TECHNICAL NOTE

D-382

EFFECT OF BLADE CUTOUT ON POWER REQUIRED BY HELICOPTERS OPERATING AT HIGH TIP-SPEED RATIOS

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SUMMARY

A numerical study was made of the effects of blade cutout on the power required by a sample helicopter rotor traveling at tip-speed ratios of 0.3, 0.4, and 0.5. The amount of cutout varied from 0 to 0.5 of the rotor radius and the calculations were carried out for a thrust-coefficient—solidity ratio of 0.04. In these calculations the blade within the cutout radius was assumed to have zero chord.

The effect of such cutout on profile-drag power ranged from almost no effect at a tip-speed ratio of 0.3 to as much as a 60-percent reduction at a tip-speed ratio of 0.5. Optimum cutout was about 0.3 of the rotor radius. Part of the large power reduction at a tip-speed ratio of 0.5 resulted from a reduction in tip-region stall, brought about by cutout. For tip-speed ratios greater than 0.3, cutout also effected a significant increase in the ability of the rotor to overcome helicopter parasite drag. It is thus seen that the adverse trends (at high tip-speed ratios) indicated by the uniform-chord theoretical charts are caused in large measure by the center portion of the rotor.

The extent to which a modified-design rotor can actually be made more efficient at high speeds than a uniform-chord rotor will depend in practice on the degree of success in minimizing the blade plan form near the center and on special modifications in center-section profiles. A few suggestions and estimates in regard to such modifications are included herein.

INTRODUCTION

The extension of top speeds for conventional-configuration helicopters to the neighborhood of 200 knots involves operation at tip-speed ratios in the vicinity of 0.4 to 0.5. At these tip-speed ratios, rotor performance charts, such as those of reference 1, indicate a marked increase in rotor profile power absorbed as compared with operation at more moderate values of tip-speed ratio, even when stall and compressibility losses are absent. Additionally, the ability of the rotor to provide the propulsive thrust required to overcome parasite drag, expressed, for example, by the power parameter $\frac{C_P - C_{P,o}}{\sigma}$ (where C_P represents total power; $C_{P,o}$, profile power; and σ, rotor solidity), is greatly reduced.

A primary source of large profile-power loss at the high tip-speed ratios is the contribution of the inner part of the retreating side of the rotor. In and near the reversed-velocity region, the highly stalled, trailing-edge-first airfoil sections are at high negative angles of attack and suffer high profile drag and produce negative thrust when the rotor is in its normal nosedown attitude. An obvious way of reducing these losses is by blade cutout, that is, by removing the airfoil sections from the inner part of the blade, leaving only a small-chord spar. Although most rotors are designed, for mechanical reasons, with small amounts of cutout (about 0.1 of the radius), it was considered worthwhile to examine the aerodynamic effects of larger amounts of cutout. The study was made for a representative rotor with varying amounts of cutout by numerical-calculating methods and the results are reported herein. In order to provide a basis for interpolation, the chord was assumed to be entirely removed in the cutout region.

SYMBOLS

b — number of blades per rotor

C_P — rotor-shaft power coefficient, $\frac{P}{\pi R^2 \rho (\Omega R)^3}$

C_T — rotor thrust coefficient, $\frac{T}{\pi R^2 \rho (\Omega R)^2}$

c — blade-section chord, ft

c_e — equivalent blade chord (on thrust basis), $\frac{\int_0^R cr^2 dr}{\int_0^R r^2 dr}$, ft

c_l — blade-section lift coefficient

$c_{d,o}$ blade-section profile-drag coefficient

I_h mass moment of inertia of blade about flapping hinge, slug-ft^2

P rotor-shaft power, ft-lb/sec

R rotor radius measured from center of rotation, ft

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r radial distance from center of rotation to blade element, ft

T component of rotor resultant force along axis of no feathering in longitudinal plane of symmetry, lb

V true airspeed of helicopter along flight path, fps

v induced velocity at rotor (always positive), fps

x nondimensional radius, r/R

x_c nondimensional radius of cutout

α rotor angle of attack; angle between flight path and plane perpendicular to axis of no feathering, positive when axis is pointing rearward, deg

α_r blade-element angle of attack, measured from line of zero lift, deg (when used in three-term drag polar in fig. 1(b), α_r is expressed in radians)

$\alpha_{(1.0)(270^\circ)}$ blade-element angle of attack at tip of blade at 270° azimuth position, measured from line of zero lift, deg

γ' mass constant of rotor blade, $\dfrac{c_e \rho R^4}{I_h}$

$\theta_{.75}$ blade-section pitch angle at 0.75 radius; angle between line of zero lift of blade section and plane perpendicular to axis of no feathering, deg

λ inflow ratio, $\dfrac{V \sin \alpha - v}{\Omega R}$

μ tip-speed ratio, $\frac{V \cos \alpha}{\Omega R}$

ρ mass density of air, slugs/cu ft

σ rotor solidity, $\frac{bc_e}{\pi R}$

ψ blade azimuth angle measured from downwind position in direction of rotation, deg

Ω rotor angular velocity, radians/sec

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Subscript:

o profile

ANALYSIS AND SAMPLE ROTOR

Rotor profile-drag and total power required were calculated for a sample rotor with varying amounts of cutout by means of an IBM 704 electronic data processing machine which was programed according to the equations and procedures described in reference 2.

The calculations were made for the flight conditions listed in the following table:

μ	λ	$\theta_{.75}$, deg, for -						C_T/σ	α, deg (for σ = 0.08)
		x_c = 0	x_c = 0.1	x_c = 0.2	x_c = 0.3	x_c = 0.4	x_c = 0.5		
0.3	-0.06	6.77	6.71	6.75	6.85	7.00	7.27	0.04	-10.4
.4	-.12	10.56	10.48	10.43	10.48	10.57	10.80	.04	-16.2
.5	-.24	18.15	17.77	17.50	17.35	17.36	17.50	.04	-25.4

Thus, at each value of μ, the effects of cutout could be studied at a constant thrust-coefficient—solidity ratio and a rotor angle of attack representative of level flight at that tip-speed ratio. $\left(\text{A value of } \frac{C_T}{\sigma} = 0.04\right.$ is considered reasonable for a high-speed helicopter.$\left.\right)$ Because λ and C_T/σ were kept constant for each value of μ, the effects of cutout could be studied at constant values of rotor angle of attack.

The sample rotor was assumed to have untapered blades that incorporate -8° twist, a mass factor of $\gamma' = 2.62$, and flapping hinges located on the rotor center line. Blade cutout was varied from 0 to 0.5 of the rotor radius in increments of 0.1. The blade-section lift and drag characteristics used are given in figure 1 as a function of angle of attack. Although the airfoil data account for stall, no effects of Mach number are considered in the calculations.

Because of the wide variations possible and in order to provide a basis for interpolation, the spar is assumed to be nonexistent over the cutout radius in the basic treatment provided.

RESULTS AND DISCUSSION

Source of Gains With Center Section Cutout

In order to illustrate the potential gains that could be realized by cutting out the inner portion of the rotor, spanwise thrust and profile-power distributions at $\psi = 270^{\circ}$ are given in figure 2 for $\mu = 0.3$, 0.4, and 0.5. The plots show the extensive regions of high negative thrust and of high profile-drag power that exist over the inner part of the rotor at the two higher tip-speed ratios. This region can be minimized in significance by cutout and the proper fairing of the remaining structural member; the practical aspects will be discussed later in this paper.

Effect of Cutout on Power

Effect on coefficients.- The results of the calculations of power required are shown in figure 3 for each of the three values of μ studied. In addition to the separate variations of C_P/σ and $C_{P,o}/\sigma$ with x_c, the variation of the "useful" or "propulsive" power parameter $\frac{C_P - C_{P,o}}{\sigma}$ is shown.

It can be seen from figure 3 that the effect of cutout is almost negligible at $\mu = 0.3$, but that an appreciable reduction in profile-drag power is obtained at $\mu = 0.4$ and considerably more at $\mu = 0.5$. The reductions are about 40 percent at $\mu = 0.4$ and 60 percent at $\mu = 0.5$, and are practically all obtained when the cutout reaches about

0.3 of rotor radius. It can be seen from the table presented in the preceding section that approximately this amount of cutout results in the minimum pitch angle required to produce the fixed value $\frac{C_T}{\sigma} = 0.04$ at $\mu = 0.4$ and 0.5. At these higher tip-speed ratios, it appears, from the variation of pitch angle required to keep thrust constant as x_c is increased, that $x_c = 0.3$ is the cutout value at which the thrust gain resulting from omitting the negative-thrust region on the retreating side of the rotor disk is offset by the loss of positive thrust in the cutout region on the advancing side.

The decrease in profile power, though important, may not be as significant as the increase in propulsive power $\frac{C_P - C_{P,o}}{\sigma}$ shown in figures 3(b) and 3(c). If $\frac{C_P - C_{P,o}}{\sigma}$ is not large enough to overcome the parasite-drag losses of the helicopter, helicopter flight is not possible without the use of an auxiliary propulsion source, regardless of the amount of power available to the rotor.

Effect on sample design.- As an example, consider the parasite-drag area that can be overcome in level flight by the sample rotor, assuming it to have a solidity of 0.08 and a radius of 28 feet. Calculations based on the values of $\frac{C_P - C_{P,o}}{\sigma}$ in figure 3 and the equations of reference 3 indicate that the rotor with $x_c = 0$ could overcome 8.3 square feet of parasite-drag area at $\mu = 0.4$, and with $x_c = 0.3$ could overcome 13.1 square feet. At $\mu = 0.5$, only 3.0 square feet of parasite-drag area could be overcome at $x_c = 0$, as compared with 9.7 square feet at $x_c = 0.3$.

If the sample rotor is assumed to operate at a tip speed of 720 ft/sec, the power requirements may be expressed in dimensional terms. For these conditions the gross weight is approximately 10,000 pounds and the dimensional quantities are shown in the following table:

Tip-speed ratio, μ	Cutout, percent rotor radius	Airspeed, V, knots	Total power, hp	Profile power, hp	Propulsive force, lb	Effects of cutout	
						Increase in propulsive force, lb	Decrease in profile power, hp
0.4	0	178	1,350	795	890		
.4	30	178	1,350	544	1,400	510	251
0.5	0	236	3,280	2,830	566		
.5	30	236	2,640	1,280	1,830	1,264	1,550

From the standpoint of the total power required, it is significant that the increase in propulsive force is achieved without an increase in total power at $\mu = 0.4$ and with a decrease in total power at $\mu = 0.5$. The decrease in horsepower at a given propulsive force would be considerably greater. Although these figures do not account for compressibility or spar losses, they do indicate that the power requirements of properly designed high-speed helicopters can be expected to be much lower and the ability to provide high propulsive forces much greater than might be inferred from sample studies (e.g., fig. 2 of ref. 3) which assume uniform chord without cutout.

Effect on blade stalling.- For flight conditions involving stall, there are additional beneficial secondary effects of cutout. As an indication of the amount of rotor stall existing for the cases studied, the angle of attack at the tip of the retreating blade $\alpha_{(1.0)(270^\circ)}$ is shown as a function of cutout in figure 4. No stall is present in the outer part of the rotor for the lower values of μ. For $\mu = 0.5$, stall is present and the figure shows that cutout substantially reduces the amount of this stall. Thus, in addition to reducing power losses in the inner part of the disk, cutout reduces power losses resulting from stall on the outer part of the disk.

Effect of Spar Drag

As mentioned earlier, there are wide variations possible in the drag of the spar that exists in the cutout portion of the blade. Such drag will, however, reduce the favorable effects of cutout shown in figure 3. As one indication of the order of magnitude of the power added by the spar, calculations were made at $\mu = 0.5$ for a spar extending from the center of rotation to 0.3 of the rotor radius, and having a chord equal to one-third of the chord outboard of the cutout section. By assuming a spar profile-drag coefficient of 0.2, the additional $C_{P,o}/\sigma$ due to the spar was calculated to be 0.0008. If this amount is added to the value of $C_{P,o}/\sigma$ shown for $x_c = 0.3$ in figure 3(c), 0.3 cutout effects a 46-percent, rather than a 55-percent, reduction in profile-drag power. Thus, even if the spar drag losses are several times the value calculated herein, the net gains to be obtained by cutout should still be substantial.

Any type of spar of fixed shape other than circular will also involve some fraction of the full-chord down load effects. The potential gains for unique spar shapes, fairings, or other arrangements are large enough, however, to warrant inventive effort in this direction. One suggestion of a possible approach is shown in figure 5. This approach involves an elliptical thickness distribution added to an S-curve mean line, with a discontinuity designed to cause separation and an effective change in camber while the spar is within the reversed-velocity region only. The possibilities of such an approach have not been experimentally assessed and it is offered only as an illustration of possible approaches.

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CONCLUDING REMARKS

The effects of 100-percent-chord blade cutout (ranging from 0 to 0.5 of the rotor radius) on the power requirements of a sample helicopter rotor were studied at tip-speed ratios of 0.3, 0.4, and 0.5. The sample rotor operated at a thrust-coefficient—solidity ratio of 0.04 and had untapered blades with -8° of twist. The calculations were made with section data that accounted for stall effects.

The effect on rotor profile-drag power of the amounts of cutout investigated varied with tip-speed ratio μ, ranging from almost no effect at $\mu = 0.3$ to as much as a 60-percent reduction at $\mu = 0.5$. A cutout value of about 0.3 of the rotor radius seemed optimum for the cases studied. Part of the reduction in power at $\mu = 0.5$ was attributed to the reduction in tip-region stall brought about by cutout. Also, the use of 0.3 cutout in rotors designed to operate at tip-speed ratios in excess of 0.3 increases the propulsive capabilities of the rotor and enables it to overcome higher values of parasite drag than with smaller cutouts.

Part of these favorable effects of cutout would be reduced by consideration of the profile-drag and down load of the structural spar in the cutout section. The potential gains indicated are large enough, however, to indicate the desirability of invention and development of practical means of minimizing center-section areas, section drag coefficients, and negative section lift coefficients.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., February 16, 1960.

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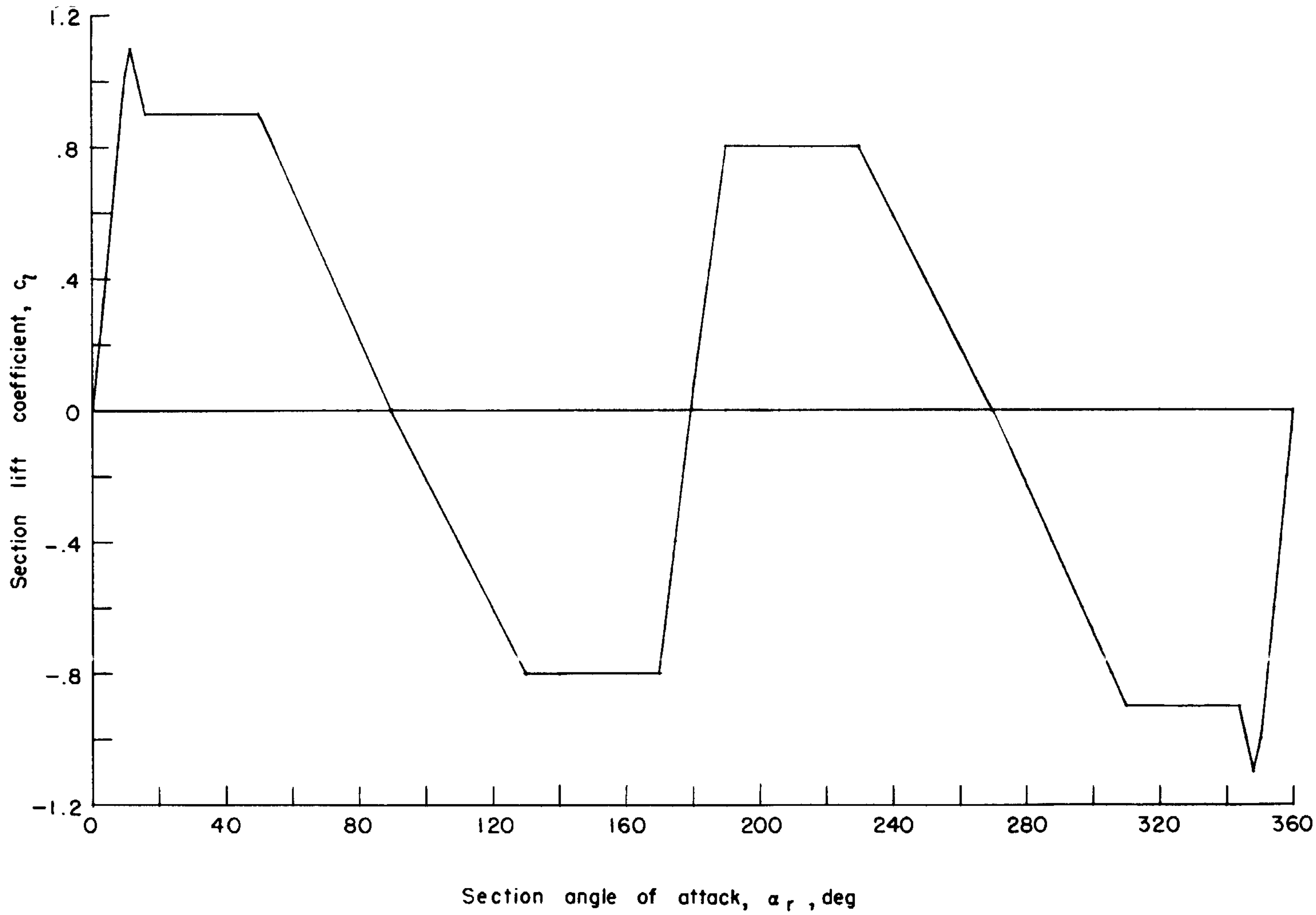
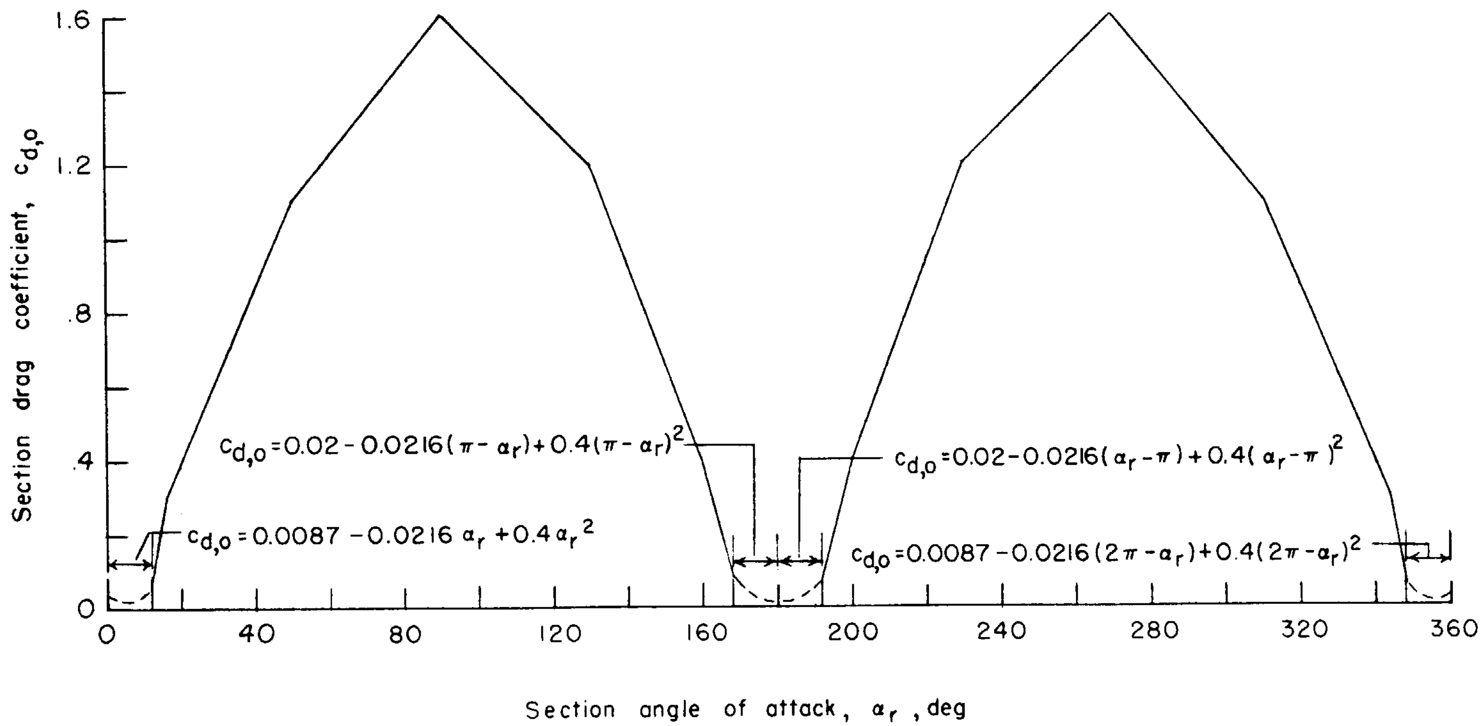
2. Gessow, Alfred: Equations and Procedures for Numerically Calculating the Aerodynamic Characteristics of Lifting Rotors. NACA TN 3747, 1956.

3. Gessow, Alfred: A Note on the Calculation of Helicopter Performance at High Tip-Speed Ratios. NASA TN D-97, 1959.



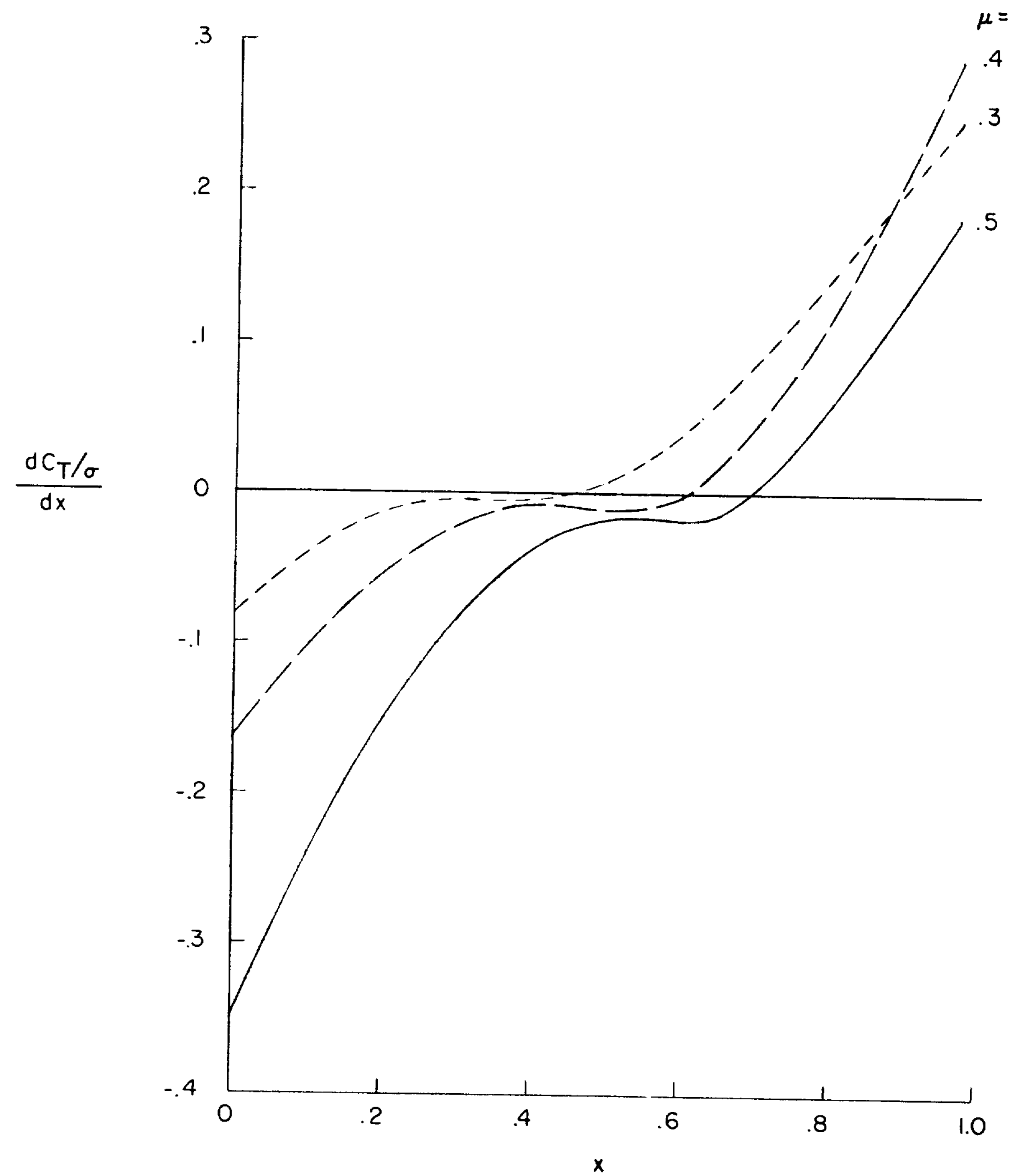
(a) C_l plotted against α_r.

Figure 1.- Section lift and drag coefficients used in sample calculations.



(b) $C_{d,o}$ plotted against α_r.

Figure 1.- Concluded.



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(a) Thrust.

Figure 2.- Thrust and profile-power distributions for sample blade. $\psi = 270^{\circ}$; $x_c = 0$; $C_T/\sigma = 0.04$.

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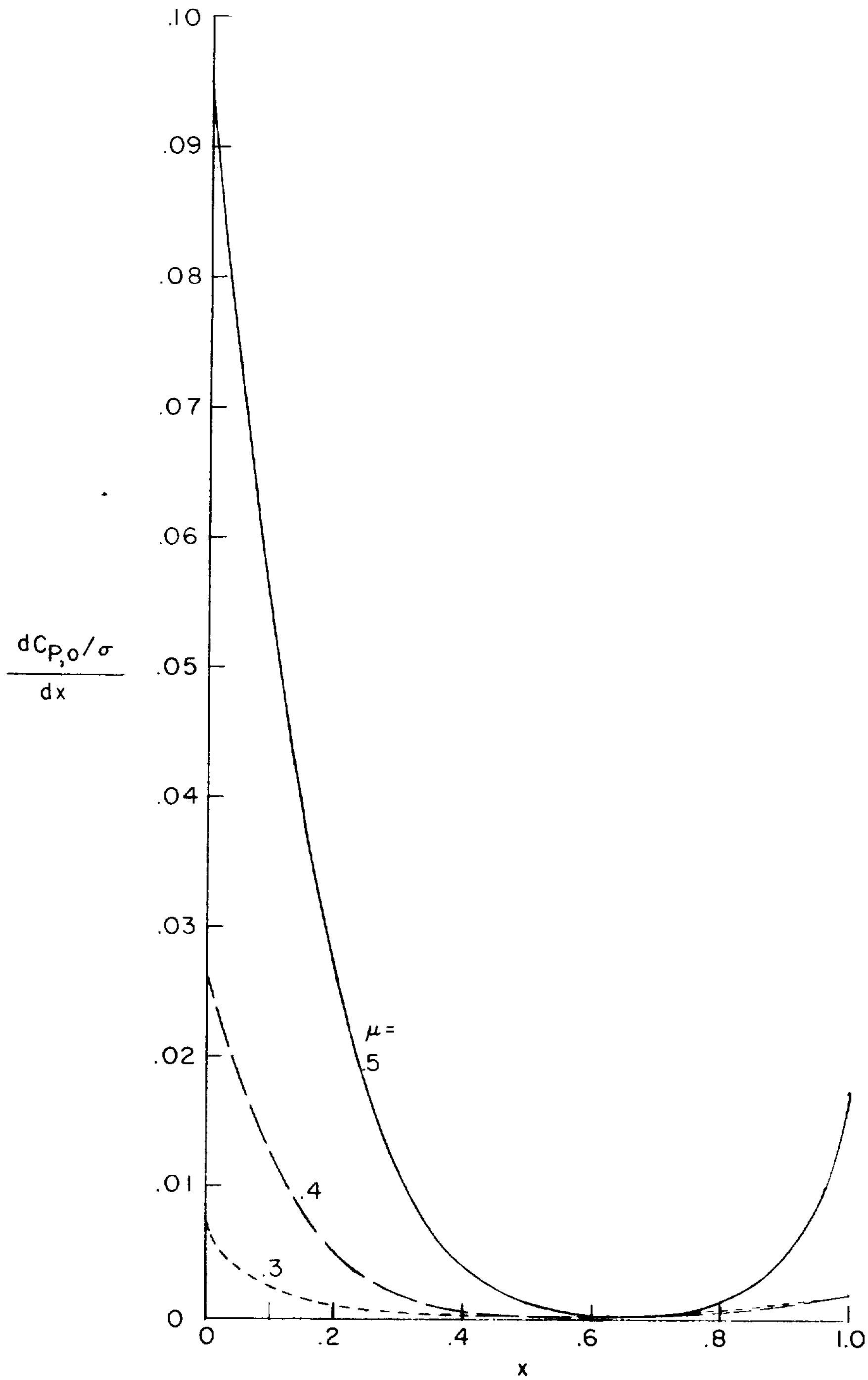
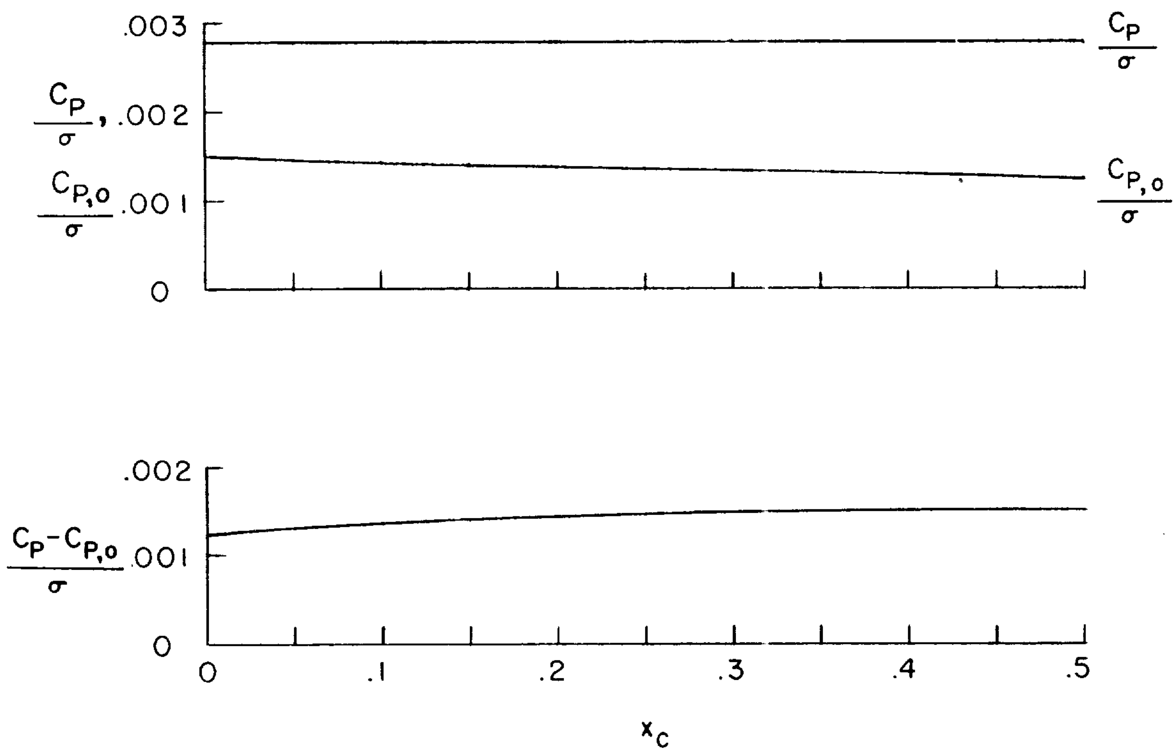


(b) Profile power.

Figure 2.- Concluded.



(a) $\mu = 0.3$.

Figure 3.- Effect of cutout on power required and on "propulsive" power of sample rotor.

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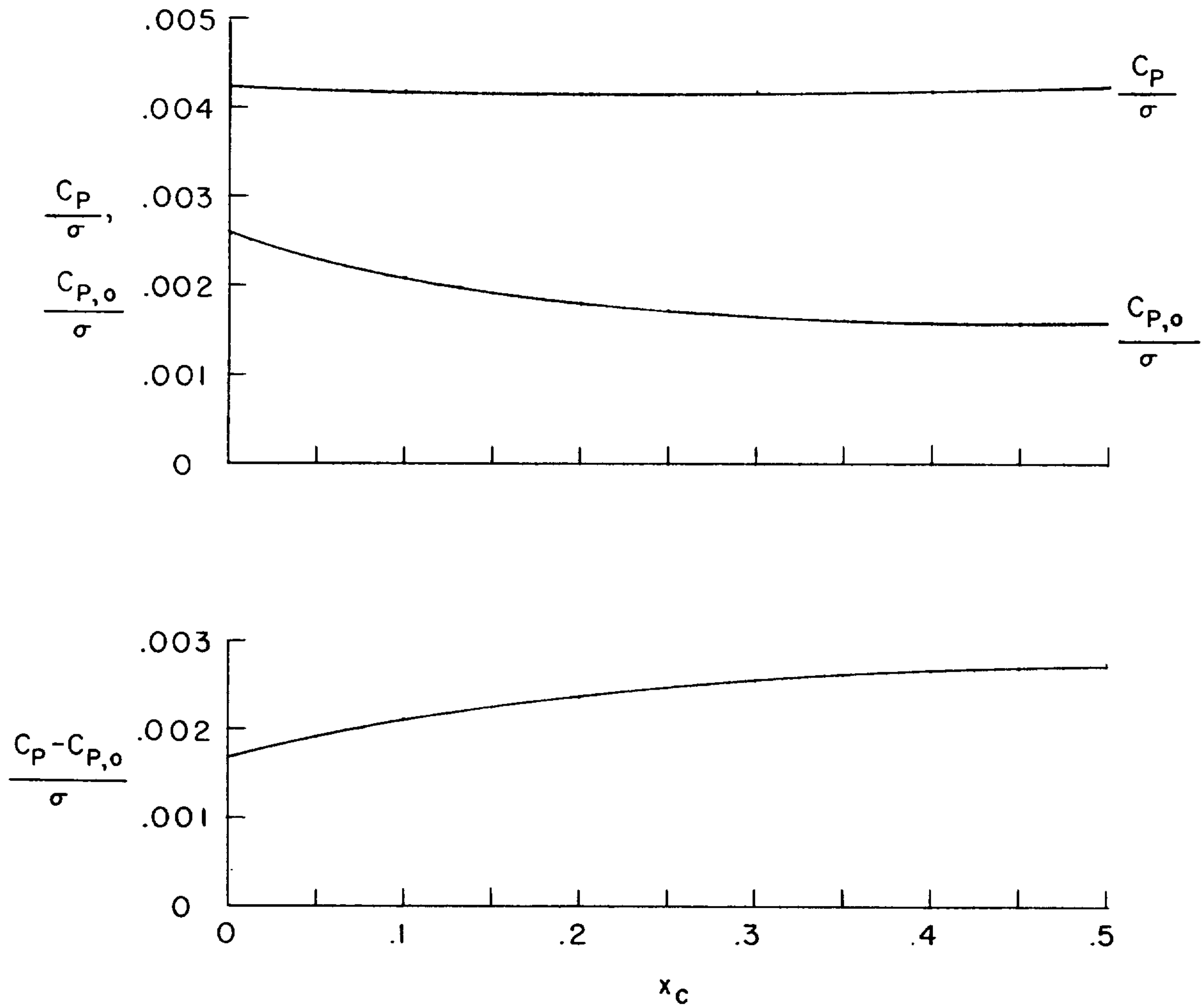
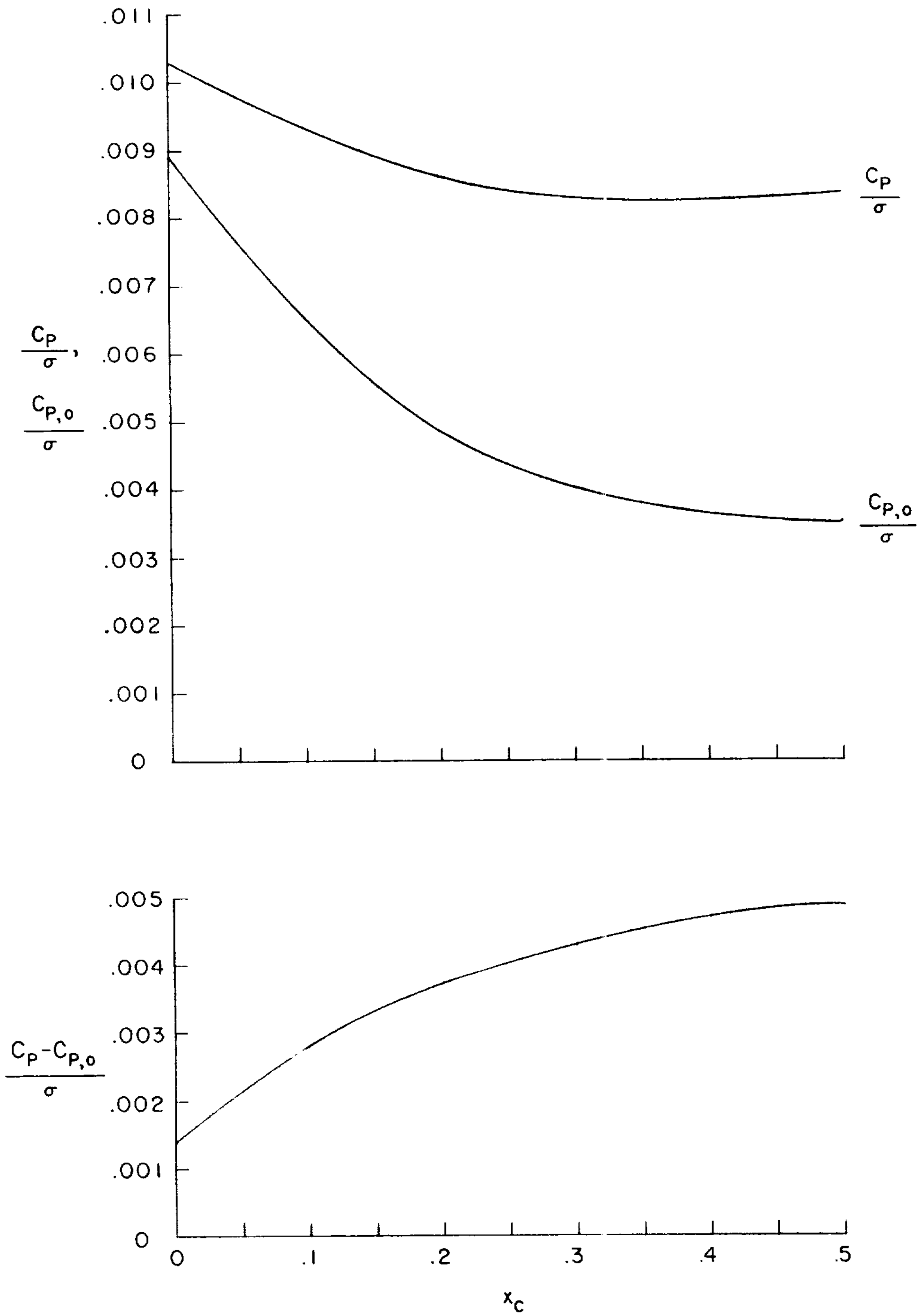


(b) $\mu = 0.4$.

Figure 3.- Continued.



(c) $\mu = 0.5$.

Figure 3.- Concluded.

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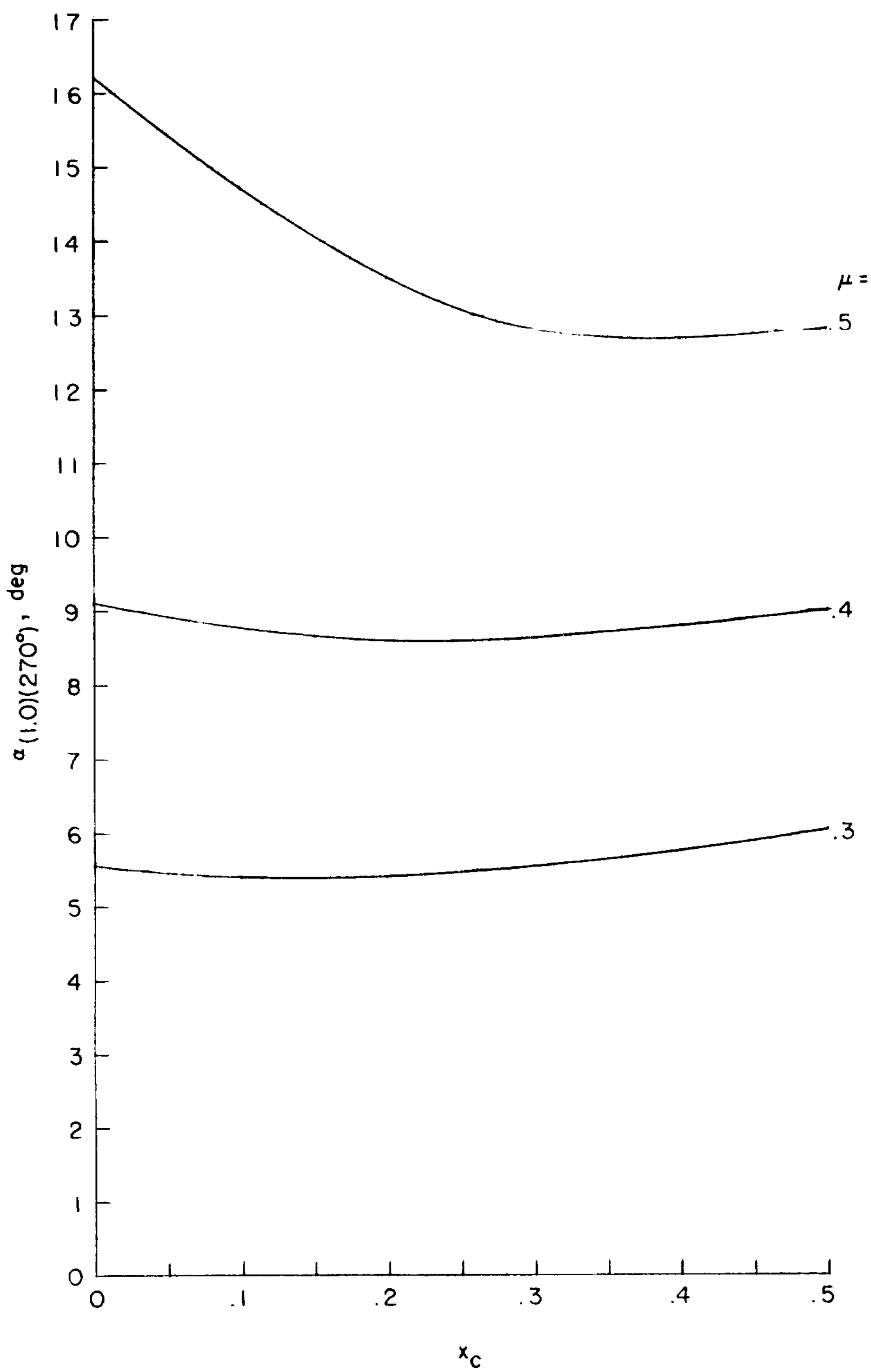
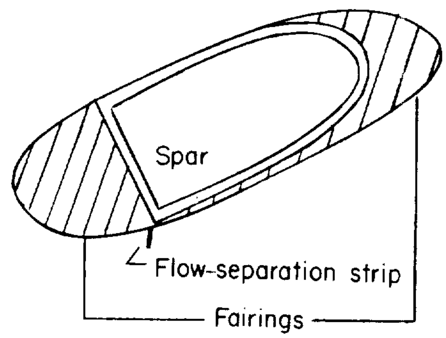
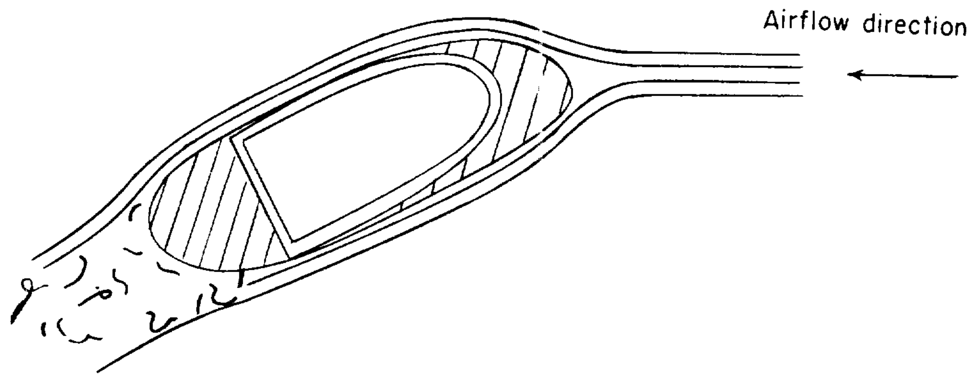
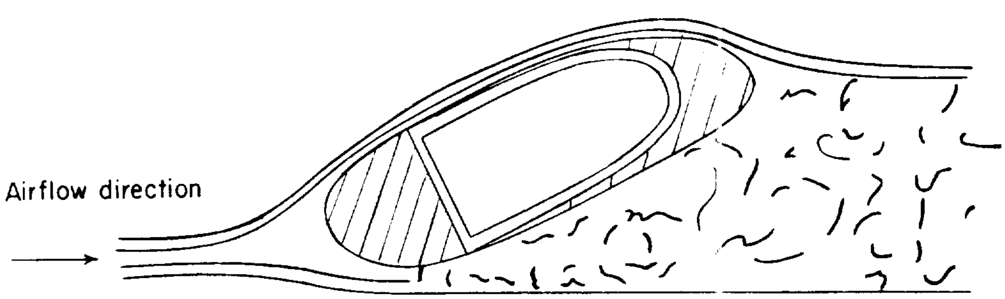


Figure 4.- Effect of cutout on retreating-blade stall for sample rotor.





Airflow on advancing side



Airflow on retreating side

Figure 5.- A possible approach to reduction of reversed-velocity-region drag and down load on the inner portions of a rotor for a high-speed helicopter.