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RESEARCH MEMORANDUM

FACTORS AFFECTING THE DESIGN OF QUIET PROPELLERS

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FACTORS AFFECTING THE DESIGN OF QUIET PROPELLERS

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SUMMARY

The problems associated with propeller noise and with the design of propellers that are less noisy than those conventionally used are presented. Three aspects of these problems are discussed: acoustical, aerodynamic, and structural.

Some of the factors which must be considered in the design of a quiet propeller are outlined. Indications are that the noise problem will not be eliminated until the rotational noise level is reduced below the vortex level of the propeller. This will require a reduction of the rotational speed to about one-half of that of present-day propellers.

INTRODUCTION

This paper gives a brief review of recent work done on airplane noise by the NACA and discusses some of the problems encountered in the design of quieter propellers. These problems are discussed under three categories: acoustical, aerodynamic, and structural.

The acoustical requirements for a quiet propeller indicate the necessity for a substantial reduction in tip and rotational speed and an increase in the number of blades. The aerodynamic requirements are that the propeller have a sufficiently large diameter and blade area to develop the required thrust efficiently. Structural considerations require the propeller to be free from flutter, vibration, and excessive stresses and to have a minimum of weight consistent with safety.

The general principles will be outlined and references will be made to various papers in which the relevant factors are discussed in detail. Sample results from some of the investigations will be presented.

SYMBOLS

B	number of blades
t	thickness of section, feet
c	chord, feet
R	propeller-tip radius, feet
γ	density of material, slugs per cubic foot
V_f	maximum flutter speed $\approx$ divergence speed
G	shear modulus of elasticity, pounds per square foot
ρ	density of air, slugs per cubic foot
x_{cg}	position of section center of gravity
s	distance from propeller, feet
I	sound intensity level, decibels
D	propeller diameter, feet
M_t	tip Mach number (rotation only)
P_H	horsepower to propeller
T	thrust, pounds
V	forward speed, miles per hour
N	propeller rotational speed, revolutions per minute
n	propeller rotational speed, revolutions per second
η	propeller efficiency
η_i	ideal efficiency
η_{opt}	optimum efficiency
$\sigma_{0.7R}$	blade element solidity at $0.7R$ $\left(\frac{Bc}{2\pi(0.7R)}\right)$
$\frac{V + w}{nD}$	advance ratio of wake helix

w	rearward displacement velocity of helical vortex surface (at infinity)
$K(x)$	circulation function for propeller blades
κ	mass coefficient for propeller
W	helical velocity at 0.7R, feet per second
U	rotational velocity at 0.7R, feet per second
S	propeller blade area, square feet
C_L	section lift coefficient at 0.7R
K_1, K_2	constants

DISCUSSION OF ACOUSTICAL FACTORS

Noise Levels of Aircraft

Dr. Wright, CAA Administrator, pointed out at the NACA Industry Conference on Personal Aircraft last September that the potential light-plane market depends on the availability of airports close to populated centers and that the location of the airports depends on the amount of noise that airplanes make.

The acceptable noise level of aircraft is that level which will eliminate the objections that people now have to airports located close to their homes. Table I shows a chart, taken from reference 1, which gives the noise levels of common noises. It is not the purpose of this paper to establish an acceptable noise level but to discuss the problems encountered in reducing the noise level of a propeller.

Recently an airplane was flown at the NACA Langley Laboratory which had a noise level of 64 decibels when flown at a speed of 130 miles per hour, 185 horsepower, at an altitude of 300 feet. The noise level of this airplane has been reduced to the point where no distinct engine or propeller frequency can be heard. The noise level of the conventional airplane for comparable conditions was 90 decibels. From table I it may be noted that the noise level has been reduced from about that shown for the "noisiest spot at Niagara Falls" to less than that for the "average automobile, 15 feet." A reduction of 10 decibels indicates a sound energy reduction to 1/10. For the airplane discussed above, the reduction of 26 decibels represents a sound energy reduction to about 1/400 the original sound energy.

It is significant that the changes made on the airplane to obtain this sound reduction resulted in a definite increase in the maximum speed of the airplane with no objectionable flying qualities. A picture of the airplane is shown on figure 1.

Types of Propeller Noise

Figure 2 shows a polar distribution of the first harmonic of the rotational noise components and vortex noise of a propeller (reference 2). It should be noted that the theory for the noise of a propeller in flight has not been completed to the point where it can be said that a solution of the problem has been obtained. In this figure and throughout the acoustical section of this paper a propeller in flight is assumed to have the same sound pattern as a propeller operating without forward velocity but developing the same thrust and torque as the propeller in flight. The rotational tip speed rather than the helical tip speed has been used for making sound calculations. This gives a conservative estimate of the noise since flight tests compared with static tests (reference 3) have shown that the noise in flight is somewhat less even though the helical tip speed has been increased.

The rotational noise, sometimes referred to as the Gutin noise, is the propeller noise due to the steady aerodynamic forces on the blade. In Gutin's theory the noise is divided into the torque and thrust components. From figure 2 it may be seen that for an airplane in flight the greatest component of the rotational noise is due to the torque of the propeller and that the thrust component has little effect. It was shown in reference 4 that the rotational noise can be made as low as desired by reducing the tip speed and increasing the number of blades. Recent tests of the sound from two-, four-, and seven-blade propellers (reference 5) show that the theory for rotational noise is in good agreement with experiment for a tip Mach number range between 0.5 and 0.9 but that for lower tip Mach numbers the measured over-all sound pressures were much greater than the theoretical rotational sound pressures. This discrepancy is due to the vortex noise of the propeller.

The vortex noise is the propeller noise due to the oscillatory aerodynamic forces on the blade associated with the vortices in the wake of an airfoil - the Kármán Vortex Street. It is usually of much higher frequency than the rotational noise and is distributed over a wide band of random frequencies. It has been shown in reference 6 that the vortex noise energy varies as the sixth power of the tip speed and the first power of the total propeller-blade area and is also a function of the drag coefficient of the blade sections. Thus for a propeller of a given total solidity and tip speed, the rotational noise may be reduced by increasing the number

of blades, but the vortex noise is independent of the number of blades. The polar distribution shown on figure 2 for the vortex noise is a maximum along the propeller axis and decreases as the cosine of the angle from the propeller axis. This is the distribution obtained in reference 7 on whirling rods. In the flight condition the distribution is probably considerably altered.

Loudness of Propeller Noise as Affected by Various Factors

The loudness level of a noise takes into account the response characteristics of the ear. It is defined in reference 8 as the pressure or intensity level of an equally loud 1000-cycle note which is the reference frequency. The loudness level contours are shown on figure 3. It is believed that the loudness level is a better criterion for comparing noises than the pressure level. It is not certain whether the loudness level is the best indication of the annoyance level which, in the final analysis, is the true criterion for the objectionability of noise. Since there is no method available for calculating the annoyance level of a noise, the present paper uses loudness levels as a basis for the comparison of propellers.

The subsequent figures on acoustics are taken from reference 2. Loudness charts are given in reference 2 covering the power range of 100 to 300 horsepower, propeller diameters of 6, 8, and 10 feet, and the forward speed range of 50 to 200 miles per hour.

Figure 4 is a sample chart giving the loudness levels as functions of rotational speed for two-, four-, six-, and eight-blade propellers for constant diameter, power, and forward velocity at 300 feet. This distance may be considered the altitude of an airplane in the approach to the airport. Rotational loudness levels are given by the solid lines. It may be seen that the greater the number of blades the lower the loudness level for a given rotational speed. The loudness levels also decrease rapidly with decrease of rotational speed. The vortex loudness level is given by the line of long dashes. It is independent of the number of blades and decreases slowly with a decrease in rotational speed. The lines of short dashes represent total loudness levels due to rotational and vortex noise. At a sufficiently low rotational speed the rotational noise drops below the vortex noise level and the propeller noise becomes predominantly vortex noise. The rotational loudness level and the total loudness level for a five-blade propeller at a rotational speed of 1000 rpm are indicated by circles on the figure. These points correspond approximately to the operating condition of one of the NACA quiet propellers. It may be seen that the loudness is almost entirely due to the vortex noise. This explains why the rotational noise cannot be heard.

The effect of diameter on the loudness level of a two-blade propeller operating at constant rpm and power is given on figure 5. An examination of the Gutin sound formula as given in equation (4) of reference 4 shows that the sound pressure is a product of several factors. Decreasing the diameter, with rpm and power held constant, results in the decrease of some factors but an increase in others. The net result is a small decrease of sound intensity with decrease in diameter at the expense of propeller efficiency. The effect of diameter on efficiency will be discussed later.

The effect of diameter on the loudness level of a two-blade propeller operating at constant tip speed and power is given on figure 6. This figure shows that for constant tip speed the loudness level decreases as the diameter is increased. This decrease is due to two factors. First, it can be shown from equation (5) of reference 4, that for constant tip speed the sound pressure varies inversely as the propeller radius. Second, for constant tip speed the large propeller will have a lower rpm; thus, the sound frequencies will be reduced toward a region where the ear has lower sensitivity.

The effect of power on the loudness of a two-blade propeller of constant diameter is given on figure 7. There is some increase in sound output with increase of power, particularly at the lower rpm's. If the rpm is reduced still further into the region where the vortex noise predominates, the loudness level does not change much with horsepower. In some preliminary tests with the NACA quiet propellers the sound pressure level was increased only 1 to 2 decibels as the power was increased from 110 horsepower to 185 horsepower.

Effect of Distance on Airplane Noise

The question of effect of distance on airplane noise was raised at the September 1946 NACA Industry Conference on Personal Aircraft Research. Some tests (reference 3) were subsequently made to determine how much atmospheric absorption affected the sound. Figure 8 gives the maximum sound intensity measured on the ground as an AT-6 airplane was flown directly over the microphone at altitudes between 300 and 5000 feet. The straight line is a theoretical line calculated on the assumption that there is no atmospheric absorption and that the decrease in intensity is due to the spreading of the sound wave from a point source. The data indicate that the atmospheric absorption is negligible for the conditions of the tests. For sound traveling along the ground, appreciable absorption was noted when the wave length of sound was about the same dimension or smaller than the dimension of the vegetation. Thus short grass will not attenuate the low frequencies but shrubbery or trees will.

DISCUSSION OF AERODYNAMIC FACTORS

Ideal Efficiency

The ideal efficiency of an actuator disk is given as a function of the power coefficient on figure 9. This curve is taken from reference 9 and is based on the work of Rankine in 1865. This curve gives the ideal efficiency for the condition that the momentum increase is distributed uniformly over the propeller disk. This curve is useful for estimating the effect of diameter on the efficiency of a propeller. Various values of diameter are indicated on this curve for 100 horsepower; the cruise condition is taken as 100 miles per hour and is shown above the line; the take-off condition, as 50 miles per hour and shown below the line. It may be seen that the take-off efficiency becomes quite low as the diameter is reduced.

Propeller Blade Area as a Function of Tip Speed

An expression for the differential thrust per unit blade area may be obtained from blade element theory (reference 9). Neglecting the section drag, the following relation is obtained.

$$\frac{dT}{dA} = \frac{1}{2}\rho C_L W U \tag{1}$$

where W is the helical velocity and U the rotational velocity of the section.

The propeller blade area required to develop a given thrust may be estimated from this equation. In figure 10 the blade area is given as a function of tip speed. These curves are based on the assumption that $W = U$ and that the velocities at the 0.7 radius are representative. A lift coefficient of 0.4 was used in these calculations. These curves show the large increase in blade area necessary to develop the required thrust at low tip speeds. They indicate the magnitude of the required blade area and are used in this paper for estimating the vortex noise and the weight of propellers and are not intended for design purposes.

Minimum Loss Theorem

Modern propeller theory is based on a theorem given by Betz in 1919 (reference 10). This theorem states: "The flow behind a propeller with minimum loss of energy is as though the path traversed

by each propeller blade was congealed and was driven astern at a given velocity . . . ." Figure 11 is a picture of celluloid helices which represent the congealed wakes of Betz' theorem. In an addendum to reference 10, Prandtl calculated the distribution of the flow over a series of disks representing the helix. From this flow Prandtl obtained the ideal circulation or load distribution for a propeller, based on the simplifying assumptions he made. In 1929 Goldstein calculated the flow about two- and four-blade helices and obtained an exact expression for the ideal circulation distribution. In 1944 Theodorsen at the NACA reexamined the entire propeller theory and by use of electrical methods checked Goldstein's circulation function for single-rotating propellers and obtained the circulation functions for dual rotating propellers. Some of the models which were used for the electrical measurements are shown in figure 11.

Since a frictionless propeller having minimum induced losses will produce a helical wake, the load distribution and performance of such a propeller may be determined from the potential flow over the wake. Thus the optimum circulation distribution or loading along the blade radius may be obtained from measurements of the voltage across the helical sheet when the helix is immersed in a tank of water having electric current flowing in the direction of the helix axis. This distribution differs for different rates of advance, number of blades, and propeller configurations. The circulation function for a four-blade propeller at a $\frac{V + w}{nD}$ of 1.55 is given in figure 12 for both single rotation and dual rotation. These curves are taken from reference 11. It may be seen that to obtain a minimum energy loss the load at the tip must be reduced on both propellers. For a single-rotation propeller the load must also be reduced at the hub, but for a dual rotation propeller the circulation is a maximum at the hub. Physically, this means that the tip load must be reduced to minimize the tip loss and the hub load must be reduced on the single-rotation propeller to reduce the rotational loss.

Theodorsen, in reference 11, introduced the concept of the mass coefficient which to a first approximation is a measure of the effective disk area of a propeller. This mass coefficient may be obtained from an integration of the circulation function, or may be obtained from a measurement of the electrical resistance of the helix when it is immersed in a tank of water. The mass coefficient κ is the ratio of the change of tank resistance caused by the wake to the change of tank resistance caused by the immersion of a solid insulator having the same diameter as the wake. The value of the mass coefficient for various numbers of blades for single rotation is

given in figure 13 (fig. 3, reference 11). This figure shows that, for a given airplane velocity and propeller diameter, the mass coefficient or effective disk area of the propeller decreases as the rotational speed decreases or $\frac{V + w}{nD}$ increases. This means that the optimum efficiency of a frictionless propeller decreases as the rotational speed is decreased. The mass coefficient and efficiency may be increased by increasing the number of blades at a given $\frac{V + w}{nD}$. Even with an infinite number of single-rotating blades the mass coefficient is less than unity for finite values of $\frac{V + w}{nD}$. It may be of interest that the mass coefficient of the counter-rotating propellers lies in the region above the curve for an infinite number of blades in single rotation. Since we do not know at present how much noise dual rotation propellers make, the discussion will be restricted to single-rotation propellers.

The efficiency formulas for frictionless propellers having ideal circulation distribution are given as functions of the ratio of thrust to mass coefficients in reference 12.

An approximate method for obtaining the efficiency of frictionless propellers is given in the following to demonstrate the use of the mass coefficient. (This method is slightly optimistic but accurate to better than 1 percent for lightly loaded propellers having an optimum efficiency greater than 90 percent. The wake velocity is assumed to be equal to the stream velocity, $V + w = V$; and the slipstream contraction is neglected.) The ideal efficiency is given in figure 9. In a propeller the air is not accelerated uniformly through the disk as in an actuator but passes through the disk in bunches, having tangential, radial, and axial velocity components. The mass coefficient gives the equivalent actuator disk of the propeller. Thus, for example, an 8-foot actuator disk absorbing 100 horsepower at 100 miles per hour has a power coefficient of 0.1 and an efficiency of 95 percent (fig. 9). Assume that an 8-foot two-blade propeller is operating at a V/nD of 0.9. This propeller has a mass coefficient of 0.5 (fig. 13); thus its efficiency will be equal to that of an actuator disk of one-half the area. Since the power coefficient varies inversely as the actuator-disk area, the equivalent actuator disk has a power coefficient of 0.2 and an efficiency of 91 percent (fig. 9). This is the efficiency of a frictionless two-blade propeller at a V/nD of 0.9 for the above operating conditions. If the propeller rotational speed is reduced so as to operate at a V/nD of 1.3, the mass coefficient becomes equal to 0.33 and the power coefficient of the equivalent actuator disk is 0.3 This corresponds to an optimum efficiency of 88 percent

for a two-blade propeller operating at a V/nD of 1.3. If the number of blades were increased to five at this $V/nD = 1.3$, the mass coefficient would be increased to 0.5 and the optimum efficiency would be the same as for a two-blade propeller operating at a V/nD of 0.9, namely 91 percent.

Propeller Efficiency Charts

The preceding discussion has dealt with the induced losses of frictionless propellers and cannot be applied directly to the design of actual propellers. Lock, at the British National Physical Laboratory, extended the work of Goldstein to other blade numbers and developed a method of calculating the propeller characteristics. Crigler and others at the NACA have extended the work of Lock and developed selection charts which greatly facilitate the work of designing high-efficiency propellers. This method (reference 13) is considered standard for the purpose of designing high-performance propellers. Efficiencies up to 95 percent have been obtained in wind-tunnel tests on propellers designed by this method.

Recently Crigler and Jaquis (reference 14) have extended this work to cover the low V/nD range and have calculated a series of propeller-efficiency charts that cover the same range of operating conditions as is covered in the loudness charts of reference 3. It is believed that references 3 and 14 will aid the designer in choosing the optimum propeller, both from a loudness and an efficiency standpoint.

Figure 14, taken from reference 14, is a sample of the efficiency charts. It shows the breakdown of losses of a propeller. The optimum efficiency of frictionless propellers is given by η_{opt} for two, four, and eight blades. As discussed in the previous section, it may be seen that the optimum efficiency decreases with decreasing rpm and that for a given rpm the greater the number of blades the higher the optimum efficiency. The solid lines give the net efficiency for the propeller, taking into account the skin friction or section drag. The loss of propeller efficiency due to section drag depends on the section lift/drag ratio and on the angle of attack of the section. Such efficiency loss is a minimum when the sections operate at helix angle of 45° and at maximum lift/drag ratio. In the calculations for figure 13 it is assumed that the propellers have the optimum pitch distribution for each speed and that the propellers have a solidity of 0.0345 per blade at the 0.7R. Thus a four-blade propeller has twice the solidity of a two-blade propeller. It can be seen that each propeller has a maximum efficiency over a limited range of rotational speeds. If the rotational speed is too high, the

losses are excessive because of skin friction losses; if the rpm is too low, the sections must operate at a high lift coefficient at high drag near the stall. In figure 13 all the propellers have about the same maximum efficiency. It is seen that a two-blade propeller operating at 1500 rpm can be replaced by eight blades operating at 700 rpm without loss of efficiency.

DISCUSSION OF STRUCTURAL FACTORS

Weight

The blade weight and area of a propeller having homogeneous blades are given by the following relations

$$\text{Weight} = K_1 BRtc\gamma \tag{2}$$

$$\text{Area} = K_2 BRc \tag{3}$$

where B is the number of blades, R the radius, t the thickness, c the chord, and γ the density of the material. K_1, K_2, . . . are constants depending on the geometry of the blades.

The above equations may be combined to give the following relations

$$\text{Weight} = K_3 \frac{t}{c} \frac{S^2}{BR} \gamma \tag{4}$$

$$\frac{\text{Weight}}{\text{Area}} = K_4 t\gamma = K_4 \frac{t}{c} c \tag{5}$$

where S is the total blade area of the propeller. Equation 4 shows that the weight of a propeller varies as the square of the blade area and inversely as the number of blades. Thus a propeller having a given thickness ratio, area, and radius will have less weight as the number of blades is increased. Equation 5 shows that the weight to area ratio is more favorable as the thickness of the blades is decreased or for a constant thickness ratio as the chord is decreased. One of the factors that determines the minimum thickness and chord is discussed in the next section.

Flutter

Considerable work has been done at the Langley Laboratory of the NACA on flutter of wind-tunnel drive fans. This work is reported in references 15 and 16. The results of these investigations are also

applicable to propellers. The following equation taken from reference 16 gives the divergence speed of propellers, which is approximately equal to the maximum flutter speed. (Because of centrifugal force effects, the effective elastic axis coincides with the section center of gravity.)

$$V_f = K_5 \frac{c}{R}\sqrt{\left(\frac{t}{c}\right)^3 \frac{G}{\rho\left(x_{cg} - \frac{1}{4}\right)}} \tag{6}$$

where

V_f speed at flutter

G shear modulus of material

ρ density of air

x_{cg} position of section center of gravity

K_5 constant depending on taper, etc.

Propellers operating in the stalled condition have a flutter speed much lower than the maximum flutter speed. For a given class of propellers, the minimum stall flutter speed is a fixed fraction of the maximum flutter speed; hence, the above equation is useful for comparing the flutter characteristics of propellers and discussing the flutter parameters.

In the previous section it was shown that by holding t/c constant the weight to area ratio could be reduced by decreasing the chord of the blade. From the above equation it may be seen that decreasing c, holding R and t/c constant, reduces the flutter speed in direct proportion to the chord. Thus, increasing the number of blades (to obtain a more favorable weight to area ratio) results in a lower flutter speed.

It was shown in the aerodynamic discussion that reducing the tip speed by one-half required a propeller of four times the area. Using the same blades but increasing the number of blades by a factor of four results in a propeller that is four times as heavy as the original propeller. This new propeller has twice the necessary flutter margin since the new propeller is operating at half speed with the same blades as were used in the original propeller. Some reduction in weight can be achieved which will give both propellers the same margin of flutter safety.

The following table shows how changing the parameters affects the weight. In each of the five propellers considered below the new propeller is assumed to have one-half the flutter speed and four times the area of the original. All numbers in the table give the ratio of the parameters of the new propeller compared to the original.

Line	Chord c	Radius R	Blades B	Thickness t	t/c	Shear modulus G	Weight
1	4	1	1	1	1/4	1	4
2	1/2	1	8	1/2	1	1	2
3	1	2	2	1	1	1	4
4	1	1	4	0.63	0.63	1	2.5
5	1	1	4	1	1	[a]1/4	1

[a]It is assumed that the density of the material varies directly as the shear modulus G.

An inspection of the above table shows that the flutter conditions are satisfied by merely increasing the chord by a factor of four (line 1), but this increases the weight by a factor of four and also gives a very thin airfoil section thickness ratio. The best weight ratio for a given material is obtained in line 2 for a propeller having $\frac{1}{2}$-blade chord and eight times the number of blades. Line 5 shows that if a lighter material is used having a density and shear modulus of one-fourth, the new propeller will have four times the number of blades but the same weight as the original propeller. This approach to the problem appears to have the greatest promise. It is believed that the designer may take advantage of the low centrifugal stresses to use new materials or fabricated blades in such a manner that there will be no weight penalty involved in the use of slow rotating quiet propellers.

An examination of equation 6 shows that if the blade-section center of gravity is located at the quarter-chord point the flutter speed becomes infinite. It is shown in reference 15 that to prevent twisting of the blade due to the aerodynamic moment an airfoil section having zero moment coefficient about quarter chord must be used if the center of gravity is at quarter-chord point. Such sections may not be desirable for propellers. Helicopter designers have obtained freedom from flutter by using such sections with the center of gravity at quarter chord, both in the main and tail rotors. Whether such techniques can be used to advantage for propellers has not been determined.

Vibration

Vibratory stresses have not been an important factor in the design of small wooden propellers of fixed pitch. In fact, one of the most successful wooden propellers in use today has the first bending frequency near the firing frequency of the engine in the take-off condition. Vibratory stresses may become dangerous in the high-pitched quiet propellers discussed in this paper. One of the propellers built by the NACA passed the electric whirl tests and also performed satisfactorily on the engine at low pitch. When the propeller pitch was increased to 30° the propeller vibrated badly with tip amplitude up to 3 inches. Strain gages on the blades showed that the blades were excited by the first firing order of the engine. Another engine having a higher gear ratio and more torsional dampers was substituted. This eliminated the vibration trouble on this propeller.

Such problems are not new but have been encountered on many high-performance designs. All the techniques which have been used to check the stresses on high-performance propellers should be used in the design of quiet propellers.

CONCLUDING REMARKS

Propeller performance and weight considerations have been the main factors affecting the design of propellers in the past. It now becomes important to consider the propeller sound as an important factor in the design. Fortunately, there is no essential conflict between the performance and sound requirements. The main problems are (1) to obtain a satisfactory geared engine, and (2) reduce the weight of the propeller. What the weight of silent propellers will be cannot be foretold. This depends on the ingenuity of industrial designers and researchers. It is believed that by use of new processes, high-speed geared engines, etc., the future quiet airplane will equal the performance of and have as light propulsive units as present-day aircraft.

The present paper has outlined some of the factors which must be considered in the design of a quiet propeller. It is believed that the noise problem will not be eliminated until the rotational noise level is reduced below the vortex level of the propeller. This will require a reduction of the rotational speed to about one-half of that of present-day propellers.

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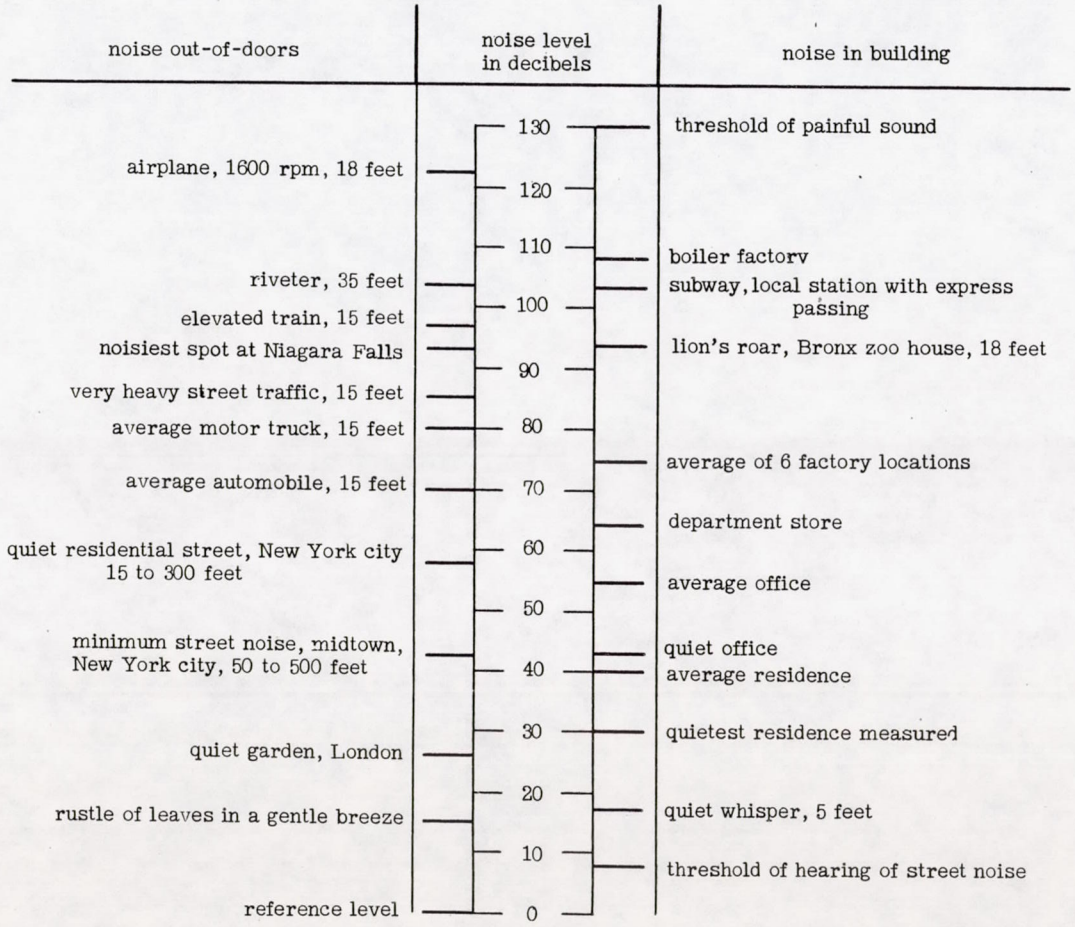

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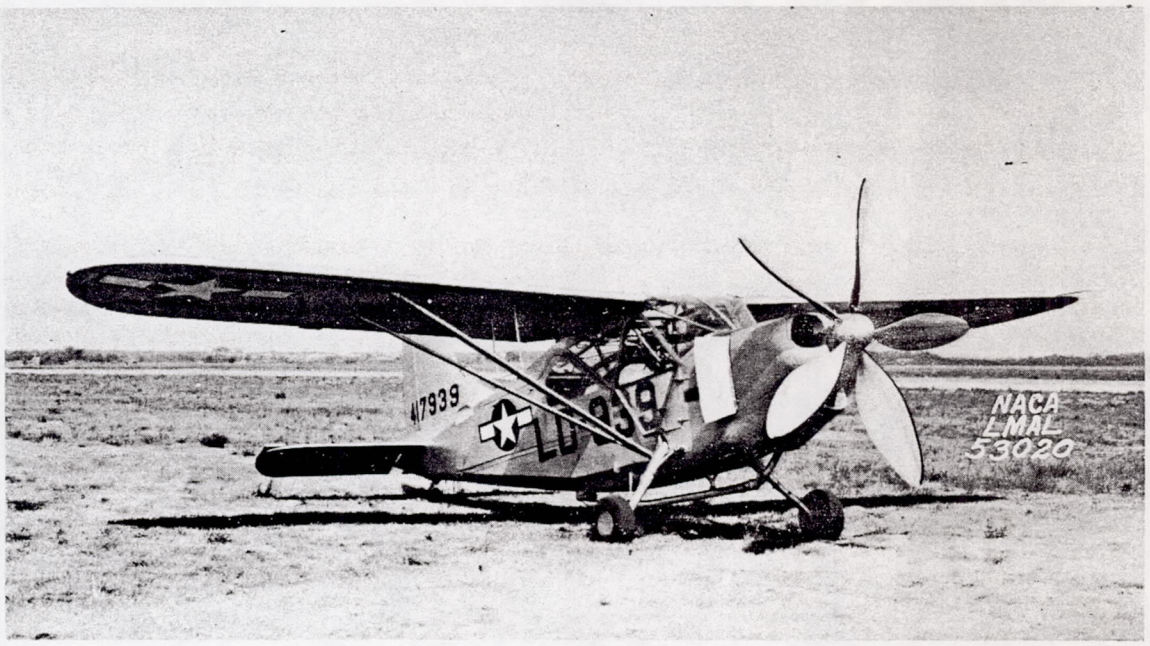

Figure 1.- Stinson L-5 airplane with five-blade 96-inch propeller, 185 horsepower at 1000 rpm.

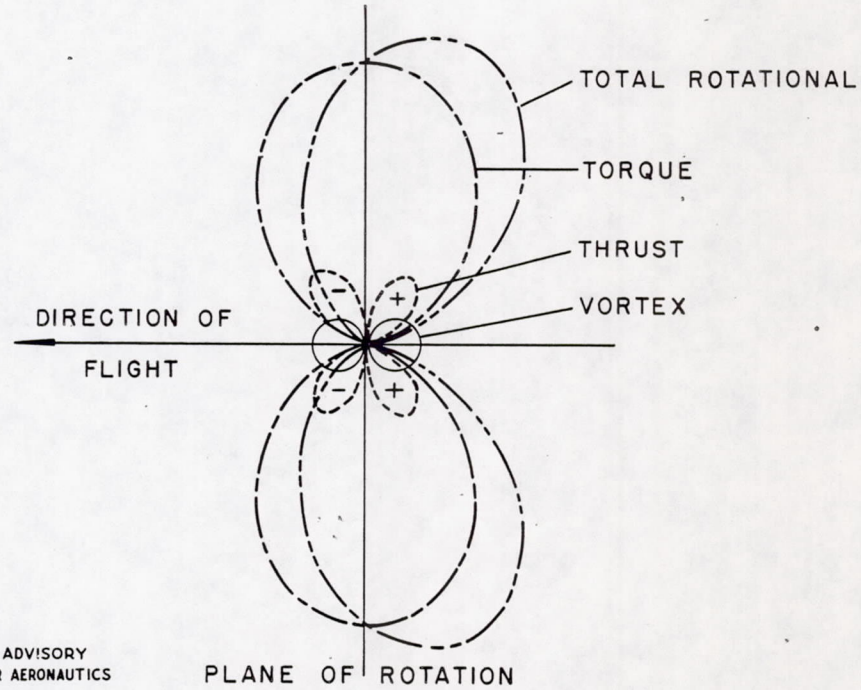

Figure 2.- Calculated sound pressures of first harmonic from two-blade propeller in forward flight. D = 6 feet; M_t = 0.57; P_H = 150 horsepower; V = 150 miles per hour. (From reference 2.)

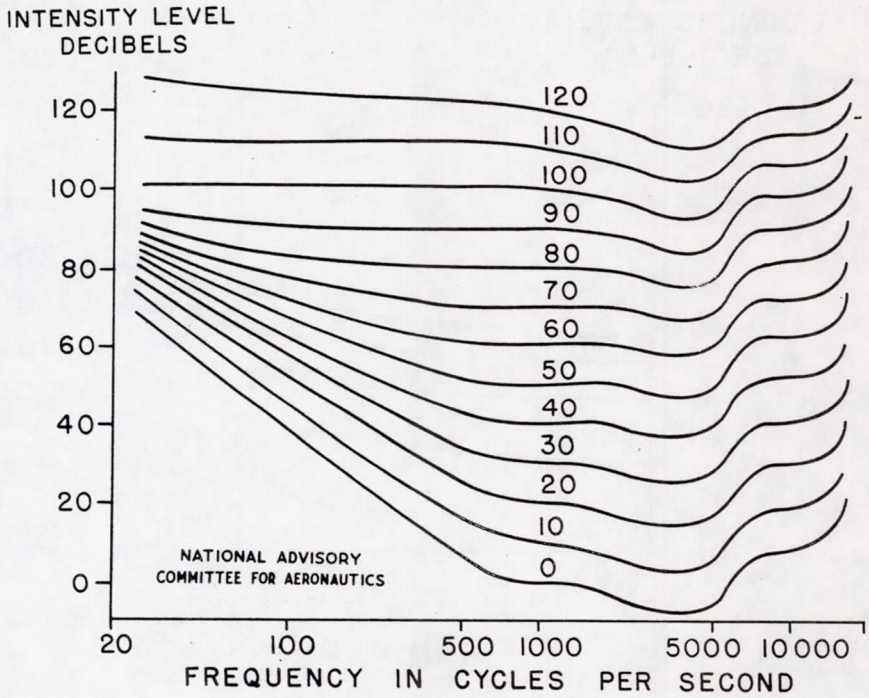

Figure 3.- Loudness level contours. (From reference 8.)

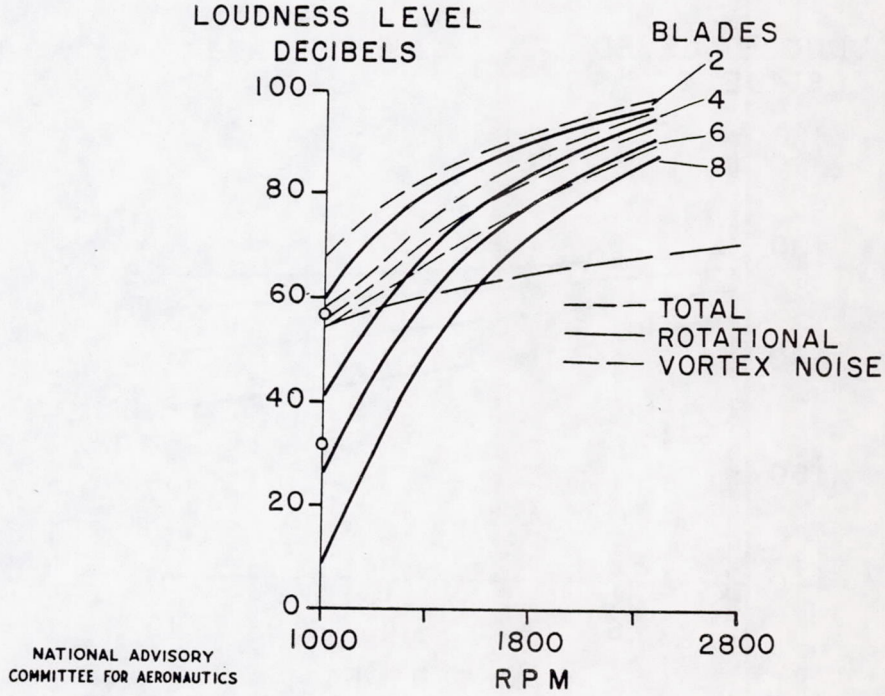

Figure 4.- Loudness as a function of rotational speed for various numbers of blades. D = 8 feet; V = 100 miles per hour; P_H = 150 horsepower. (From reference 2.)

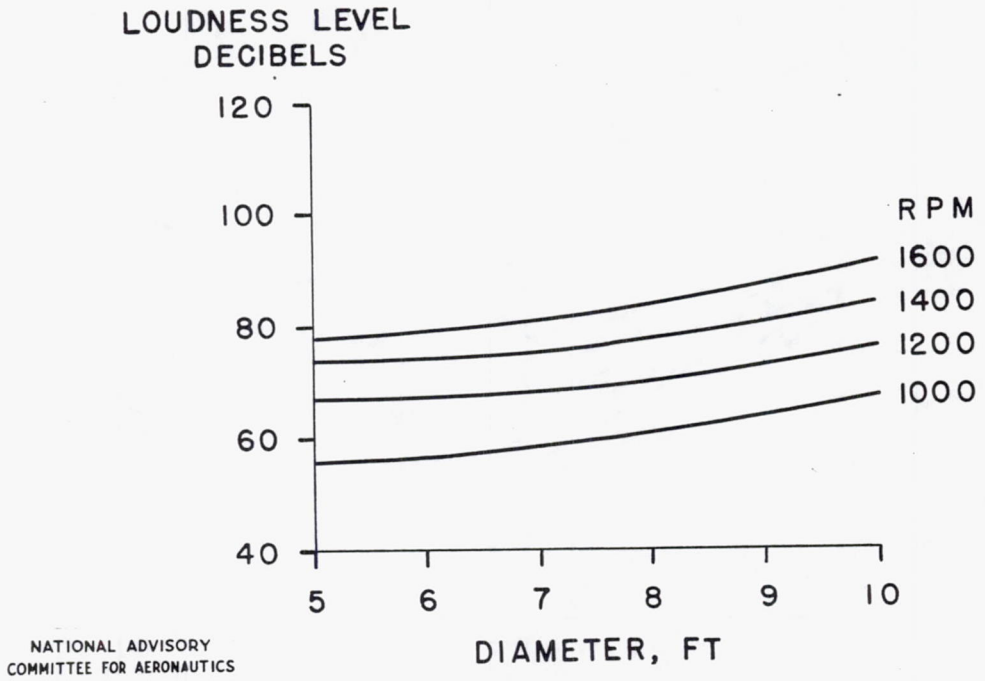

Figure 5.- Effect of diameter at constant rotational speed N on propeller loudness. V = 50 miles per hour; P_H = 100 horsepower; S = 300 feet; B = 2. (From reference 2.)

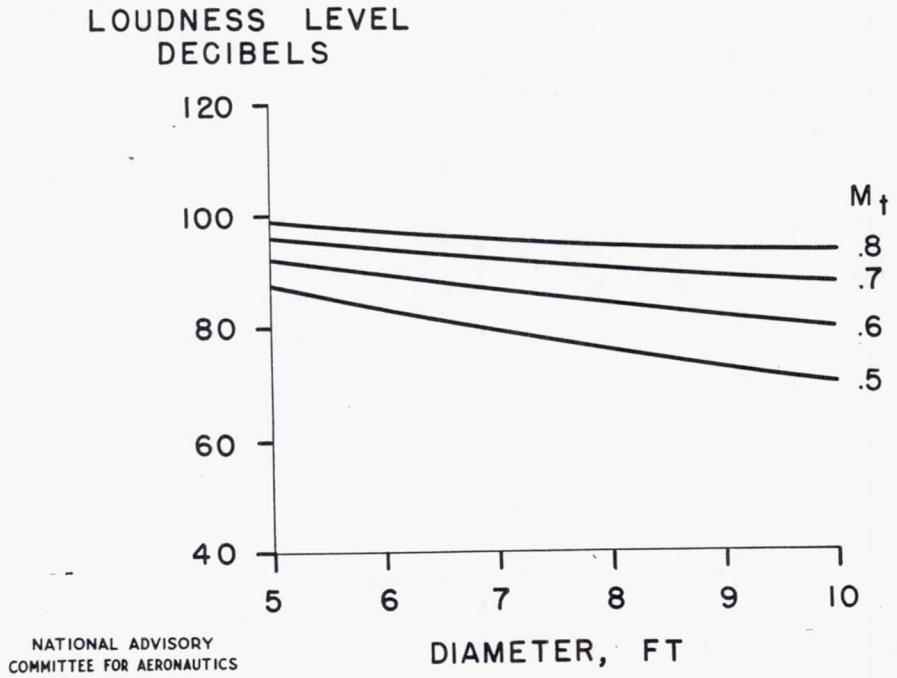

Figure 6.- Effect of diameter at constant tip Mach number on propeller loudness. V = 50 miles per hour; P_H = 100 horsepower; S = 300 feet. (From reference 2.)

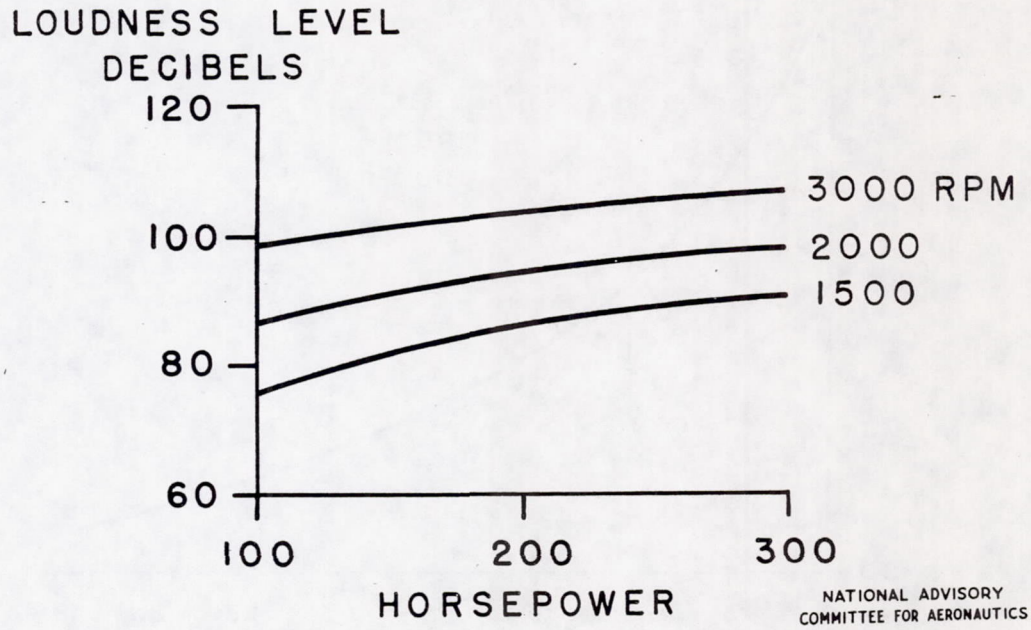

Figure 7.- Effect of power absorbed on propeller loudness. V = 50 miles per hour; D = 6 feet; B = 2 blades; S = 300 feet. (From reference 2.)

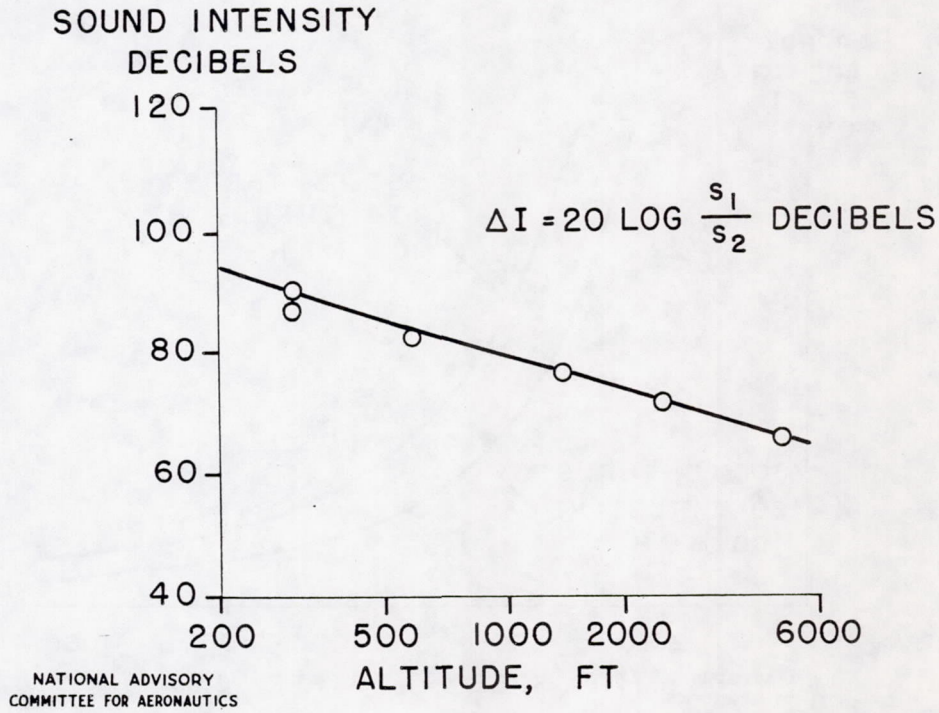

Figure 8.- Sound pressure levels as a function of altitude of trainer airplane (AT-6). V = 164 miles per hour; P_H = 400 horsepower; N = 2000 rpm; relative humidity, 40 percent; temperature, 72° F. (From reference 3.)

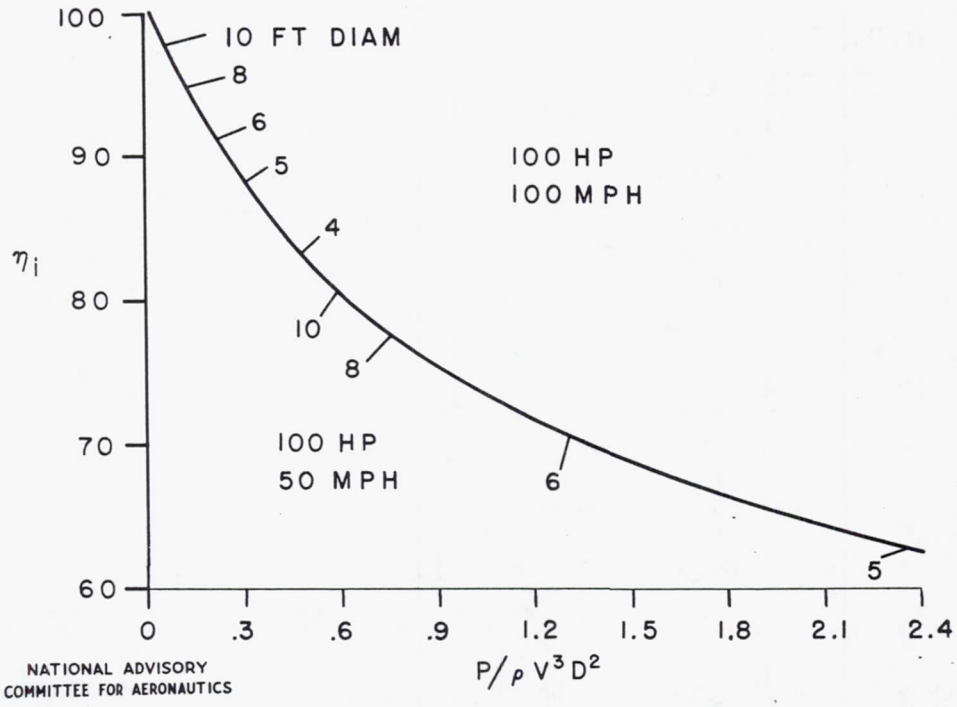

Figure 9.- Ideal efficiency as a function of power coefficient. (From reference 9.)

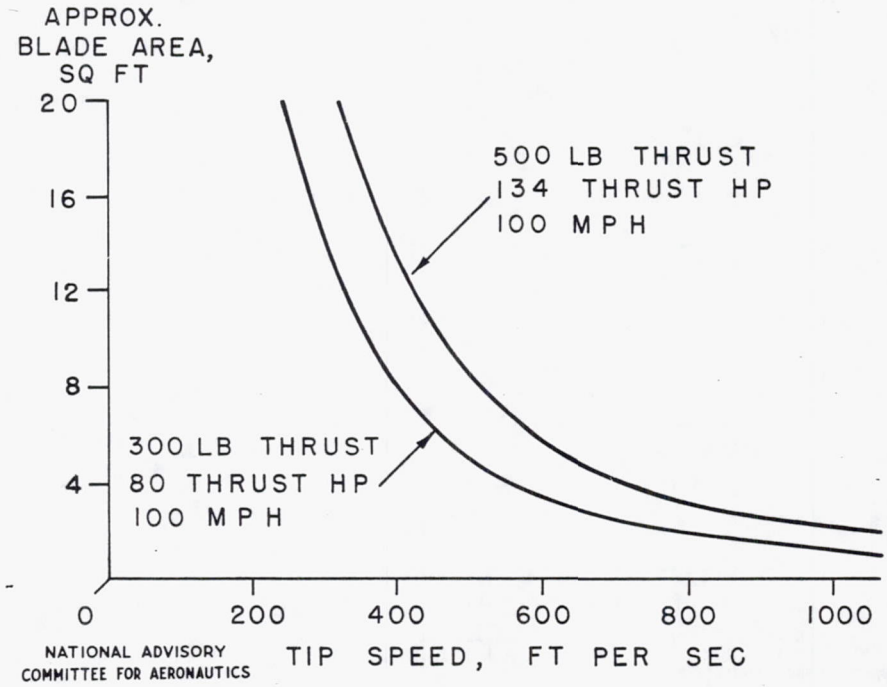

Figure 10.- Approximate blade area as a function of tip speed.

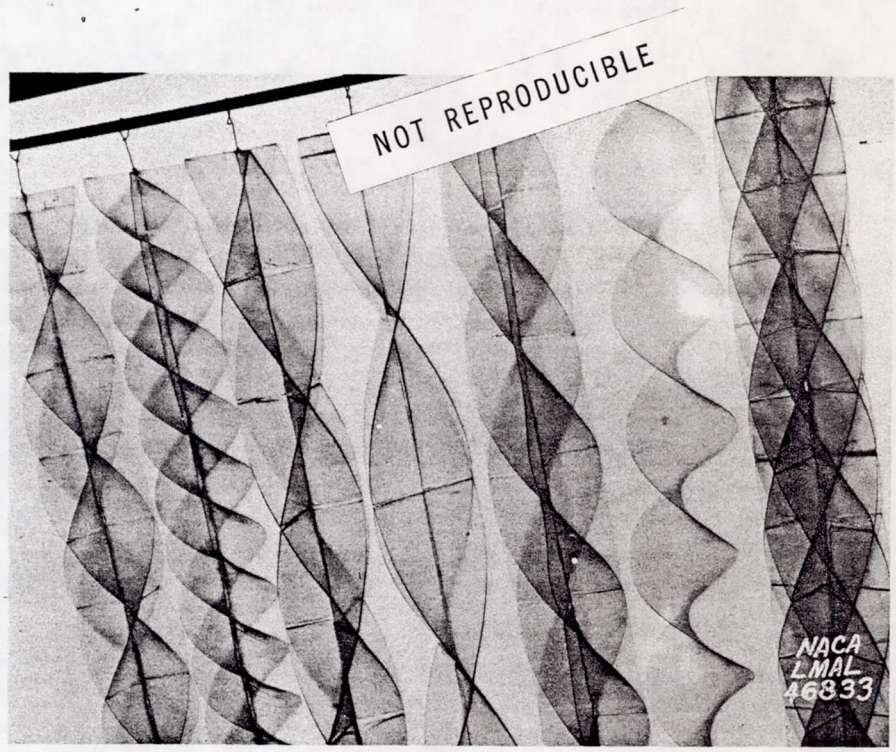

Figure 11.- Propeller wake models.

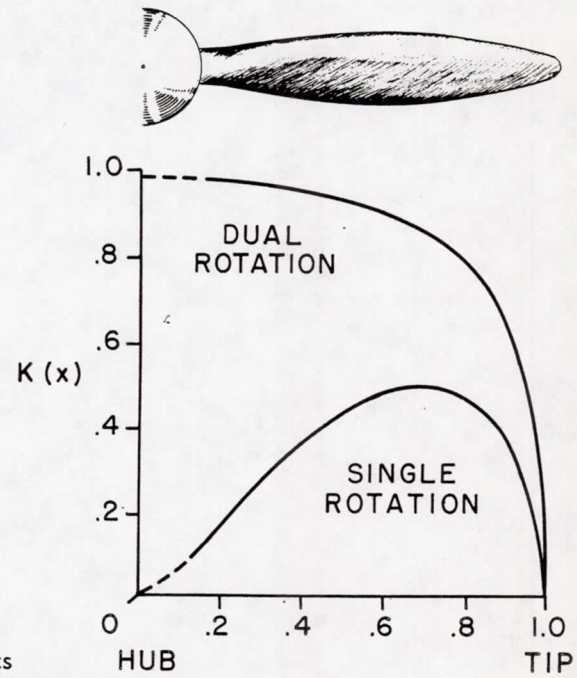

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Figure 12.- Circulation function for four-blade propeller. $\frac{V + w}{nD} = 1.55$. (From reference 11.)

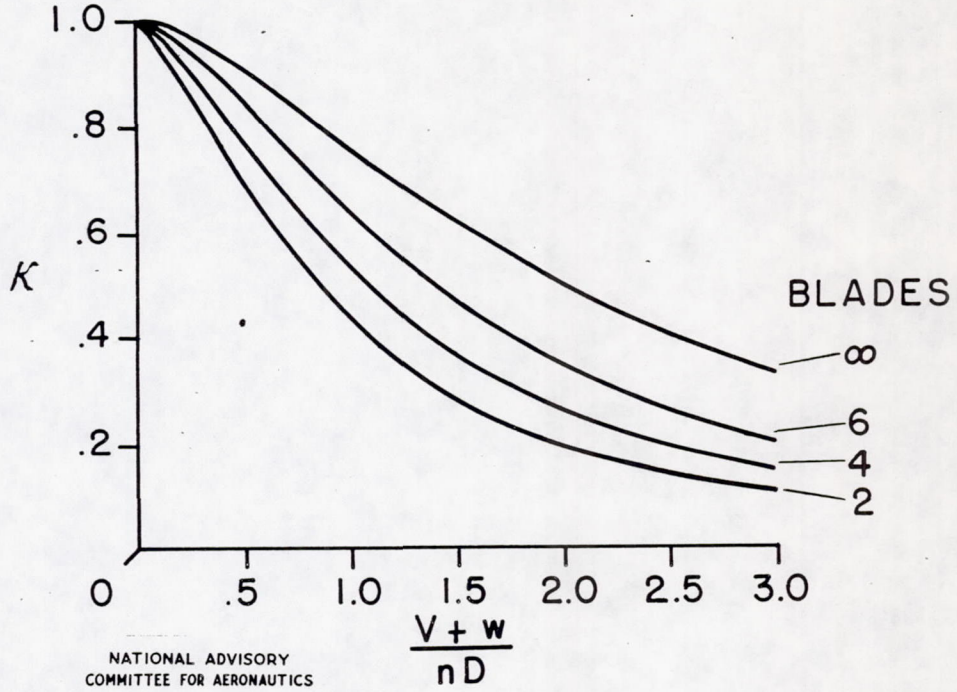

Figure 13.- Mass coefficient for propeller. (From reference 11.)

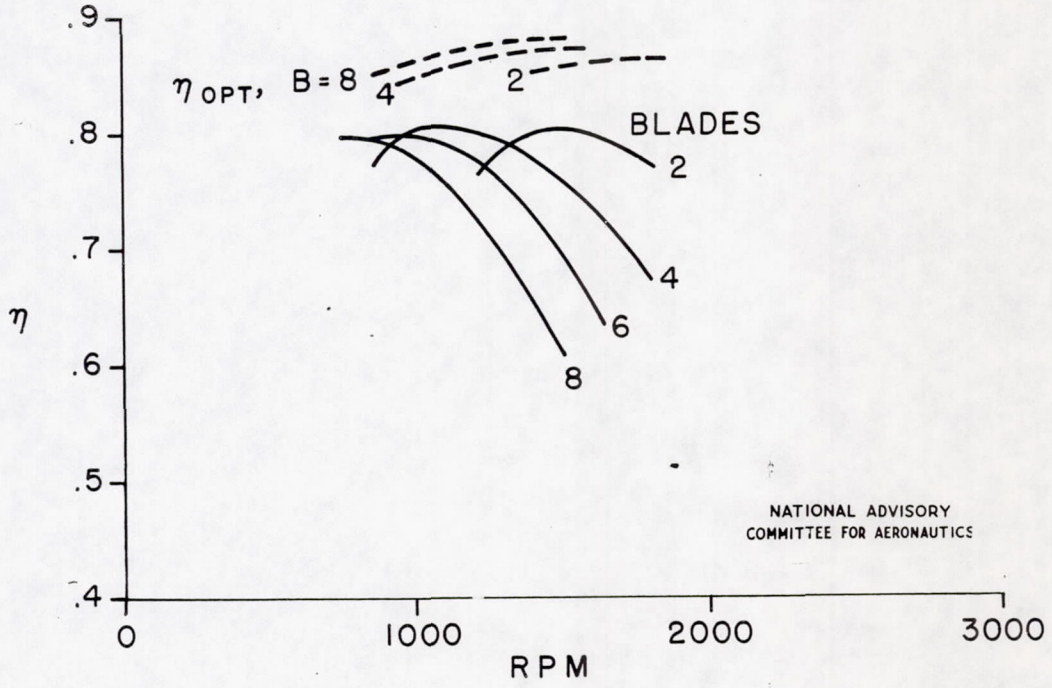

Figure 14.- Propeller efficiency. V = 100 miles per hour; P_H = 300 horsepower; D = 10 feet; $\sigma_{0.7R}$ = 0.0345 B. (From reference 14.)