NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2968

PROPELLER-NOISE CHARTS FOR TRANSPORT AIRPLANES

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Page 9, equation (1): The power term $\frac{P_H}{c(0.8M_t)^2}$ should be multiplied by the factor 550, so that this equation reads:

$$p = \frac{169.3 \pi BD \lambda}{2s \pi} \left[ \frac{550P_H}{c(0.8M_t)^2} - T \cos \beta \right] J_n(x) \tag{1}$$

The text following this equation should also be amended to include the following explanation:

The pressures given by equation (1) are free space pressures and for purposes of this paper were doubled to account for ground reflection.
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SUMMARY

Calculations of rotational-noise and vortex-noise levels at a distance of 300 feet for engine ratings of 1,000 to 10,000 horsepower have been made for a large number of propellers in static operation. Propellers with three, four, six, and eight blades and diameters of 8, 12, 16, and 20 feet are considered. The results are presented in chart and table form for rapid estimation of the noise levels and spectra in the range of tip Mach numbers from 0.40 to 1.00. Applications of the data to tandem and dual-rotating configurations are given and the supersonic-type propeller is also briefly considered.

It is emphasized that, if noise reductions are to be obtained or if present noise levels are to be maintained for higher power ratings, future propeller designs should operate at lower tip Mach numbers than are currently being used. Single- rather than dual-rotating propellers were found to generate the lowest over-all noise levels for a given number of blades.

INTRODUCTION

The principal neighborhood nuisance factor in connection with airports is the noise resulting from ground and flight operations of aircraft. The external-noise problems are currently overshadowing the ever-present problem of proper protection for the passengers and crew. Reference 1 indicates that increasing engine power ratings, greater traffic densities, and greater concentrations of population near airports are combining to intensify the airport noise problem.

Although the possibility is recognized that the operation of jet engines may eventually create another very serious transport-airplane noise problem, the propeller is currently one of the major sources of external noise. As engine power ratings increase, propeller noise levels, in general, will also increase unless a concerted effort is made in the interest of noise reduction. For future propeller aircraft, the adherence to current design trends will probably not be feasible if noise reductions are to be obtained or even if present levels are to be maintained.
References 2 and 3 deal with the noise and performance, respectively, of propellers of personal-owner airplanes. The present paper and reference 4, which cover approximately the same ranges of propeller parameters, are essentially extensions of the studies of references 2 and 3 to propellers of transport airplanes. Information in regard to noise levels is presented in the present paper to enable the designer to evaluate new configurations in the early design stage and to evaluate the benefits from possible modifications to existing configurations.

### SYMBOLS

- $M_t$: rotational tip Mach number
- $V_{0.7}$: section velocity at the 0.7-radius station, fps
- $A$: propeller-disk area, sq ft
- $A_B$: propeller-blade area, sq ft
- $N$: propeller rotational speed, rpm
- $s$: distance from propeller to observer, ft
- $B$: number of blades
- $T$: thrust, lb
- $P_H$: power input to propeller, hp
- $D$: propeller diameter, ft
- $I$: sound-pressure level, db $\approx 0.0002 \mu \text{bar}$
- $\overline{I}$: over-all sound-pressure level, db
- $\overline{I}_V$: sound-pressure level of vortex noise, db
- $\overline{I}_R$: sound-pressure level of rotational noise (summation of first four harmonics), db
- $p$: root-mean-square sound pressure of a given harmonic, dynes/sq cm
- $J_{mB}(x)$: Bessel function of order $mB$ and argument $x = 0.8M_t mB \sin \theta$
- $\beta$: angle between propeller axis of rotation and line from center of propeller to observer (ranges from $0^\circ$ in front of propeller to $180^\circ$ behind it), deg
ESTIMATION OF PROPELLER NOISE

General Considerations

Most external-noise problems result from static operation of aircraft or from take-off and landing operations. The aircraft in these operations is relatively close to the observer and, in the take-off condition particularly, is using maximum power. For the purposes of the present paper, the noise for various transport propeller configurations has been calculated for static conditions. These results may also be assumed to apply approximately to conditions of low forward speed as in take-off and landing.

Noise from propellers consists of a rotational component and a vortex component. The rotational component is due to the steady aerodynamic forces on the propeller blade, whereas the vortex component results from the shedding of vortices from the propeller blade. Since the laws of generation of these two components are different, they may vary in importance as the operating conditions of the propeller change and also as the configuration changes. These effects are illustrated qualitatively in figure 1, which also indicates the nature of these two noise components. Figure 1(a) is a noise spectrum of a propeller operating near a tip Mach
number of 1.0. For this condition, the major contribution is from the rotational component. The spectrum consists of several discrete frequencies which are harmonically related to the blade passage frequency and are of constant amplitude.

Figure 1(b) is the vortex-noise spectrum from a rotating circular rod and illustrates the nature of vortex noise from propellers. This noise is random and has a continuous spectrum over a range of frequencies determined by the section velocity and geometry. The frequencies are associated with the Kármán vortex street in the wake and may be predicted by the Strouhal relation as given in reference 5. The maximum intensity in figure 1(b) corresponds to the Strouhal frequency in the wake of the blade at its half-radius section. In the case of a propeller, the vortex-noise spectrum will usually be broader than that of figure 1(b) because of the variation in blade thickness along the span.

For the case in which a propeller operates at a low rotational speed, the rotational and vortex components may be of the same order of magnitude; if they are, the type of spectrum shown in figure 1(c) results. In general, the vortex component has a higher frequency content than the rotational component and increases in intensity at a slower rate as a function of tip speed. As a result, high- and low-tip-speed propellers will have quite different noise spectrums. The vortex component is assumed to be most intense on the axis of rotation in front of and behind the propeller plane (β = 0° and β = 180°), whereas the rotational component is usually a maximum at values of azimuth angle β between 90° and 120°.

Charts and Tables

Calculations of propeller rotational- and vortex-noise levels have been made by the methods outlined in appendixes A and B and in accordance with the simplifying aerodynamic assumptions of appendix C. Intensities and frequencies of the first four rotational harmonics, as calculated for a distance of 300 feet by the method of Gutin (ref. 6) in appendix A, are listed in table I for a wide range of propeller parameters. Figures 2 to 7 give the rotational- and vortex-noise levels as functions of tip Mach number for propellers of three, four, six, and eight blades and for engine ratings of 1,000, 2,000, 4,000, 6,000, 8,000, and 10,000 horsepower. The rotational-noise values, plotted as the solid-line curves in these figures, were obtained by a summation of the noise from the first four rotational harmonics as listed in table I. In order to estimate the noise levels for two and four propellers in random phase, the values given in figures 2 to 7 should be increased by 3 and 6 decibels, respectively.

Vortex-noise levels, presented in figures 2 to 7 as the dashed lines, were estimated by means of the method outlined in appendix B, which is based on reference 7. The vortex-noise levels for a given propeller are
higher for the stalled condition than for the unstalled condition. The levels of figures 2 to 7 are calculated for the unstalled condition and hence may be as much as 10 decibels too low for some operating conditions.

Single-rotating propellers.- The data presented in table I and in figures 2 to 7 are directly applicable to single-rotating propellers. A special type of single-rotating propeller is the tandem configuration which consists of two stages of blades having the same thrust axis and direction of rotation. On the basis of the results of reference 6, the noise field from this configuration is believed to be approximately the same as for a conventional single-rotating propeller with the same number of blades and with the same angular blade spacing.

Dual-rotating propellers.- The data of figures 2 to 7 may also be used to estimate the noise from dual configurations with the aid of figure 8. The noise from a dual-rotating propeller may be determined from the noise fields of both of its component propellers (ref. 8). Figure 8 has been prepared to illustrate the manner in which these noise fields add up. The noise from a propeller has been shown to be independent of its direction of rotation and hence, in the dual-rotating case, the instantaneous phasing of the blades determines the nature of the sound field generated. This phenomenon is illustrated in figure 8, in which the radiation pattern is shown by the solid line for a four-blade dual-rotating propeller and by the dashed lines for a two-blade single- and a four-blade single-rotating propeller. The two stages of blades of the dual-rotating propeller are geared so that the blades overlap on axes AA' and BB' and are equally spaced along axes CC' and DD'. The sound intensity is a maximum on the overlap axes where the propeller appears to the observer as a two-blade propeller and is a minimum on the axes where it appears as a four-blade propeller. In addition to the change in overall levels as a function of the observer's position, the spectrums also change. On axes AA' and BB' the spectrums have all the harmonics of a two-blade propeller, whereas on axes CC' and DD' the spectrums have only the frequencies of a four-blade propeller.

The intensity variations as a function of the observer's position can be estimated for various dual configurations with a wide range of operating conditions from the data of figures 2 to 7. For example, it can be shown with the aid of figure 4(b) that the noise levels for a six-blade dual-rotating propeller absorbing 4,000 horsepower at a tip Mach number of 0.80 would vary from 111 to 116 decibels depending on the observer's position relative to the overlap axis. The maximum and minimum values correspond to those for a three-blade and a six-blade single-rotating propeller, respectively, at the same power loading as the dual configuration.
Supersonic-type propellers. - The over-all noise from a propeller operating at supersonic tip speeds may be estimated from the curves of figure 9, which have been prepared by extrapolating the measurements of reference 9 to greater distances and to higher powers. The tests of reference 9 indicated that the noise from this type of propeller was a maximum in the plane of rotation, that for a given power loading the noise was essentially independent of tip Mach number in the low supersonic range, and that only a small reduction in noise could be expected from an increased number of blades. Although figure 9 applies directly to a two-blade propeller at a tip Mach number of 1.20, the data of the figure may be interpreted as the maximum noise levels that would be encountered in the low supersonic range of tip speed for any propellers at the appropriate power loadings.

DISCUSSION OF RESULTS

Tip Mach Number

The variation of sound pressure as a function of tip Mach number at a constant power is shown in figures 2 to 7 for various propellers in the subsonic tip Mach number range. These figures show that a reduction in tip Mach number is always beneficial in reducing the noise and that the reductions occur at a faster rate for propellers with a larger number of blades. Since the vortex noise decreases at a slower rate with tip Mach number than the rotational noise, it may become relatively important at the low tip Mach numbers. In that range the propeller noise spectrum may contain a relatively high proportion of vortex noise.

Although the supersonic-type propeller offers certain weight and performance advantages, its use commercially may be greatly limited because of its high noise levels. If any effort is made in the interest of noise reduction, the trend would be toward lower tip speeds than are currently being used rather than toward higher ones.

Number of Blades

An increase in the number of blades is generally beneficial in reducing noise. This principle is well-established for conventional single-rotating propellers and is believed to be equally applicable for tandem configurations with uniform angular blade spacing. The variation of sound pressure as a function of number of blades at a constant power is given in figures 2 to 7 for various tip Mach numbers. In general, the largest noise reductions are obtained at the lower tip Mach numbers and relatively small reductions are obtained at the higher ones. In the tip Mach number range, where the vortex noise may be an appreciable part
of the total, however, an increase in the number of blades may result in little or no over-all noise reduction.

Dual-rotating propellers have unique directional patterns which tend to minimize the benefits from an increased number of blades. Figure 8 shows, for example, that an eight-blade dual propeller has eight maxima and eight minima in its radiation pattern. As the number of blades increases, the maxima and minima are spaced closer together and hence it becomes more difficult to derive benefits from these directional effects. As a result of this nonuniform noise field, a small change in the orientation of the propeller with respect to the observer may cause a rather large change in the level of noise at the observer's position. The magnitude of this variation in noise level is a function of the propeller tip Mach number, and for a tip Mach number of 0.50 this variation would be of the order of 20 decibels for the conditions of figure 5(c). An observer inside the airplane would normally not be subjected to this intensity variation since the orientation of the propeller with respect to the airplane is fixed. This phenomenon would be especially annoying to observers on the ground during maneuvering flight at low altitudes.

Power Loading

The power loading of the propeller is a function of both the power input to the propeller and the propeller diameter; figure 10 shows that the noise generated is a function of both of these parameters. For any given propeller diameter the sound levels are seen to increase by approximately 5 to 6 decibels as the power is doubled. This finding is general and applies approximately to all tip speeds.

An apparent discrepancy arises when the power loading is changed by changing the diameter of a propeller. Figure 10 indicates, for instance, that a halving of the diameter for a given power increases the sound levels by 5 to 6 decibels, whereas a 10 to 12 decibel increase would be expected solely on the basis of a resultant quadrupling of the power loading. Two effects are involved one of which partially compensates for the other. A halving of the diameter effectively doubles the distance from the observer to the source and thus tends to neutralize the effect of increased power loading. For a given power input the use of as large a diameter as possible to reduce the power loading to a minimum is advantageous.
CONCLUDING REMARKS

Information with which to estimate the noise from propellers of transport airplanes for various operating conditions has been presented. It is emphasized that, if noise reductions are to be obtained or if present noise levels are to be maintained for higher power ratings, future propeller designs should operate at lower tip Mach numbers than are currently being used. Single- rather than dual-rotating propellers were found to generate the lowest over-all noise levels for a given number of blades.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 18, 1953.
APPENDIX A

CALCULATION OF ROTATIONAL NOISE

Rotational-noise values of the present paper have been calculated by the method of Gutin in reference 6, which has been confirmed by the experiments of reference 9. The Gutin equation in a form convenient for engineering use is as follows:

\[
p = \frac{169.3mBMDt}{2sA} \left( \frac{P_H}{c(0.8M_t)^2} - T \cos \beta \right) J_{mB}(x)
\]  

(1)

The sound pressure \( p \) corresponding to a given harmonic is thus seen to be a function of the power \( P_H \), tip Mach number \( M_t \), number of blades \( B \), propeller-diameter \( D \), propeller-disk area \( A \), and azimuth angle of the observer \( \beta \). For the purposes of this paper, \( \beta \) was assumed to be 105° since that value corresponds to the angle of maximum radiation for most of the propeller configurations considered. Calculations were made for a distance \( s \) of 300 feet, sound speed \( c \) of 1,126 feet per second, and values of thrust \( T \) which were estimated by the method of appendix C.

Calculations of the sound pressure \( p \) for values of \( mB \) corresponding to the first four rotational harmonics have been made and converted to sound-pressure levels. These values are given in table I along with the corresponding frequencies for various combinations of propeller tip Mach number, number of blades, and power input. Summations have been made by taking the square root of the sum of the squares of the pressures of the first four harmonics and these results, after conversion to levels \( T_R \) in decibels, are plotted as the solid-line curves in figures 2 to 7.
APPENDIX B

CALCULATION OF VORTEX NOISE

Vortex-noise levels were calculated by a method based on the work of Yudin in reference 7. For rotating rods having airfoil sections, as well as for those having circular cross sections, the vortex-noise energy was concluded to be proportional to the first power of the blade area and to the sixth power of the section velocity. Thus the following equation was used to calculate the vortex-noise levels in decibels for figures 2 to 7:

\[ \bar{I}_V = 10 \log_{10} \frac{k A B V^6}{10^{-16}} \]  

(2)

where \( k \) is the constant of proportionality evaluated tentatively as \( 3.8 \times 10^{-27} \) in the work of reference 2.

A plot of the vortex-noise levels as a function of blade area for a range of tip Mach number is given in figure 11. Figure 11 is a summary of the vortex-noise levels plotted as the dashed curves of figures 2 to 7 and should be considered tentative pending further experimental confirmation.
ESTIMATION OF STATIC THRUST AND PROPELLER-BLADE AREA

In order to make calculations of the noise levels generated by various propeller configurations by means of equations (1) and (2), some of the interrelated aerodynamic and geometric parameters must be known. Some simplifying assumptions were made in order to expedite the calculation of static thrust and propeller-blade area. Although they are not considered adequate for aerodynamic studies, the resulting equations are considered satisfactory for the purposes of this paper.

Figure 12 gives $C_p$ per unit horsepower as a function of tip Mach number for various propeller diameters. For any other power rating, $C_p$ is easily obtained by multiplying the ordinate of figure 12 by the horsepower. For given values of $C_p$, $D$, and $M_t$ the associated static thrust for use in equation (1) was determined from figure 13. The thrust calculations of figure 13 made use of the relation

$$C_T = k'C_p^{2/3}$$

where $k'$ is a constant of proportionality evaluated as 0.75. This value was chosen on the basis of experimental results of reference 10 and appears to be valid for propellers operating near the stall.

From the expression for differential thrust given in reference 11, the following equation, which assumes that the lift is approximately equal to the thrust, may be derived:

$$A_B = \frac{2T}{\rho C_L V_{0.7}^2}$$

For the purposes of this paper it is assumed that $C_L = 0.4$, that $\rho = 0.002378$ slugs per cubic foot, and that $V_{0.7}$ is the section velocity at the 0.7-radius station. This expression for blade area is evaluated for the ranges of static thrust and tip Mach number of the present studies for use in calculations of vortex noise levels from equation (2).
REFERENCES


| B | Nt | Frequency, cps | I1 | I2 | I3 | I4 | P_H = 1000 | P_H = 2000 | P_H = 4000 | P_H = 6000 | P_H = 8000 |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 0.4 | 51 | 107 | 161 | 215 | 74 | 74 | 51 | 21 | 108 | 79 | 57 | 29 | 106 | 85 | 63 | 35 | 109 | 89 | 66 | 39 | 112 | 91 | 69 | 41 | 113 | 93 | 71 | 43 |
| 3 | 0.5 | 67 | 134 | 202 | 269 | 96 | 83 | 60 | 50 | 102 | 88 | 73 | 56 | 106 | 96 | 70 | 52 | 111 | 98 | 70 | 52 | 112 | 99 | 71 | 52 | 113 | 100 | 72 | 53 |
| 3 | 0.6 | 81 | 162 | 242 | 323 | 100 | 81 | 79 | 73 | 106 | 96 | 85 | 73 | 111 | 102 | 90 | 78 | 125 | 105 | 93 | 82 | 120 | 111 | 106 | 97 | 121 | 116 | 108 | 99 |
| 3 | 0.7 | 91 | 182 | 283 | 377 | 103 | 97 | 89 | 80 | 108 | 103 | 95 | 86 | 114 | 108 | 100 | 91 | 137 | 112 | 103 | 95 | 120 | 111 | 106 | 97 | 121 | 116 | 108 | 99 |
| 3 | 0.8 | 107 | 215 | 324 | 430 | 106 | 103 | 95 | 95 | 112 | 108 | 100 | 97 | 117 | 111 | 105 | 103 | 120 | 117 | 109 | 106 | 123 | 119 | 118 | 115 | 123 | 123 | 122 | 117 |
| 3 | 0.9 | 121 | 254 | 383 | 518 | 109 | 107 | 105 | 105 | 111 | 112 | 110 | 106 | 120 | 118 | 119 | 115 | 125 | 123 | 121 | 119 | 117 | 127 | 127 | 126 | 126 |
| 3 | 1.0 | 134 | 269 | 403 | 538 | 111 | 112 | 110 | 110 | 117 | 116 | 115 | 111 | 122 | 122 | 121 | 119 | 125 | 125 | 124 | 121 | 127 | 127 | 126 | 126 |

**TABLE X**

**CALCULATED SOUND-PRESSURE LEVELS OF THE FIRST FOUR ROTATIONAL-NOISE HARMONICS FOR VARIOUS PROPELLER OPERATING CONDITIONS**

**B = 8 feet**
<table>
<thead>
<tr>
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<th>Frequency, cps</th>
<th>Sound-pressure level, db</th>
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<td>f₂</td>
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<tr>
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</table>

**Table I. Continued**

**CALCULATED SOUND-PRESSURE LEVELS OF THE FIRST FOUR ROTATIONAL-NOISE HARMONICS FOR VARIOUS PROPPELLER OPERATING CONDITIONS**

( p = 12 feet)
### Table I.

**Calculated Sound-Pressure Levels of the First Four Rotational-Harmonics for Various Propellers Operating Conditions**

| B | M<sub>r</sub> | Frequency, cps | 1<sub>I</sub> | 2<sub>I</sub> | 3<sub>I</sub> | 4<sub>I</sub> | 1<sub>H</sub> | 2<sub>H</sub> | 3<sub>H</sub> | 4<sub>H</sub> | 1<sub>P</sub> | 2<sub>P</sub> | 3<sub>P</sub> | 4<sub>P</sub> | 1<sub>H</sub> | 2<sub>H</sub> | 3<sub>H</sub> | 4<sub>H</sub> | 1<sub>P</sub> | 2<sub>P</sub> | 3<sub>P</sub> | 4<sub>P</sub> |
| 3 | 0.5 | 36 | 72 | 108 | 143 | 80 | 36 | 18 | 100 | 80 | 36 | 50 | 30 | 106 | 80 | 36 | 30 | -- | -- | -- | -- | -- | -- | -- | -- |
| 1.0 | 0.5 | 36 | 72 | 108 | 143 | 80 | 36 | 18 | 100 | 80 | 36 | 50 | 30 | 106 | 80 | 36 | 30 | -- | -- | -- | -- | -- | -- | -- | -- |
| 6 | 0.5 | 36 | 72 | 108 | 143 | 80 | 36 | 18 | 100 | 80 | 36 | 50 | 30 | 106 | 80 | 36 | 30 | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| 1.0 | 0.5 | 36 | 72 | 108 | 143 | 80 | 36 | 18 | 100 | 80 | 36 | 50 | 30 | 106 | 80 | 36 | 30 | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| 1.0 | 0.5 | 36 | 72 | 108 | 143 | 80 | 36 | 18 | 100 | 80 | 36 | 50 | 30 | 106 | 80 | 36 | 30 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

**Notes:**
- B is the blade number.
- M<sub>r</sub> is the rotational speed ratio.
- Frequency, cps, is the frequency in cycles per second.
- Sound-pressure levels are given in decibels (dB).
- The table includes data for different harmonics (I, H, P) at various sound-pressure levels (1000, 2000, 6000, 10,000).

**Sources:**
- NACA 1968.
<table>
<thead>
<tr>
<th>B</th>
<th>W,</th>
<th>Frequency, cps</th>
<th>Sound-pressure level, db</th>
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TABLE I. Calculated Sound-pressure levels of the first four rotational-noise harmonics for various propeller operating conditions.

[D = 20 feet]
(a) Rotational noise from high-speed propeller.

(b) Vortex noise from rotating rods.

(c) Composite spectrum of rotational and vortex noise.

Figure 1.- Spectrums of components of propeller noise.
Figure 2.- Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. 

(a) D = 8 feet.

$P_H = 1,000$ horsepower; $s = 300$ feet.
Figure 2.- Continued.

(b) \( D = 12 \) feet.
Figure 2.- Continued.

(c) $D = 16$ feet.
Figure 2.- Concluded.

(d) $D = 20$ feet.
Figure 3.- Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. 

\( P_H = 2,000 \) horsepower; \( s = 300 \) feet.

(a) \( D = 8 \) feet.
Figure 3—Continued.

(b) \( D = 12 \) feet.
(c) \( D = 16 \) feet.

Figure 3.- Continued.
Figure 3.- Concluded.
Figure 4.- Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. $P_H = 4,000$ horsepower; $s = 300$ feet.
(b) $D = 12$ feet.

Figure 4.- Continued.
(c) $D = 16$ feet.

Figure 4.- Continued.
Figure 4.- Concluded.

(d) D = 20 feet.
Figure 5. - Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. 

(a) $D = 8$ feet. 

$P_H = 6,000$ horsepower; $s = 300$ feet.
(b) $D = 12$ feet.

Figure 5.- Continued.
(c) $D = 16$ feet.

Figure 5.-- Continued.
Figure 5.— Concluded.

(d) D = 20 feet.

6000 ft.
300 ft.
Figure 6.- Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. 

$P_H = 8,000$ horsepower; $s = 300$ feet.
(b) $D = 12$ feet.

Figure 6.– Continued.
Figure 6.- Continued.

(c) D = 16 feet.
Concluded.

(d) $D = 20$ feet.

Figure 6.- Concluded.
Figure 7.- Propeller sound-pressure levels as functions of tip Mach number and rotational speed for various numbers of blades. $P_H = 10,000$ horsepower; $s = 300$ feet.
(b) $D = 12$ feet.

Figure 7. Continued.
(c) \( D = 16 \) feet.

Figure 7.- Continued.
Figure 7.- Concluded.

(d) D = 20 feet.
Figure 8.- Free-space radiation pattern in the plane of rotation of three different propellers at the same power and tip Mach number.
Figure 9.- Chart for estimating the over-all noise from supersonic-type propellers. (Dashed lines indicate distances of 300 feet for four different values of propeller diameter.)
Figure 10. - Sound-pressure level of propeller rotational noise as a function of power input and diameter. \( B = 6; \ M_t = 0.6; \ s = 300 \text{ feet}. \)
Figure 11.- Sound-pressure levels of vortex noise as a function of propeller-blade area and tip Mach number.
Figure 12. - Power coefficient per unit horsepower as a function of tip Mach number and propeller diameter. $\rho = 0.002378$ slugs per cubic foot.
Figure 13. - Static thrust for a given power coefficient as a function of tip Mach number and propeller diameter.