width is 400 cycles per second and is constant at all points in the frequency spectrum. The frequency range displayed for analysis on the cathode ray tube may be varied between 5000 cps and 200,000 cps. Furthermore, the initial point of the frequency range to be analyzed may be adjusted to start at any frequency from 800 to 200,000 cps. Frequency discrimination has been found to be accurate within ±1% of the frequency range displayed on the cathode ray tube for ranges from 10,000 to 100,000 cps. Voltage readings have been found to be accurate within ±1 decibel.

Since one analysis per second is presented graphically on the cathode ray tube of the analyzer, it is possible to locate visually such points as one desires to measure and to adjust the frequency and voltage output of a calibrating oscillator (Hewlett Packard Model 200 C) until the location and height of its deflection matches the deflection produced by the sound field. A vacuum tube voltmeter (Hewlett Packard Model 400 A) across the oscillator input at the analyzer was used to measure the R.M.S. voltage required to produce the calibrating deflection. This voltage together with the frequency indicated on the oscillator dial were used to describe the unknown deflection. Since the sound spectra were found to consist of high levels at a few frequencies, low levels at a few frequencies and fairly constant levels over wide bands of frequencies, the points chosen for measurement by the above method were the peaks of the high levels, the dips of the low levels, and the ends of the constant level ranges. The data thus obtained was plotted by connecting the measured points with straight lines.

The third sound pressure system included a Massa model M-113 microphone(4), model M-114, preamplifier, model M-116 power supply and a Hewlett Packard model 450 A amplifier. The electrical output of the system was led to the Aero Medical Laboratory panoramic sound frequency analyzer. The frequency response of the amplifier system was flat within ±0.5 db from 400 to 65,000 cps. The free field sensitivity of the microphone(2) (normal incidence) is 100 db below one volt per dyne per square centimeter up 15,000 cps. From 15,000 to 45,000 the sensitivity increases to 91 db below one volt per dyne per square centimeter. Between 45,000 cps and 65,000 cps the sensitivity varies erratically between 91 and 105 db below one volt per dyne per square centimeter. From 65,000 cps to 100,000 cps the sensitivity is constant at 95 ±2 db below one volt per dyne per square centimeter.

The technique used with this system differed in that photographs of the analyzer cathode ray tube screen were taken with a sweep synchronized recording camera (type O-5). Photographs were taken in sequence for each analysis of (a) the deflections produced at 10,000 cps intervals on the cathode ray tube by the analyzer's internal calibrator, (b) the deflections produced by the microphone in the unknown sound field, and (c) a deflection produced by an external oscillator at a known frequency and known R.M.S. voltage. Because the sound fields varied so much with time, usually ten to twenty records of the microphone output were photographed. This sequence of photographs was taken for each and every change of gain setting or frequency range setting on the panoramic analyzer. The unknown sound field was analyzed in detail in the laboratory by comparison on a film reader to the deflections of the frequency and voltage calibrations. This procedure has the advantage of taking much less time in the field. Its disadvantage is that due to the slight non-linearity of the analyzer responses (3), the method is not quite so accurate as the point for point matching technique described above. However, the lability of the sound fields measured makes any errors introduced by this method negligible.

The fourth instrument combination included a Western Electric Type 630-A dynamic microphone, an Electrical Research Products, Inc., Type RA-277 sound frequency analyzer and a Type RA-246 graphic level recorder. This analyzer has a half-band width of five (5) cycles per second. Calibration of the microphone and analyzer by the National Bureau of Standards show the error to be less than plus or minus 2 db for frequencies less than 3,300 cps and a maximum of plus 4.6 db at 7,000 cps.

Analysis of the sound level data, as recorded on the instrument tape, was carried out through tabulation of the frequency and level in decibels represented by each peak appearing in the sound spectrum and then summing the energy of all peaks present in each arbitrarily selected frequency band. Band widths of 100 cps were chosen for the frequency range below 1000 cps and band widths of 500 cps were chosen for the frequency range 1000 cps to 10,000 cps. This instrument combination was supplied by the Civil Aeronautics Authority for a sound study conducted jointly with the Aero Medical Laboratory at the Civil Aeronautics Technical Development Laboratories, Indianapolis, Indiana.

SECTION II

SOUND FIELD PRODUCED BY THE J-33 TURBO-JET ENGINE

The J-33-9 turbo-jet engine as a sound source was studied with the engine mounted seven (7) feet above the ground on an outside test rig. This arrangement has the advantage of minimizing sound reflections and standing wave patterns near the engine. The first analyses of the sound spectrum were made using a Massa Model M-101 microphone and a Hewlett Packard harmonic wave analyzer. The microphone locations used were twenty-six (26) inches from the air intake and twenty-six (26) inches out from the end of the tail pipe on a line perpendicular to the long axis of the tail pipe.

The overall sound pressures recorded as a function of engine r.p.m. are shown for both locations in Table I. It can be seen that the overall sound pressure increases rapidly with increasing r.p.m. which also corresponds to increasing thrust produced by the engine.

The sound level as a function of frequency for an engine speed of 11,000 r.p.m. is shown in Figure 1. It should be noted that except for one peak at 5,700 cps this sound spectrum is quite flat up to 16,000 cps, which frequency represents the upper limit of the harmonic wave analyzer. The peak level at 5700 cps was found to decrease in both sound pressure and frequency with decreasing r.p.m. (see Table I). It is believed that this component is the result of the siren-like action of the engine compressor and turbine. At present no reasonable explanation has been found for the shift of the peak energy frequency to 5300 cps when the engine ran at 5000 r.p.m.

The results of a second analysis made on the same type engine and on the same outside test rig are shown in Figure 2. These measurements were made with the M-106 microphone and the Aero Medical Laboratory panoramic sound frequency analyzer. The microphone position was behind the end of the tail pipe twenty-six (26) inches out on a line making an angle of forty-five (45) degrees with the long axis of the tail pipe. The engine speed was 11,500 r.p.m. In addition to the previous general observations it should be noted that placing the microphone nearer the stream of exhaust gases increased the sound pressures at the lower

TABLE I

Peak Energy Frequencies and Overall Sound Pressures as a Function of Engine r.p.m. for the J-33-9 Turbo-jet Engine.

Engine R.P.M.	26 inches from Compressor		Overall sound level 26 inches from tail pipe
	Overall sound level	Peak energy frequency	
5000	125.8 db	5300 cps	128.3 db
6000			129.9
7000	134.8	3600	130.9
8000			133.1
9000	144.9	4800	135.3
10000			136.9
11000	146.6	5700	140.7

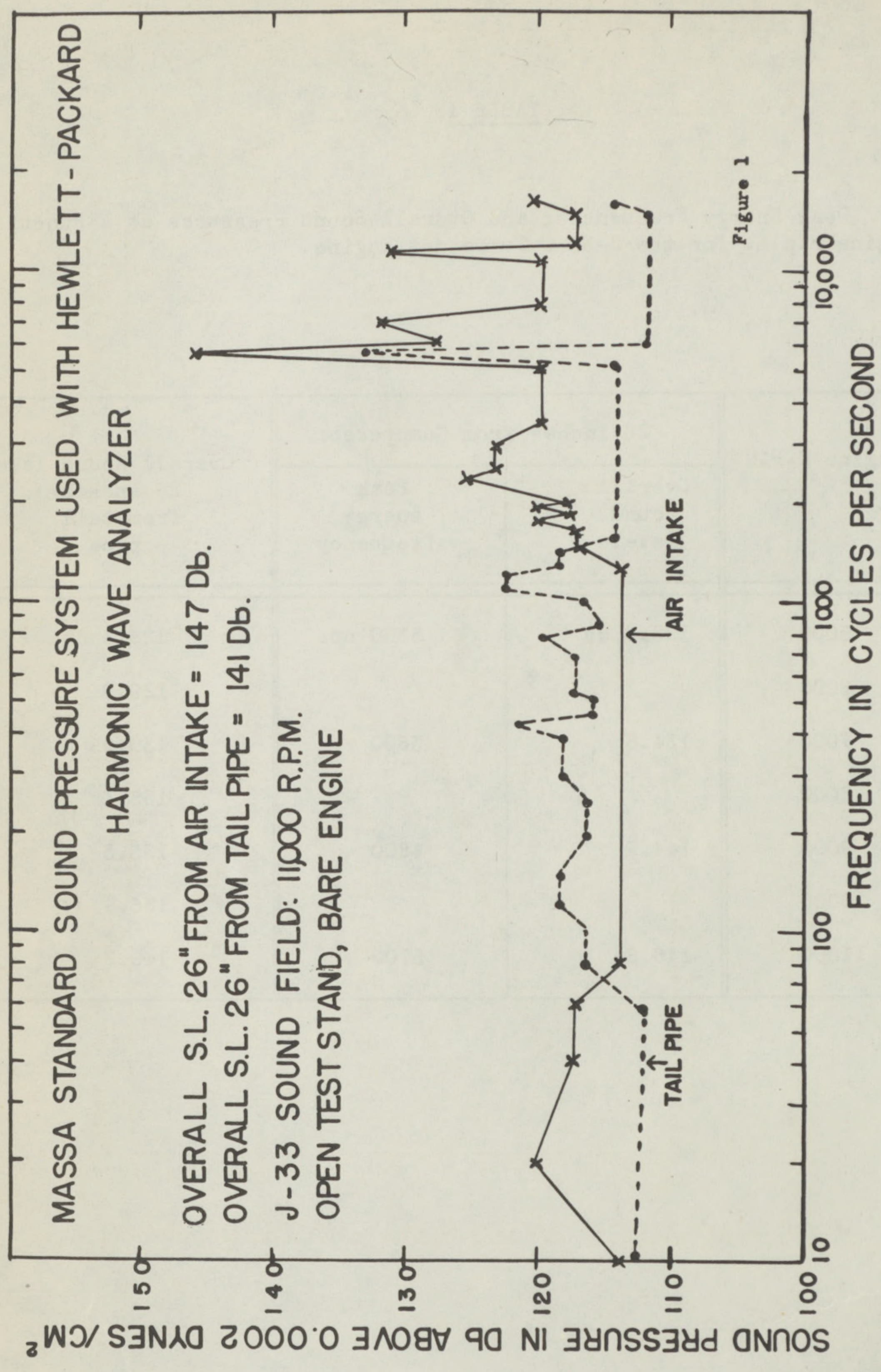
MASSA STANDARD SOUND PRESSURE SYSTEM USED WITH HEWLETT-PACKARD
HARMONIC WAVE ANALYZER
OVERALL S.L. 26" FROM AIR INTAKE = 147 Db.
OVERALL S.L. 26" FROM TAIL PIPE = 141 Db.
J-33 SOUND FIELD: 11,000 R.P.M.
OPEN TEST STAND, BARE ENGINE
AIR INTAKE
TAIL PIPE
SOUND PRESSURE IN Db ABOVE 0.0002 DYNES/CM²
100
110
120
130
140
150
10
100
1000
10,000
FREQUENCY IN CYCLES PER SECOND

Figure 1

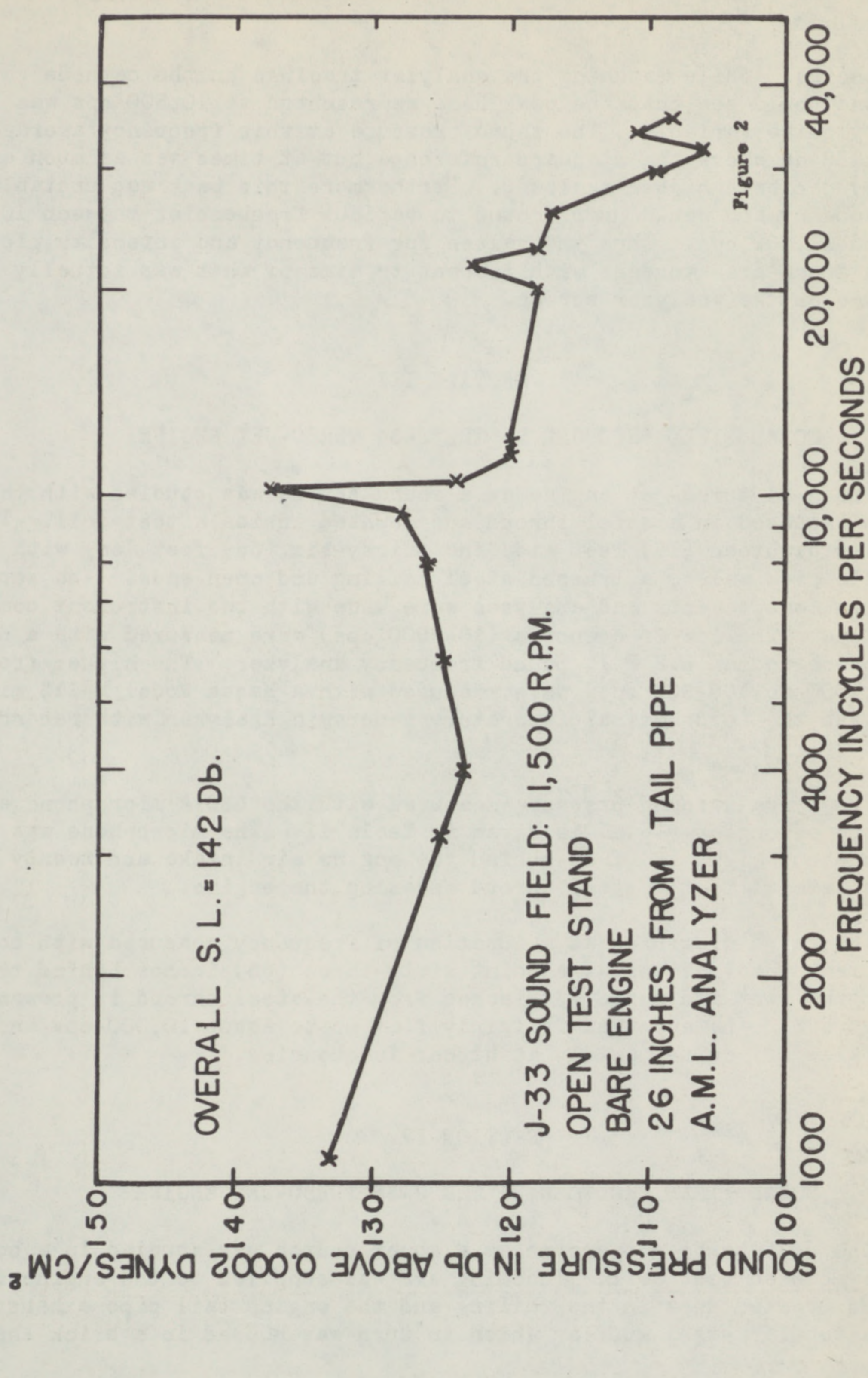
OVERALL S. L. = 142 Db.
J-33 SOUND FIELD: 11,500 R.P.M.
OPEN TEST STAND
BARE ENGINE
26 INCHES FROM TAIL PIPE
A.M.L. ANALYZER
SOUND PRESSURE IN DB ABOVE 0.0002 DYNES/CM²
150
140
130
120
110
100
FREQUENCY IN CYCLES PER SECONDS
1000
2000
4000
10,000
20,000
40,000

Figure 2

frequencies. While watching the analyzer tracings on the cathode ray tube one could see that the peak here represented at 10,500 cps was in reality quite variable. The sound pressure at this frequency averaged about 138 db above the standard reference but at times was as much as six (6) decibels higher or lower. Furthermore this peak was unstable as to frequency and would jump around to various frequencies between 10,000 cps and 11,000 cps. Thus the values for frequency and intensity plotted on the graph are averages with respect to time of what was actually observed on the analyzer screen.

SECTION III

SOUND FIELD PRODUCED BY THE J-34 TURBO-JET ENGINE

The J-34 turbo-jet engine as a sound source was studied with the engine enclosed in a steel shroud and mounted inside a test cell. This cell was eighteen (18) feet wide and thirty-six (36) feet long with concrete side walls, a trussed steel ceiling and open ends. The sound pressure measurements and analyses were made with two instrument combinations. The low frequencies (10-9500 cps) were measured with a 630A microphone and an E.R.P.I. Sound frequency analyzer. The higher frequencies (1000 to 100,000 cps) were measured with a Massa Model M-113 microphone and the Aero Medical Laboratory panoramic analyzer with recording camera.

The overall sound pressure measured with the 630 A microphone as a function of engine r.p.m. is given in Table II. The microphone was placed about eight (8) feet behind the engine air intake and twenty (20) inches lateral to the steel shroud encasing the engine.

The sound pressures as a function of frequency measured with both instrument combinations at a point sixty-three (63) inches behind the air intake vent and three (3) inches from the steel shroud is presented in Figure 3. The spectrum is fairly flat up to about 10,000 cps and then falls off quite rapidly at higher frequencies.

SECTION IV

SOUND FIELD PRODUCED BY THE J-35 TURBO-JET ENGINE

The J-35 turbo-jet engine as a sound source was studied in a completely closed test cell. Incoming air was supplied to the engine from a sound treated duct in the ceiling and the engine tail pipe exhausted into a tubular steel muffler which in turn was housed in a brick shed.

TABLE II

Overall Sound Pressures as a Function of
Engine r.p.m. for the J-34 Turbo-jet Engine

Engine r.p.m.	Overall Sound Pressure in db above 0.0002 dynes/cm^2
4300	109 db
5000	113
6000	116
7000	119
8000	121
9000	123.5
10000	125

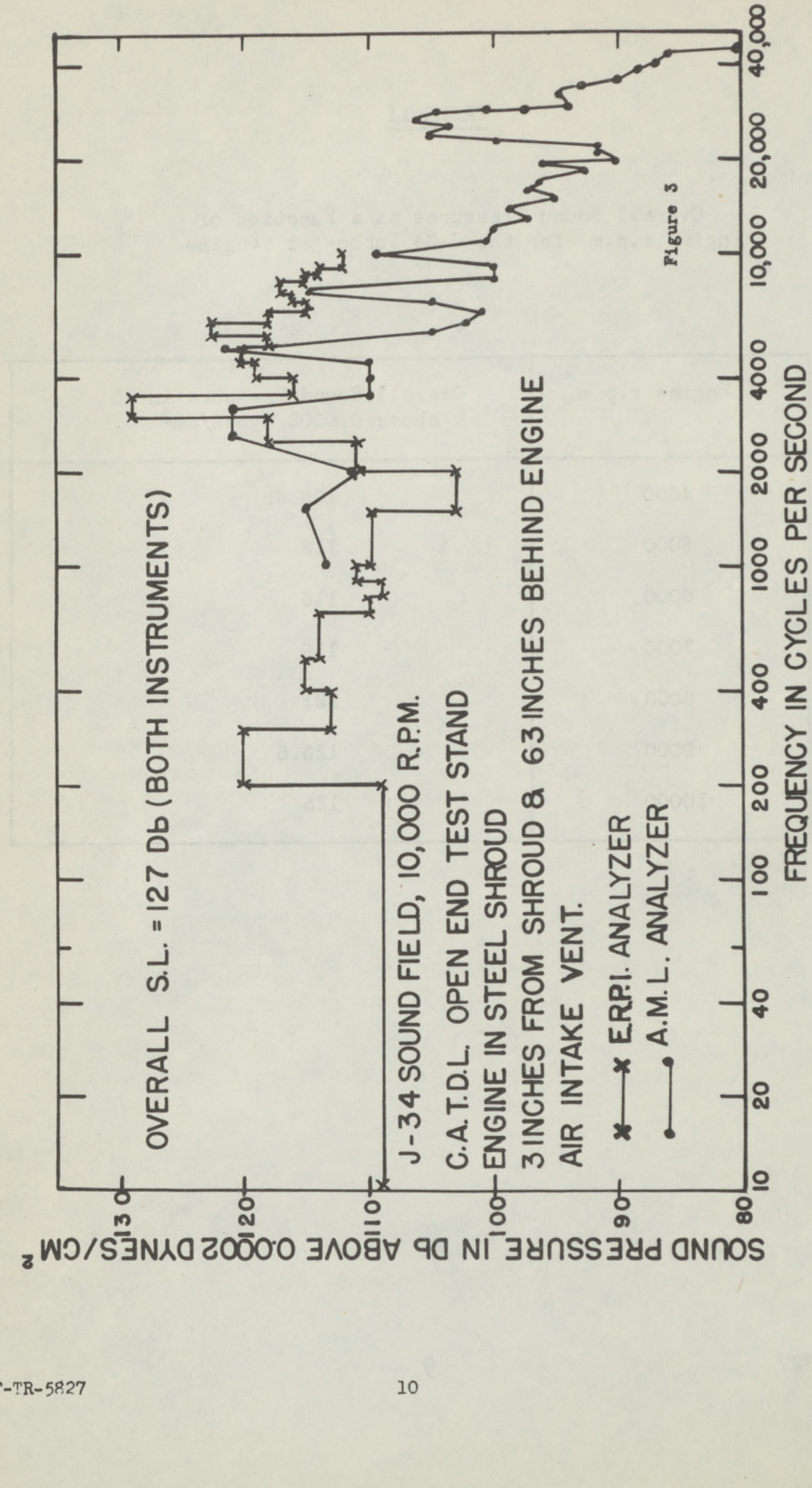
OVERALL S.L. = 127 Db (BOTH INSTRUMENTS)
J-34 SOUND FIELD, 10,000 R.P.M.
C.A.T.D.L. OPEN END TEST STAND
ENGINE IN STEEL SHROUD
3 INCHES FROM SHROUD & 63 INCHES BEHIND ENGINE
AIR INTAKE VENT.
E.R.P.I. ANALYZER
A.M.L. ANALYZER
80
90
100
110
120
130
SOUND PRESSURE IN Db ABOVE 0.0002 DYNES/CM²
10
20
40
100
200
400
1000
2000
4000
10,000
20,000
40,000
FREQUENCY IN CYCLES PER SECOND

Figure 3

The control room for the engine was separated from the cell proper by a seventeen (17) inch thick solid brick wall. That portion of the wall opposite the engine turbine consisted, instead of brick, of steel armor plate faced on a twenty-four (24) inch thick concrete wall. In addition there were two small multiple layer observation windows for each cell. The interior of the control room was sound treated on ceiling and walls.

The Massa Model M-113 microphone with the panoramic analyzer was used for the sound measurements within the test cell proper. The microphone was placed twenty (20) inches lateral to the engine air intake bell. The 630 A microphone and the E.R.P.I. analyzer were used to measure the sound level in the control room. The sound spectrum in one cell with an engine speed of 7665 r.p.m. is compared in Figure 4 with the sound spectrum in the control room with engines running at 7665 r.p.m. in each of the two adjacent cells. Sound pressure in db reference 0.0002 dynes per cm^2 is plotted as a function of frequency. From this it can be seen that the sound attenuation from cell to control room is of the order of forty (40) decibels both for the overall readings and for the various individual frequencies.

SECTION V

DISCUSSION

The nature of the sound pressure around jet engines as a function of engine r.p.m. has been shown in the preceding figures and tables. The results are not directly comparable because they represent three engine types in three very different test installations. However, certain basic similarities exist and several general observations can be made from this data.

If one first considers the various sound spectra, it can be seen that, except for one or two outstanding frequencies, the sound pressure distribution by frequency is roughly flat up to 5000 cps and sometimes flat up to 15,000 cps. Above these frequencies the sound pressure decreases rapidly so that sound pressures in excess of 120 decibels above the standard reference are rarely seen at frequencies above 20,000 cps and have never been recorded in these studies at frequencies above 30,000 cps.

Observation of the Aero Medical Laboratory panoramic analyzer screen shows another characteristic of all the sound fields that is difficult to depict graphically. The various components of the sound field have been found to be extremely labile with regard to both frequency and intensity. This can be seen most clearly when observing such a peak as that shown for a frequency of 10,500 cps in Figure 2. With the analyzer

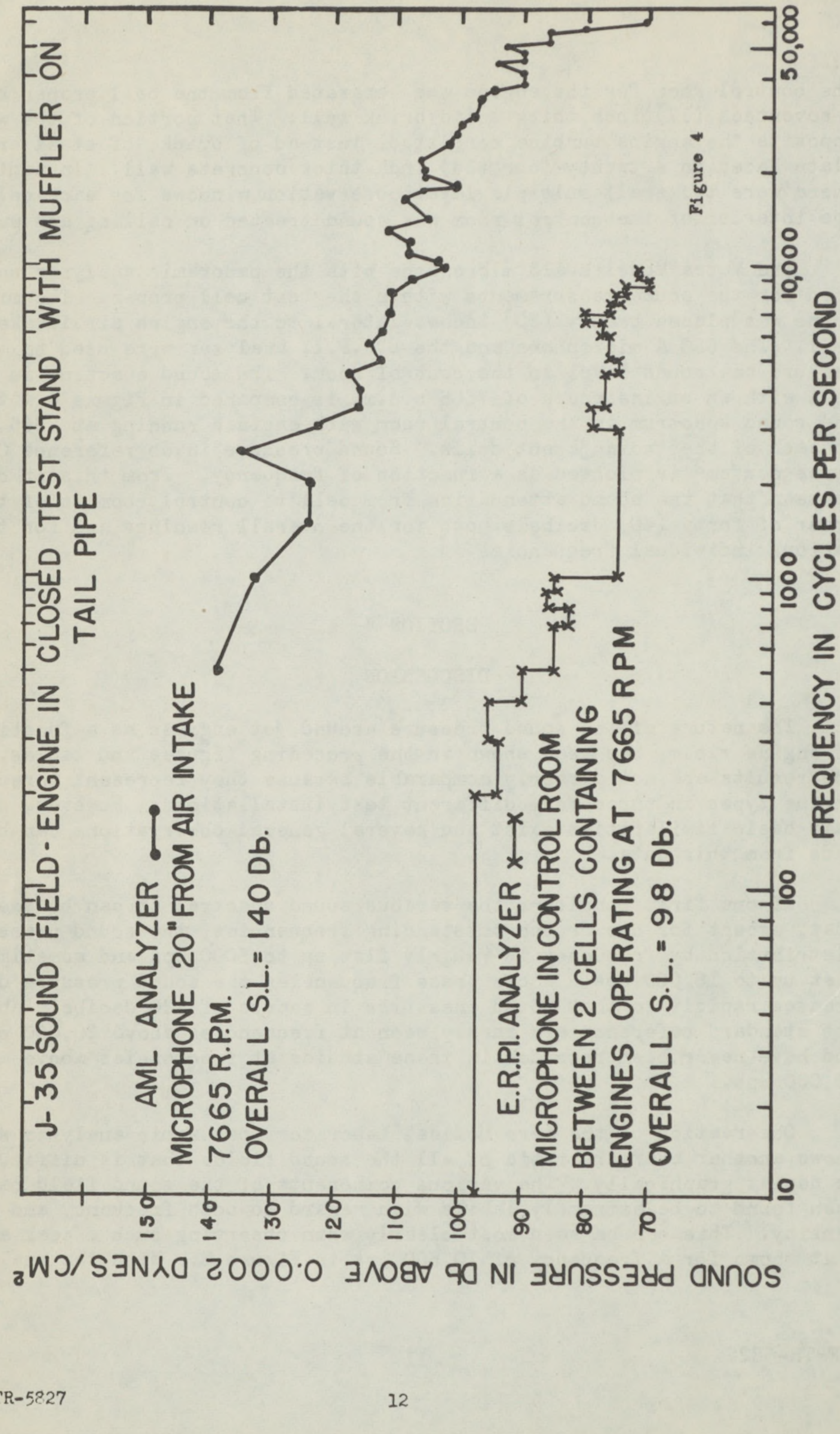
J-35 SOUND FIELD - ENGINE IN CLOSED TEST STAND WITH MUFFLER ON TAIL PIPE
AML ANALYZER
MICROPHONE 20" FROM AIR INTAKE
7665 R.P.M.
OVERALL S.L. = 140 Db.
E.R.P.I. ANALYZER
MICROPHONE IN CONTROL ROOM
BETWEEN 2 CELLS CONTAINING
ENGINES OPERATING AT 7665 R P M
OVERALL S.L. = 98 Db.
SOUND PRESSURE IN Db ABOVE 0.0002 DYNES/CM²
FREQUENCY IN CYCLES PER SECOND
150
140
130
120
110
100
90
80
70
10
100
1000
10,000
50,000

Figure 4

set to sweep through a frequency band once every second, this peak deflection would appear anywhere from 10,000 to 11,000 cps during the course of several sweeps and the amplitude of the deflection would vary through a range of plus or minus six (6) decibels. In all such cases we have recorded the median frequency and median voltage for the points plotted in the figures.

Some further general information about these sound fields may be had by considering the various components of jet engines that may act as sound sources. One source of sound energy is the rush of gases into or out of a tube; that is into the air intake duct or out of the tail pipe. Such nozzles or jets produce a broad frequency spectrum or "white" noise. For the jet engine this "white" noise is most intense on a line about forty-five degrees to the longitudinal axis in back of the tail pipe or in front of the air intake if this is a tube. Further, the intensity of this "white" noise increases with the thrust produced by the engine. This can be seen by comparing the noise produced by any engine operating at its various power settings (see Tables I and II) or by comparing the sound produced by engines of different maximum thrust capacities at their respective maximum power settings.

A second sound source is the compressor assembly. This acts like a siren and produces high sound pressures at a few frequencies. Figures 1 and 2 show such peaks and Table I demonstrates the variation of such a peak with engine r.p.m. In any turbo-jet engine sound field both the white noise and the compressor siren-like noise will exist. Depending on the type engine and the observer's position, either may be the principal sound component. It seems worthwhile to point out that of the three engines described in this report, the J-33 is the only one with a radial flow compressor. For this engine the compressor seems to be the major contributor to the overall sound pressure. The J-34 and J-35 engines have axial flow compressors. These compressors are more deeply hidden in the engine and the addition of a tubular air intake provides a source of white noise for the front end of the engine. This may explain why these axial flow engines do not show such discrete high level peak frequency components.

A third characteristic of turbo-jet engines further explains the nature of the observed sound fields. Fuel burning rates in these engines are not uniform but tend to peak in a completely random manner at frequencies somewhere between 60 and 300 times a second. This irregular burning probably accounts for the fluctuations in frequency and intensity of the high level frequency components produced by the compressor and for the low frequency components produced at the tailpipe. With unusually uneven burning or "rough runs" an engine will produce a rapid series of explosions resulting in a similar series of shock waves and low frequency sound.

CONCLUSIONS

It is apparent from all the measurements that have been made that most of the sound produced by a turbo-jet engine is in the audible frequency range. Unlike sound fields produced by reciprocating engines with conventional propellors, this sound field contains high level sound components at all frequencies up to at least 5000 cps and is on the whole a "white" noise. It is none the less true that sound frequencies as high as 60,000 cps may be present at measurable sound pressures. However, these components have been invariably of low intensity and constituted only minor portions of the sound fields.

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