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EFFECT OF DISTANCE ON AIRPLANE NOISE

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SUMMARY

A review of the literature has been made to determine the frequency of sound of a given source strength that is loudest at various distances from the source. If the greater absorption of sound at the high frequencies and the insensitivity of the human ear to the low frequencies are considered, the sounds in a frequency range between 500 and 1000 cycles are found to be loudest at distances greater than 1 mile from the source. At shorter distances the higher frequencies will be loudest.

Sound data obtained with a light trainer airplane flying at various altitudes up to 5000 feet show good agreement with the inverse square law which assumes that there is no atmospheric absorption and that the sound energy from the airplane is a constant. The increase of sound output of the propeller with altitude may balance the atmospheric absorption under certain conditions.

INTRODUCTION

The higher frequencies of sound are generally known to be attenuated by the atmosphere more than the lower frequencies. The question has therefore been raised as to the desirability of designing airplanes so that the noises will occur in the higher frequency ranges in order to take advantage of the greater atmospheric absorption at high frequencies. To obtain an answer to this question requires a quantitative determination of the atmospheric absorption of sound at various frequencies. The characteristics of the human ear, particularly the low-frequency cut-off, must also be taken into consideration.

Fairly accurate determinations of the absorption of sound in air have been made in the frequency range from 3000 to 1,000,000 cycles per second. (See, for example, references 1 and 2.) No reliable data exist for lower frequencies, chiefly because the absorption in the air becomes fairly small compared with the absorption of the boundaries of the test chamber. The question of the absorption in the atmosphere of the earth introduces even more variables, such as wind and temperature gradients, turbulence, and so forth. These variables make it impossible to predict accurately the sound due to a known source at distances greater than a few thousand feet. The literature gives many instances in which extremely loud sounds have been inaudible at a distance of several miles but audible at a distance of over 100 miles. (See, for example, reference 1, p. 169.)

The magnitude of some of the factors affecting the sound intensity are indicated in the present paper. A review of the literature on this subject is given as well as the results of a few tests made to obtain data on the noise from an airplane and sound from loud speakers. The results are presented in engineering units which should facilitate their use by persons not acquainted with acoustics.

BASIC CONCEPTS AND EQUATIONS

The fundamental equation used in the present discussion is based on a spherical free wave from a point source. The sound rays are assumed to be straight lines and the loss in total sound energy as a function of distance is expressed in terms of a coefficient m. Thus

$$\frac{d}{ds}(4\pi E s^2) = -4\pi m E s^2 \tag{1}$$

where E is the sound energy per unit area normal to the sound rays, m is the fraction of sound energy lost per unit distance, and s is the distance from the source.

Equation (1) reduces to

$$\frac{dE}{E} = -2\frac{ds}{s} - m\,ds$$

Integrating and putting in the limits give

$$\log_e \frac{E_2}{E_1} = -2 \log_e \frac{s_2}{s_1} - m(s_2 - s_1)$$

which may be written in the form

$$\frac{E_2}{E_1} = \left(\frac{s_1}{s_2}\right)^2 e^{-m(s_2 - s_1)} \tag{2}$$

The first factor on the right hand side of equation (2) gives the well-known inverse square law (reference 1); the second factor gives the attenuation.

The ratio of sound energy intensities E_2 and E_1 or sound pressures p_2 and p_1 is expressed in decibels as

$$I = 10 \log_{10} \frac{E_2}{E_1}$$

or

$$I = 20 \log_{10} \frac{p_2}{p_1} \tag{3}$$

where I is the difference in sound-intensity level expressed in decibels.

The difference in sound-intensity level is the same regardless of whether energy units or pressure units are used. The relation between energy and pressure p is given by $E = \frac{p^2}{\rho c}$, where ρ is the density and c is the velocity of sound. Substituting the right-hand side of equation (2) in equation (3) gives

$$I = -20 \log_{10} \frac{s_2}{s_1} - 10 \log_{10} e^{m(s_2 - s_1)}$$

or

$$I = -20 \log_{10} \frac{s_2}{s_1} - 4.34\, m(s_2 - s_1) \text{ decibels} \tag{4}$$

Equation (4) shows that the losses due to the spreading of the wave vary as the logarithm of the ratio of the distances, whereas the losses due to absorption are proportional to the loss coefficient m and the distance between the two points under consideration. Since the absorption term varies linearly with distance, it may be expressed in terms of decibels per unit length. In the present paper the absorption is expressed in terms of decibels per thousand feet. In the literature m is usually expressed as the loss coefficient per centimeter. The relation between m and I expressed in decibels per thousand feet is

$$I = -4.34\, m\, (30.4 \times 1000)$$

$$= -1.32 \times 10^5 m \quad \text{decibels per thousand feet} \tag{5}$$

Equation (4) shows that the losses may be expressed separately in terms of decibels and that the total loss is the algebraic sum of the losses expressed in decibels. The loss due to the spreading of the wave is independent of frequency, but the loss coefficient m changes greatly with frequency and atmospheric conditions.

TYPES OF SOUND DISSIPATION

The loss coefficient m may be considered in two separate categories; namely, loss due to sound absorption and loss due to sound deflection.

The absorption losses are those in which the sound energy is converted to heat energy. Such losses are caused by viscosity, heat conduction, reaction with water vapor, and friction with the terrain.

The deflection losses are apparent losses resulting from a deflection of the sound rays from straight lines by scattering, partial reflections, and refraction. These losses are caused by the inhomogeneous nature of the atmosphere and vary over such a wide range that they are almost unpredictable.

The value of m is taken to be a constant independent of source or distance. For losses that are uniformly distributed throughout the atmosphere the value of m is probably constant. For certain losses such as terrain loss, scattering, and refraction, the value of m probably is not a constant but varies with distance and directional properties of the source.

Losses due to viscosity and conduction.- The classical absorption in air has been calculated theoretically with the consideration of the losses due to heat conduction and viscosity. The value for m is given in reference 1, page 130 as

$$m = \frac{2\alpha}{\lambda^2} \qquad (6)$$

where α is the amplitude attenuation constant.

The value of α is given as 1.56×10^{-4} for air at 59° F, where the wavelength λ and the loss coefficient m are expressed in centimeters. Table I gives the theoretical values of the absorption for various frequencies. These losses are seen to be extremely low and may be considered negligible for any audible frequencies except those that are very high.

Losses due to reaction between water vapor and oxygen gas in air.– Numerous investigators have measured absorption coefficients many times the aforementioned theoretical values. Knudson (reference 2) investigated the effect of temperature and humidity in the frequency range from 3,000 to 10,000 cycles per second. The maximum absorption for any frequency was found to be many times as great as the value given herein and the maximum absorption was found to vary as the first power of the frequency instead of as the square of the frequency. The maximum absorption occurred at some fairly low value of the relative humidity, namely, 5 percent to 20 percent depending on the frequency. The absorption in oxygen at various values of the relative humidity was also found to be five times as great as that for air. Since air is about one-fifth oxygen, the sound absorption was concluded to be due to a reaction between water and oxygen molecules. The absorption in nitrogen was found to be unaffected by the humidity and was of the order calculated for the absorption due to viscosity and conduction.

Kneser (reference 3) has given a theory for the sound absorption in air and oxygen and equations for calculating the loss at any frequency, temperature, and humidity. These equations have been used to calculate the sound absorption in air at a temperature of 68° F. The absorption is plotted in figure 1 in units of decibels per thousand feet as a function of the relative humidity for frequencies of 100, 500, 1000, 3000, and 10,000 cycles per second. Knudsen's experimental curve for 10,000 cycles (reference 2) is also shown. Agreement between theory and experiment is seen to be very good up to about 30 percent relative humidity. At the higher values of the relative humidity the theory underestimates the losses, by a factor of approximately 5 at 100 percent relative humidity. A comparison of the 3000-cycle curve of Knudsen (reference 3) shows about the same results. No reliable experimental data are available to check the theory at the lower frequencies.

The effect of temperature may be estimated from results given in reference 2. Knudsen found that the absorption was approximately twice as great at 131° F as it was at 68° F. Some measurements made at temperatures of 5° F showed that the absorption was very low and of the order given in table I.

Absorption due to terrain.– If the sound wave travels parallel to the surface of the earth, part of the sound is dissipated at the edge of the wave as it travels over the ground. Experiments described on page 160 of reference 1 have shown that the frictional absorption due to long grass, shrubs, and trees is probably large.

Some tests were made in the present investigation to determine the absorption of sound passing over 2-inch-high grass. The measurements were made of sound from loud speakers at various distances from the speakers. Two speakers were mounted 10 feet from the ground about 3 feet apart. They were driven in phase at various frequencies from 100 to 10,000 cycles per second. The microphone was about 15 inches from the ground. The terrain was slightly rolling, but the microphone was in a clear line of sight to the loud speakers. The measurements were made at sundown and there was a slight breeze from the speakers toward the microphone. The temperature was 70° F and the relative humidity was 40 percent. The values of the combined terrain and atmospheric attenuation are based on the measurements made over the distance from 100 to 1200 feet from the source. Since the value of the attenuation may be a function of distance, the values given in table II must be considered as average values for the conditions of the test. The short grass did not attenuate the 100-cycle note, but at the higher frequencies the measured attenuation was many times the value calculated for the atmosphere alone.

Extensive measurements of the sound absorption of long grass and trees are given in reference 4. Terrain absorption coefficients taken from reference 4 are given in table III. The terrain absorption has small effect on the noise from an airplane flying overhead, but it is the predominant source of absorption for noises which approach the observer in a horizontal plane. Grass has little effect on the frequencies near 100 cycles per second but it absorbs the higher frequencies. Trees and shrubbery are more effective than grass in absorbing the lower frequencies as well as the higher frequencies.

Scattering due to gusts and turbulence.- The effect of turbulence in the atmosphere is considered theoretically in reference 5. If the turbulence scale is large compared with the wavelength, the sound rays will be refracted without change of intensity which results in fading of the sound; if the scale of turbulence is small, scattering of the sound results. This scattering is shown to vary as the cube root of the frequency and depends on the atmospheric turbulence which is effected by the wind conditions. A value of the scattering for normal conditions is given as $m = 1 \times 10^{-5}$ per centimeter or 1.32 decibels per 1000 feet at a frequency of 500 cycles per second. The tests of H. Sieg mentioned in reference 5 indicate that the scattering is of this order but that it is independent of frequency in the range from 250 to 4000 cycles per second.

At present sufficient experimental data are not available to evaluate the loss in terms of atmospheric conditions.

Partial reflection due to variation of acoustic impedance.- As a sound ray passes from one medium to another, part of the sound wave is reflected. If the ray is normal to the boundary of the different mediums, the expression for the reflected wave is given on page 148 of reference 1 as

$$\frac{S_r}{S_i} = \frac{c_2\rho_2 - c_1\rho_1}{c_2\rho_2 + c_1\rho_1}$$

where S_r is the reflected condensation, S_i is the incident condensation, c is the sound velocity, and ρ is the density. The subscript i refers to the medium of the incident ray. A negative sign for S_r simply denotes a phase reversal of the reflected wave.

In the investigation of reference 6, sound signals were sent vertically into the atmosphere and the reflections measured. An expression for the pressure-amplitude reflection coefficient per unit length is given in reference 6 as

$$r(s) = \frac{1}{2\rho c}\frac{d(\rho c)}{ds}$$

which is analogous to the previous equation.

For a normal atmosphere the value of $r(s)$ is shown to be approximately equal to 5×10^{-7} per centimeter. Multiplying this value by 2 to convert it to energy-reflection coefficient gives a value of $m = 1 \times 10^{-6}$ per centimeter which by equation (5) gives

$$I = -0.13 \text{ decibels per 1000 feet}$$

This loss for a normal ideal atmosphere is extremely small. The experimental results obtained in reference 6 show that the measured reflections were greater than those predicted herein and that they were greatest when the atmosphere was in a turbulent condition such as exists when the wind is blowing more than 5 miles per hour. Temperature inversions also caused increased reflections. The sound energy therefore appears to be propagated from the low densities at the high altitude to the high densities on the earth with no appreciable reflection loss, unless discontinuities exist in the atmosphere.

Refraction due to temperature and wind gradients.— The speed of sound relative to a fixed point on the earth depends on the temperature and on the wind velocity. If a gradient of the speed of sound exists, the rays will be curved.

The normal atmospheric temperature gradient of -3.5° F per 1000 feet results in the curvature of the sound rays away from the earth's surface. For a sound ray starting parallel to the earth's surface the radius of curvature of the sound ray is 52 miles (reference 1, p. 168). Such a sound ray will be curved upward about 200 feet in a distance of 2 miles. This curvature may be in the reverse direction at night. This curvature upward and the terrain losses are believed to be the principal reasons that sound sources near the horizon or on the earth's surface are usually not heard at great distances.

In addition to the aforementioned effect there are secondary effects caused by the curvature of the sound rays. First, the length of the sound path will be increased if the rays are curved; and second, for normal temperature gradient, the curved rays spread apart at a greater rate than do the straight rays. For an airplane flying at 40,000 feet only the sound rays in a cone of about 120° below the airplane reach the earth's surface. About half the sound energy that would reach the earth if the rays were straight is therefore refracted into space by the curvature of rays. A 3-decibel total loss is due to this refraction. This effect is a minimum directly under the airplane and is estimated to be in the order of 1 decibel for 40,000 feet.

Wind velocities on the earth are usually lower than at some distance from the surface; hence, if the sound is traveling against the wind, it will be slowed up more at higher altitudes and the sound ray will be curved away from the earth. If the sound is traveling with the wind, the rays will be curved toward the earth.

Representative values at room temperature of the various losses are summarized in table IV.

DETERMINATION OF FREQUENCY MOST EASILY HEARD

The frequency which is most easily heard will depend on the source intensity, atmospheric conditions, distance from the source, and characteristics of the human ear. In the following discussion a variable-frequency point source is assumed to have a pressure level of 100 decibels at a distance of 100 feet from the source. The sound pressure levels for distances to 100,000 feet, calculated by use of equation (4), are shown in figure 2. The value of m is taken from figure 1 for an assumed relative humidity of 40 percent. All other atmospheric losses are neglected because they are either too small or too variable. It is further assumed that the source is high enough in the air so that the terrain loss may be neglected.

Figure 2 shows that up to a distance of 1000 feet the sound-pressure-level curves for all frequencies below 3000 cycles per second lie close to the curve for no atmospheric losses. At 10,000 feet a 1000-cycle note is reduced from 100 decibels to 56 decibels. Of this reduction 40 decibels is due to the spreading of the sound wave (inverse square law) and only 4 decibels is due to atmospheric absorption.

The loudness levels of tones of various frequencies are given in figure 3. This figure is taken from reference 7 and is considered standard for converting pressure levels of pure tones to loudness levels. Figure 4 gives the loudness levels corresponding to the pressure levels of figure 2. At short distances the 3000-cycle note is loudest and at greater distances the 500-cycle note is loudest.

Some experimental confirmation of these calculations may be obtained from experiments by Aigner given in reference 8. This work was done to determine the optimum sending frequency of whistles or sirens. The results are given in table V.

The preceding data depend on the type and loudness of the source as well as on weather conditions and the characteristics of the listener's ear. The data show, however, that noises in the frequency range between 500 and 1000 cycles per second are most easily heard at large distances from the source and that frequencies in the neighborhood of 100 cycles per second are not heard well because the human ear does not respond to the low frequencies at low amplitudes.

EXPERIMENTAL DETERMINATION OF SOUND FROM AIRPLANE

Measurements were made to determine the effect of altitude on the sound pressure level of an airplane flying directly over the observer. The measurements consisted in measuring the total sound output of an airplane as it passed over the microphone at various altitudes. The airplane used is a light trainer type airplane having a nine-cylinder engine directly connected to a two-blade propeller, 9 feet 1 inch in diameter. The airplane flew at approximately 164 miles per hour with manifold pressure and rotational speed constant. The engine speed was 2000 rpm and the horsepower, about 400. A General Radio Company sound level meter was used to measure the maximum sound as the airplane passed directly overhead at altitudes from 300 to 5000 feet. Atmospheric conditions were clear, there was a slight breeze, the relative humidity was 40 percent, the temperature was 72° F on the ground.

The results of these measurements are given in figure 5. The results show good agreement with the curve obtained by use of the inverse square law which is based on the assumption that the source strength is a constant and that there is no atmospheric attenuation. The effect of the change of the speed of sound with altitude on the sound output of a propeller may be calculated from formulas and curves given in reference 9. These calculations show that for the test in which the propeller speed and power were kept constant, the sound intensity level in the plane of the propeller is 2 decibels greater at an altitude of 5000 feet than at sea level. It appears that there may be a slight atmospheric absorption approximately equal to the increase of sound radiation from the propeller. This absorption is of the order of 0.4 decibel per 1000 feet for the frequencies and conditions of the test. The predominate frequencies were in the range between 70 and 300 cycles per second. Since this value of the absorption is within the accuracy of the experiment, no definite value can be assigned to the absorption coefficient which appears to be extremely small.

In order to obtain a comparison of flight tests with static tests, the sound from the airplane was measured while the airplane was run on the ground. The sound was measured near the plane of propeller rotation at a distance of 300 feet from the propeller. These measurements showed the sound pressure level to be 6 decibels higher in the static test than in the flight tests for the same distance.

CONCLUSIONS

An investigation was made to determine the frequency of sound that is loudest at various distances from the source, and sound measurements were obtained on a light trainer airplane flying at various altitudes up to 5000 feet. The following conclusions were indicated:

1. If the atmospheric absorption and the characteristics of the human ear are considered, for a source having a pressure level of 100 decibels at 100 feet, the frequencies in the range from 500 cycles to 1000 cycles per second are found to be most easily heard even at distances of several miles.

2. Sound data obtained with a light trainer airplane flying at various altitudes up to 5000 feet showed good agreement with the inverse square law. This agreement indicates that for test conditions and for frequencies (70 to 300 cps) at which this airplane radiates the maximum noise, the atmospheric absorption is negligible.

3. The inverse square law for change in sound intensity with distance accounts for almost all the attenuation, particularly for frequencies less than 1000 cycles per second. Additional attenuation is obtained from the real losses which are due to viscosity and conduction, reaction with water vapor, and friction with the terrain,

and from the apparent losses which are scattering due to turbulence, partial reflection, and refraction. Of the real losses, the terrain loss is usually the greatest. Of the atmospheric losses, the losses due to water vapor and turbulence are the most important.

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National Advisory Committee for Aeronautics
Langley Field, Va., May 12, 1947

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TABLE I

THEORETICAL ABSORPTION LOSSES DUE TO VISCOSITY AND CONDUCTION

Frequency (cps)	m (per cm)	I (db per 1000 ft)
100	0.27×10^{-8}	0.00035
500	6.65×10^{-8}	.0088
1,000	0.27×10^{-6}	.035
3,000	2.4×10^{-6}	.316
10,000	27×10^{-6}	3.56
20,000	108×10^{-6}	14.3

TABLE II

TERRAIN AND ATMOSPHERIC ATTENUATION AS OBTAINED FROM MEASUREMENTS OVER 2-INCH-HIGH GRASS

Sending frequency (cps)	Measured terrain and atmospheric attenuation (db per 1000 ft)	Calculated atmospheric attenuation, (db per 1000 ft) (fig. 1)
100	0	0.0035
500	2	.085
1000	16	.34
5000	26	9.0

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TABLE III

TERRAIN ABSORPTION COEFFICIENTS IN DECIBELS PER 1000 FEET

[Data taken from reference 4]

Frequencies (cps)	Thin grass 6 in. to 12 in. high	Thick grass 18 in. high	Average jungle 300-ft. visibility
100	2	2	20
500	10	30	20
1,000	--	30	40
5,000	--	30	63
10,000	--	60	70

TABLE IV

SUMMARY OF LOSSES IN DECIBELS PER 1000 FEET

[Room temperature]

Type of loss	Value of loss	
	Frequency of 100 cps	Frequency of 1000 cps
Viscosity and conduction	0.00035	0.035
Water vapor, 80 percent relative humidity	0.001	0.9
Water vapor, maximum value	0.8 at 2 percent humidity	8.0 at 6 percent relative humidity
Terrain, short grass	0	16.0
Turbulence	0.8	1.7
Partial reflection	0.13	0.13
Refraction, vertical direction	0.025	0.025
Refraction, horizontal direction	Possible total loss	Possible total loss

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TABLE V

OPTIMUM SENDING FREQUENCY

[Data taken from reference 8]

Distance (miles)	Frequency (cps)	Distance (miles)	Frequency (cps)
0.62	2000	18.6	765
1.86	1446	24.8	716
3.10	1240	31.0	658
4.35	1123	37.3	653
4.97	1080	43.5	630
5.59	1050	49.7	610
6.20	1020	55.9	593
12.4	848	62.1	580

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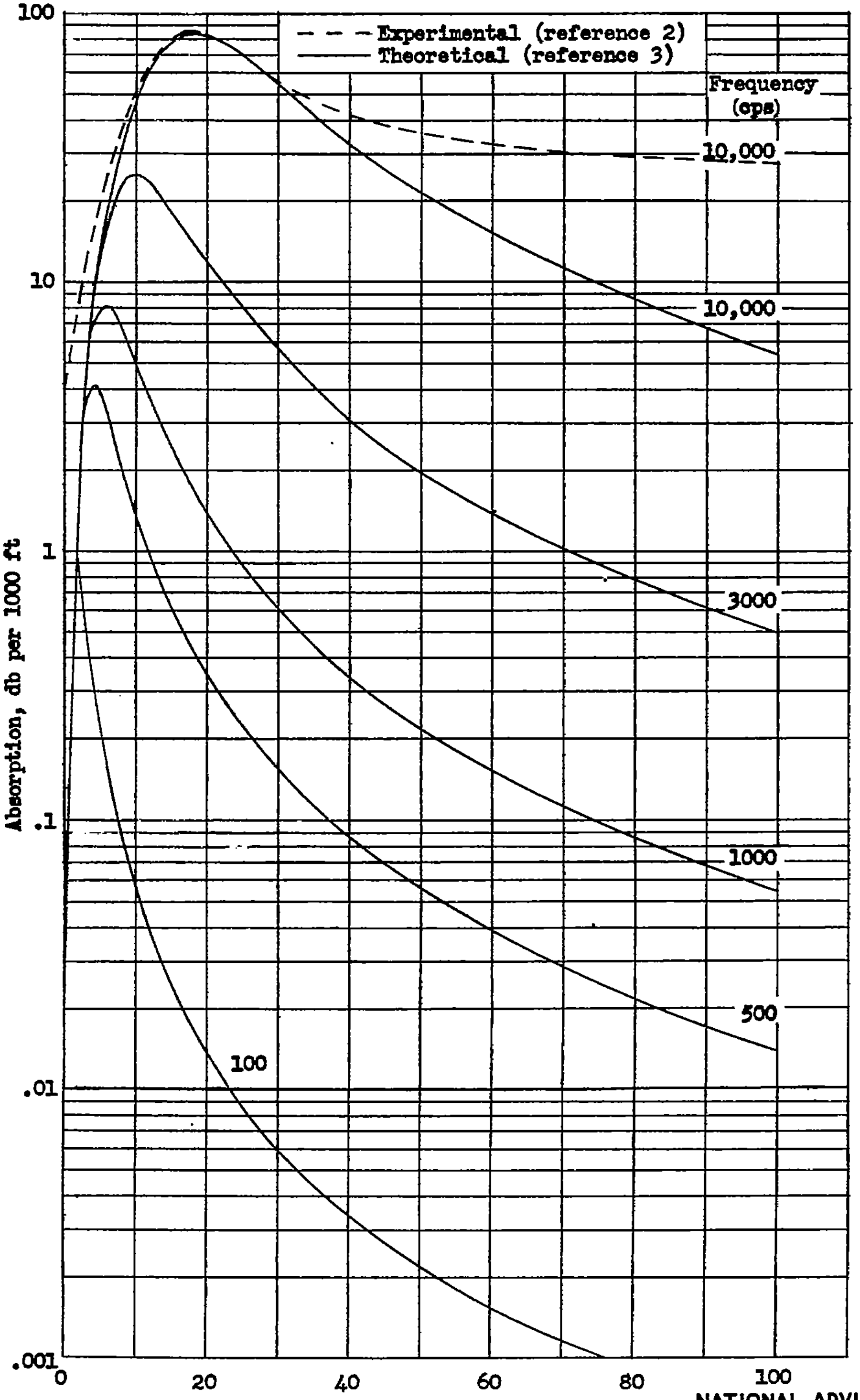

68°F

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Figure 1.- Calculated absorption of sound in air as function of the relative humidity.

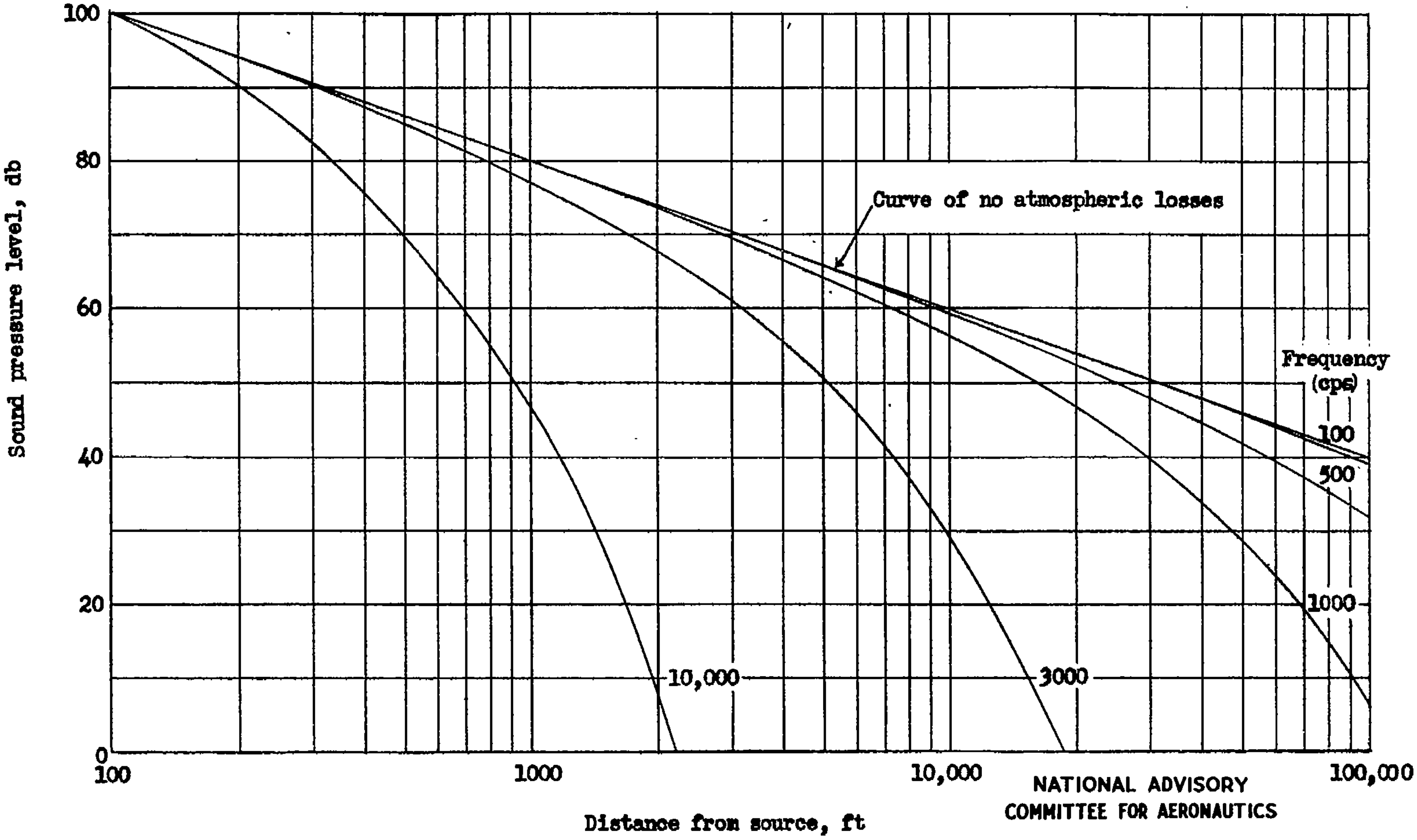

Figure 2.- Sound pressure level as function of distance from source. Calculated for 40-percent humidity and 68° F.

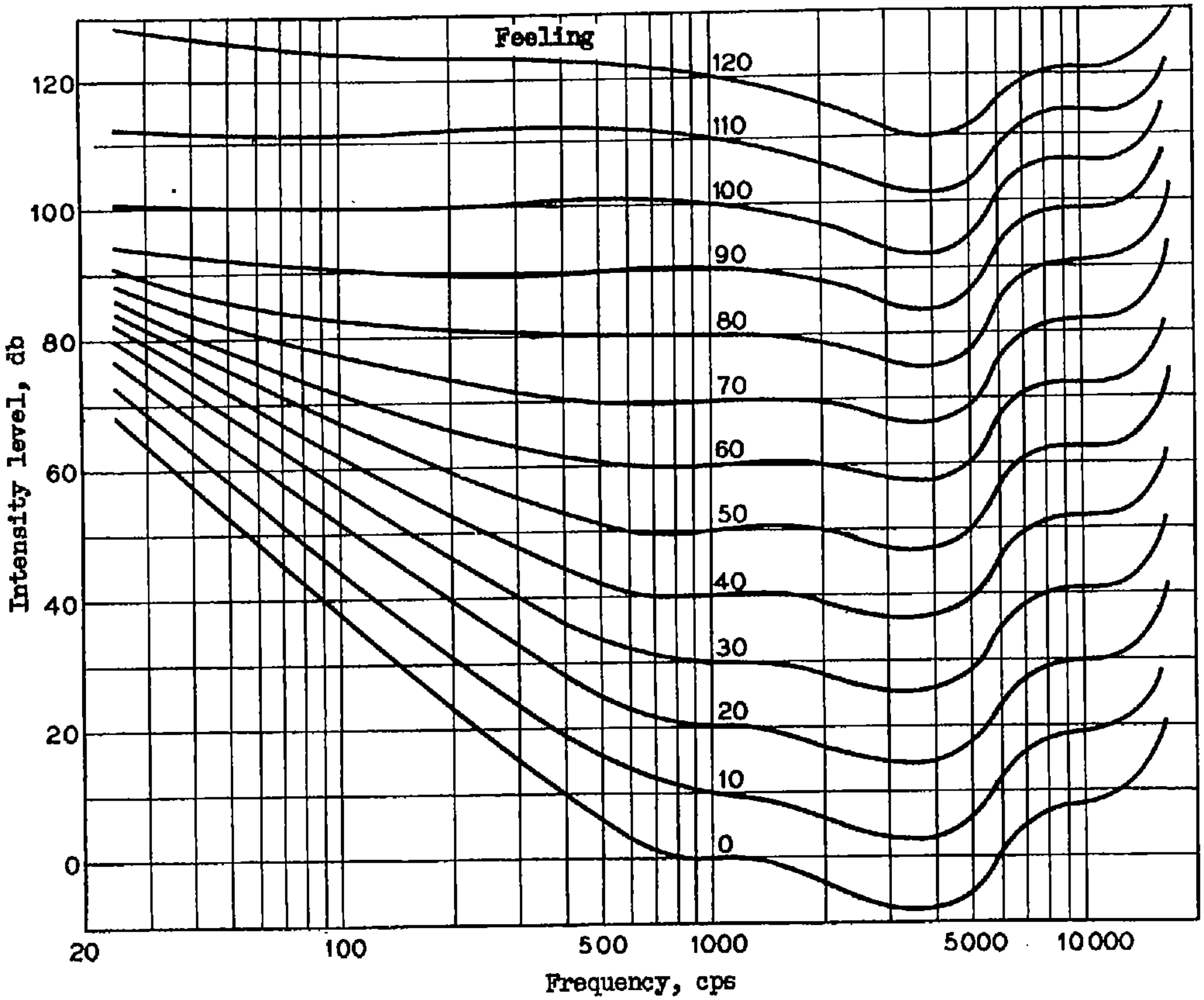

Figure 3.- Loudness-level contours. Taken from reference 7.

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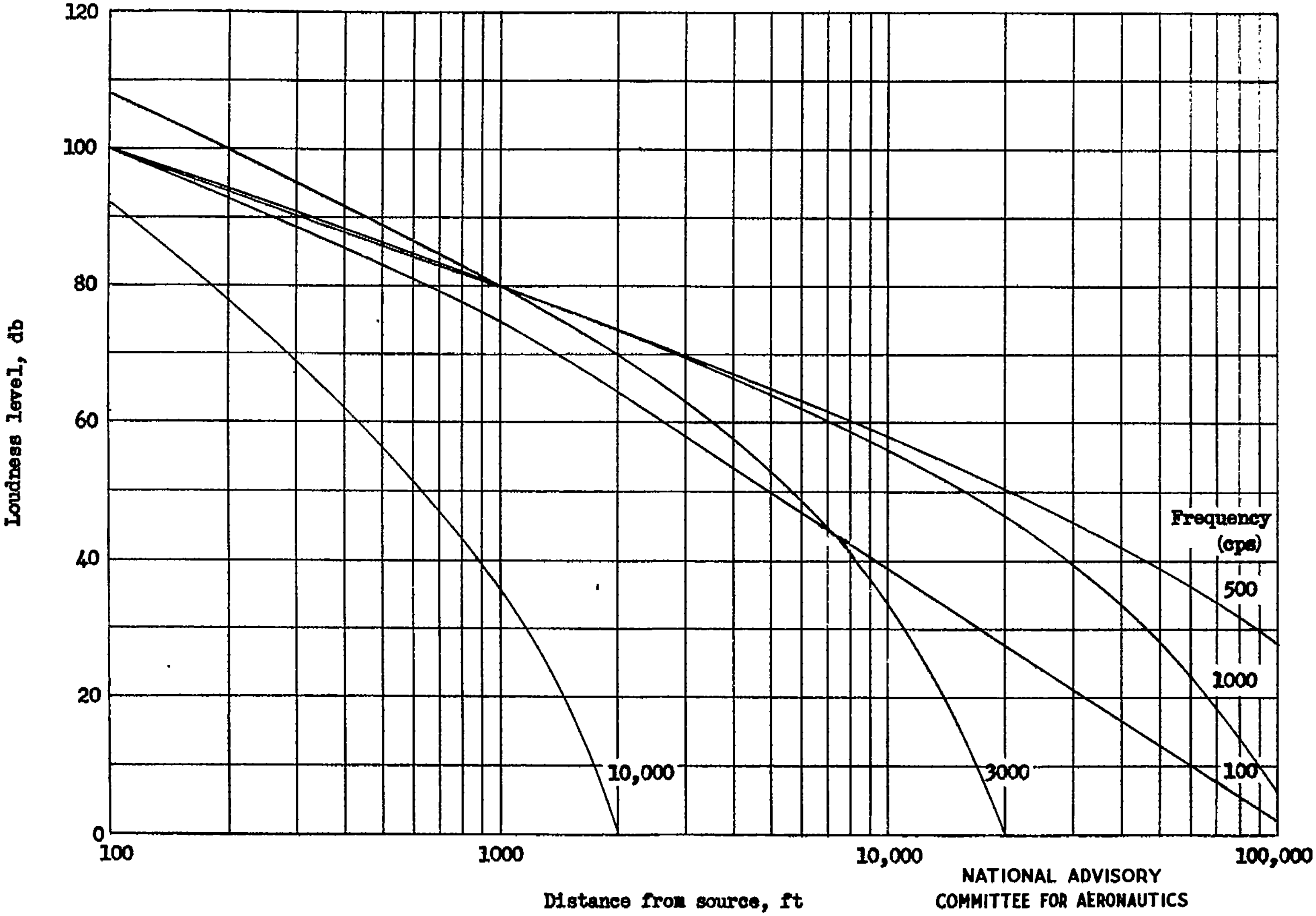

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Figure 4.- Loudness level of source as function of distance from source.

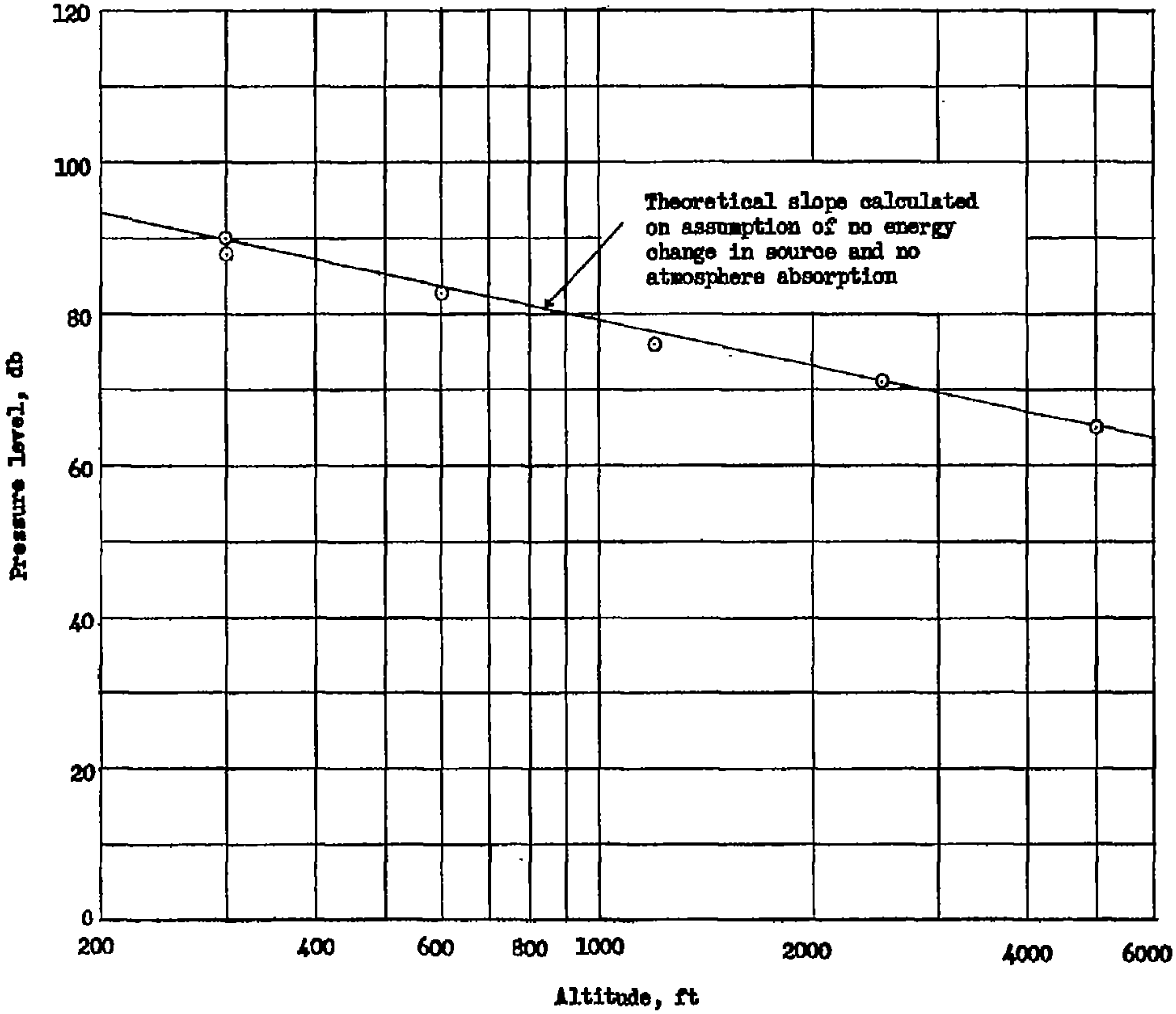

Figure 5.- Maximum sound pressure level from airplane flying directly over microphone. Airspeed, 164 miles per hour; rotational speed, 2000 rpm; power, 400 horsepower; relative humidity, 40 percent; temperature, 72° F.

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