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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3236

WIND-TUNNEL STUDIES OF THE PERFORMANCE OF

MULTIROTOR CONFIGURATIONS

By Richard C. Dingeldein

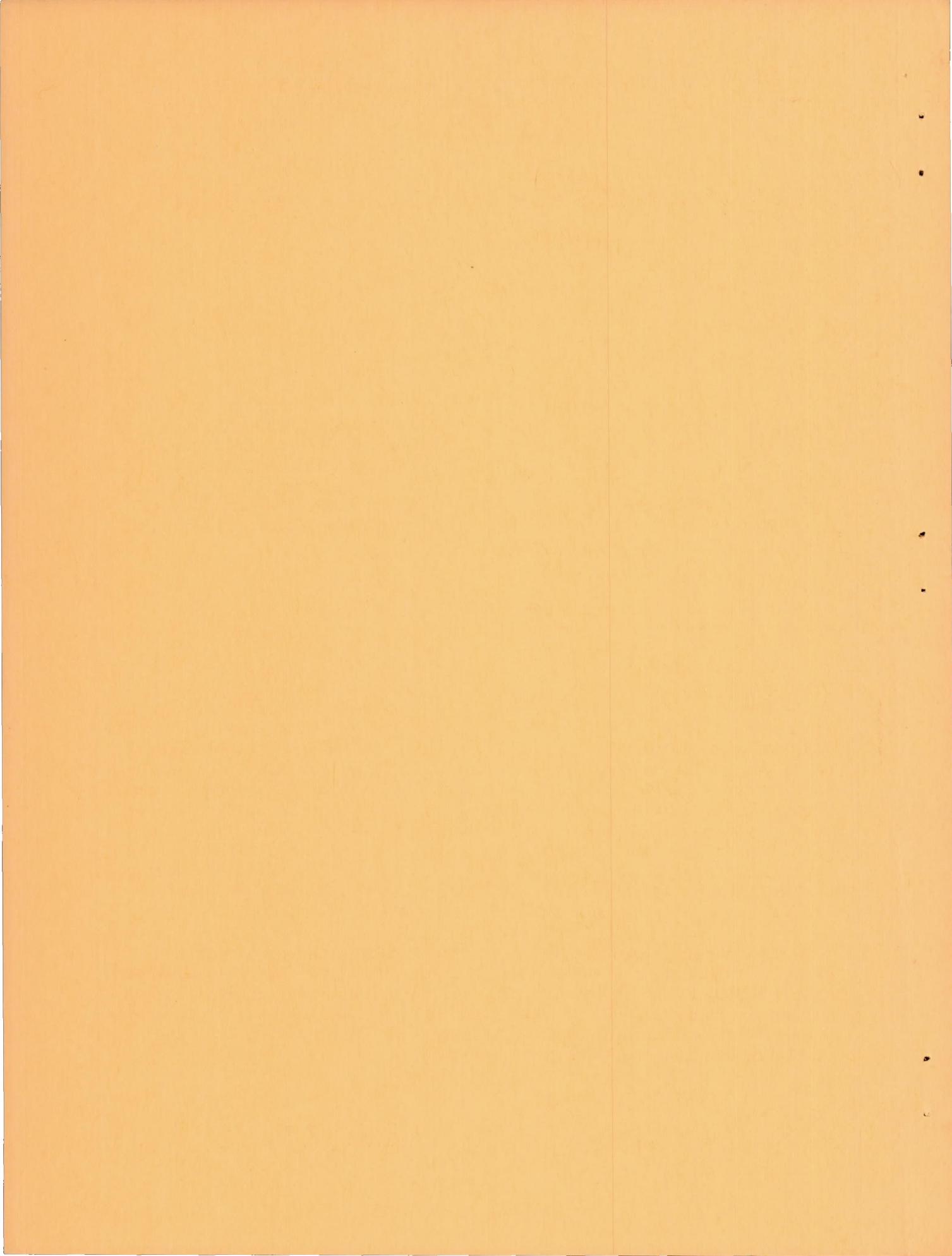Langley Aeronautical Laboratory
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SUMMARY

The power requirements measured in static thrust and in level for-
ward flight are presented for two helicopter rotor configurations. One
is a coaxial rotor arrangement having the rotors spaced approximately
19 percent of the rotor radius; the other is a tandem configuration in
which the rotor-shaft spacing is 3 percent greater than the rotor diam-
eter and in which the rotors lie in the same plane. The experimental
measurements are compared with the results of calculations based on
existing NACA single-rotor theory.

INTRODUCTION

For several years a general research program on the subject of
helicopter rotor configurations has been underway at the Langley full-
scale tunnel. This program is set up to evaluate different rotor
arrangements on the basis of relative aerodynamic efficiency and, in its
broadest sense, may involve measuring for various flight conditions the
power required, the blade motions, the flow angles in the rotor wake,
and the rotor static stability. The advantages and disadvantages asso-
ciated with different rotor configurations in regard to such things as
overall dimensions, center-of-gravity travel, structural weight, and
so forth, are generally known and are not repeated here. These are
items the designer must evaluate for himself and consider along with
the aerodynamic gains or losses. The purpose of the general research
program is to provide this latter information.

This paper presents some of the results obtained so far on two
rotor configurations - one a coaxial arrangement and the other a tandem
system having no rotor overlap or vertical offset. The emphasis is on
the power requirements in hovering and in level flight, and a comparison
between the experimental results and what can be predicted from the
available single-rotor theory is included.

SYMBOLS

D   propeller diameter, ft

Ω angular velocity, radians/sec

R   rotor radius, ft

C_T rotor thrust coefficient, $\dfrac{\text{Rotor thrust}}{\rho(\Omega R)^2 \pi R^2}$

C_Q rotor torque coefficient, $\dfrac{\text{Rotor torque}}{\rho(\Omega R)^2 \pi R^2 R}$

μ rotor tip-speed ratio

ρ air density, slugs/ft^3

TEST EQUIPMENT

The rotor configurations tested are shown in figure 1. The coaxial rotor system was part of an actual helicopter and had a diameter of 25 feet and a rotor spacing equal to 19 percent of its radius. Each rotor had two blades, and the total solidity of the coaxial configuration, based on the projected area, was 0.054. A complete description of this equipment is given in reference 1.

The tandem model had two two-blade rotors 15 feet in diameter. The rotor shafts were parallel. Each rotor had a solidity of 0.054. The blades were untwisted and untapered and had an NACA 0012 airfoil section. This is a general research model constructed to investigate side-by-side and tandem rotor arrangements. The rotors could be moved toward each other to mesh the blades up to 75 percent of the radius and could be offset vertically to cover a range of gap ratios of interest in tandem helicopters. The results discussed in this paper are confined to the tandem configuration shown in figure 1, for which the rotor-shaft spacing was 3 percent greater than the rotor diameter.

RESULTS AND DISCUSSION

It is known from some early flow-visualization studies that the air flow through and around rotors operating near one another may be very

different from what occurs for an isolated single rotor or from what is considered in the general rotor theory. As an illustration, figure 2 shows the flow through a model coaxial rotor in a hovering condition. Balsa-wood dust introduced into the air above the rotor defines the flow lines associated with the blade-tip-vortex filaments and, in this case, indicates the strong downflow affecting the lower rotor inboard of the 0.8-radius station. Since this configuration is usually operated with equal power input to each rotor to provide trim in yaw, there would be a tendency for the tips of the lower rotor to stall at the higher thrust coefficients. Because of the unsymmetrical downflow over the lower rotor, some question would exist as to whether the single-rotor theory would apply in making a performance analysis of this configuration.

Static Thrust

Coaxial rotor.- The static-thrust performance measured on the full-scale coaxial rotor shown in figure 1 is given in figure 3, in which is plotted the variation of rotor thrust coefficient and rotor torque coefficient for the coaxial rotor configuration and for the upper and the lower rotors tested separately. There were some rather obvious contour defects on these blades which made it desirable to test the rotors separately in order to adjust the drag polar to be used in succeeding theoretical calculations. The polar was initially determined for the airfoil section at the 0.75-radius station considering smooth blades by using the method of reference 2.

The extent of the adjustment was to alter the value of the constant term of the polar to provide agreement with the measured data at zero thrust. The circles represent data points measured on the upper and lower rotors tested separately, and the curve shows the calculated performance based on the adjusted drag polar and using blade-element momentum theory (ref. 3). Data points measured on the coaxial system, trimmed in yaw, are plotted as squares. The curve passing through most of these data points represents the calculated hovering performance of a single rotor having the same solidity as the coaxial arrangement. It is seen that the performance of this equivalent single rotor closely approximates the measured coaxial results. The measurements show the coaxial rotor to be slightly more efficient as the thrust coefficient is increased, although this advantage disappears at the highest thrust coefficients shown, perhaps as a result of stalling on the outboard portions of the lower rotor. A similar comparison with theory has also been obtained on a different coaxial rotor system having about the same rotor spacing but approximately three times the solidity of this rotor (ref. 1). The general conclusion is that the available single-rotor theory can be used to predict the static-thrust power requirements of a coaxial rotor with fairly good accuracy.

Tandem rotor.- The static-thrust performance of the tandem configura-
tion (which, in hovering, can also be considered as a side-by-side rotor
arrangement) is shown in figure 4, with circles showing measured points
obtained for one rotor, squares showing the points measured on the tandem
configuration, and a single curve representing the calculated performance
for both of these configurations (ref. 3). Again, the agreement is excel-
lent for the single rotor. The measured performance of the tandem rotor
is much better than that for the single rotor. At a typical thrust coef-
ficient of 0.0035, the measured data show approximately 18 percent less
power required than for the single rotor. This improved performance is
probably due to a reduction in induced power associated with a favorable
interference effect. Several possible reasons for this favorable inter-
ference have been studied. These include an interference upwash experi-
enced by each rotor from the adjacent rotor, ground effect on the tandem-
rotor configuration, and the consideration of an effective tandem-rotor-
disk area that is larger than the total swept area.

Flow studies made in the vicinity of a single rotor have failed to
indicate an interference upwash. Some crude small-scale-model studies
have tended to indicate that the improved tandem-rotor performance over
the equivalent single rotor may be due to a combination of the two latter
effects mentioned previously, the sources of which will be discussed in
more detail. The tests in the Langley full-scale tunnel were made with
the rotors located approximately 1 diameter above a reflection plane or
ground board mounted in the tunnel. The excellent agreement between
theoretical predictions of the performance of the single rotor and the
measured results indicates that ground effect was insignificant for the
single rotor, as would be expected. For the tandem-rotor arrangement,
the possibility exists that the rotor diameter to which the height of
the rotors is referenced should be some equivalent diameter - perhaps
based on the total swept area or something of that nature. Use of such
an equivalent diameter, which would be larger than the geometric diameter
of the individual rotors, would indicate the need for a ground-effect
correction to be applied to the tandem-rotor hovering data presented in
this paper. The last possibility mentioned is that the two rotors in
combination may influence a larger mass of air than the total of what
they would influence if placed far apart. As a result, the induced veloc-
ity would be lower and the induced power would be reduced. Improved
hovering performance of the order shown in this figure would occur if
the effective disk area were increased by 15 or 20 percent. This amount
is roughly equivalent to the cusp-shaped areas between the two rotor
disks. A reliable explanation for the results shown in figure 4, however,
cannot be given at this time. From a practical standpoint, this improved
hovering efficiency may not be so important after all, as is discussed
later in this paper.

Level Flight

Coaxial rotor.- The horsepower required for a coaxial helicopter using the rotor system tested and operating in level flight over a range of tip-speed ratios at a constant rotor thrust coefficient and tip speed is shown in figure 5. For this small coaxial helicopter, an equivalent flat-plate parasite-drag area of 10 square feet was used. Measurements made with one rotor compared with a calculated performance curve based on references 2 and 4 and corrected empirically for the effect of blade stalling (ref. 5) show very good agreement. The test results obtained with the coaxial rotor, trimmed in yaw, are shown at the top of the figure. The hovering point is also given, together with the power estimated for a single-rotor helicopter of equivalent solidity.

The data measured by using the coaxial rotor arrangement show that up to 14 percent more horsepower is required for this configuration than would be required for a single rotor of equivalent solidity operating under the same conditions. This difference represents increases in profile and induced power associated with rotor interference effects, but so far analysis based on the theory of reference 6 has not indicated how these losses arise. The indications remain, however, that the coaxial arrangement tested required more power in forward flight than an equivalent single rotor, although there are certain advantages to the configuration which may offset the larger power requirement in certain applications.

Tandem rotor.- The level-flight performance curve obtained by using the tandem rotor configuration tested, as well as a breakdown of the power absorbed by the front and rear rotors, is given in figure 6. The equivalent flat-plate parasite-drag area used in this test was 2 square feet, which is representative of a very clean tandem helicopter having a disk area equal to that of the model. This test was made with the total rotor thrust measured on the tunnel balance. The circles designate the points obtained with one of the rotors removed. There is quite a bit of scatter in the data; however, the calculated performance curve (refs. 2 and 4) is a good fairing of the test points and shows the accuracy of the theory in predicting the forward-flight power requirements for this particular set of rotor blades.

Next, the rear rotor was added to form the tandem configuration. The resultant rotor lift and useful drag forces that were set at each tip-speed ratio for the single rotor were doubled for the tandem arrangement by adjusting the controls of the rear rotor only. The reduced downwash field in the plane of the front rotor created by the rear rotor probably resulted in greater lift on the front rotor, which means that the measured performance data are representative of a tandem helicopter having its center of gravity located slightly forward of the midpoint between the two rotors. The power absorbed by the front and rear rotors

was measured at each tip-speed ratio and is plotted separately in the figure. The single-rotor theory is seen to be applicable to the front rotor of this particular tandem arrangement. The power required by the rear rotor is considerably higher. Most of this difference represents greater induced losses, since flow surveys show that the rear rotor is operating in the fully developed downwash of the front rotor (see ref. 7). If this is taken into account in applying the rotor theory, a curve that is in fair agreement with the measured points is calculated. Adding the power required for the front and rear rotors gives the diamond-shaped points, which are compared with the equivalent calculated curve. Agreement with the theory tends to be good at low and at high tip-speed ratios. However, the measured power is higher than the calculated power at cruising conditions, much the same as noticed for the coaxial rotor, although the percentage difference is much less. An important thing to see here is the unusual shape of the measured tandem-helicopter power-required curve at the low-speed end. Instead of the customary flattened performance curve, the increased hovering efficiency that was measured on the tandem and discussed previously in this paper has reduced the hovering power required so that the curve has a different shape. The manner in which the measured data points should be faired at the extremely low values of tip-speed ratio has not been determined from these tests. This favorable interference effect is probably confined to a true hovering condition and probably disappears at extremely low forward speeds. It is therefore not expected to be of any practical importance.

CONCLUDING REMARKS

As a result of these tests, it appears that the power requirements of a coaxial rotor in static thrust can be predicted with good accuracy from the available theory, although more power is required in level flight than for the equivalent single rotor. The tandem rotor configuration which has the rotor shafts spaced approximately a rotor diameter apart is indicated to have greatly improved hovering efficiency that is probably due to a reduction in induced power, but which is not expected to be of any practical importance. The power requirements for this tandem arrangement in level flight can be predicted fairly well from the available single-rotor theory by considering the rear rotor to be operating in the fully developed downwash of the front rotor.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., June 10, 1954.

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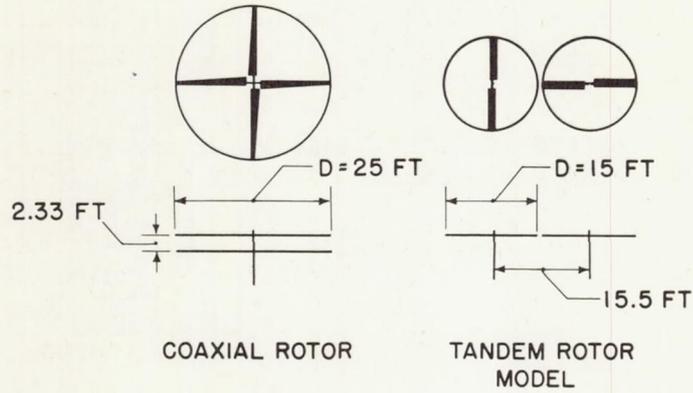
ROTOR CONFIGURATIONS TESTED

COAXIAL ROTOR

TANDEM ROTOR
MODEL

Figure 1

AIR FLOW THROUGH A MODEL COAXIAL ROTOR IN STATIC THRUST

Figure 2

STATIC THRUST PERFORMANCE OF A COAXIAL ROTOR
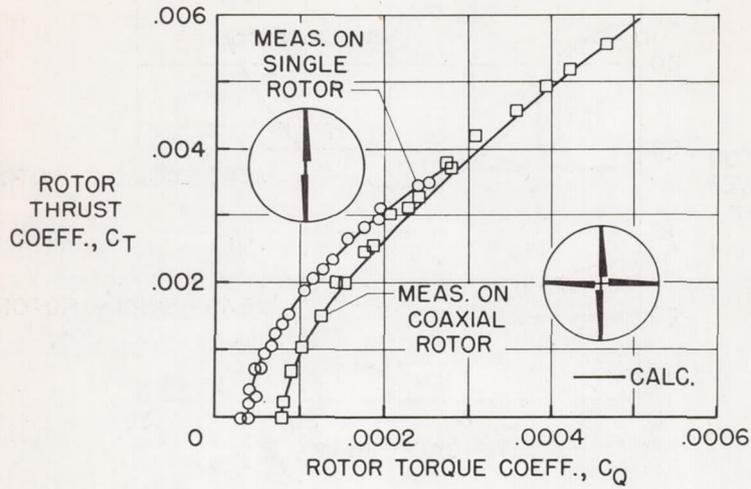### $\Omega R = 500$ FPS

Figure 3

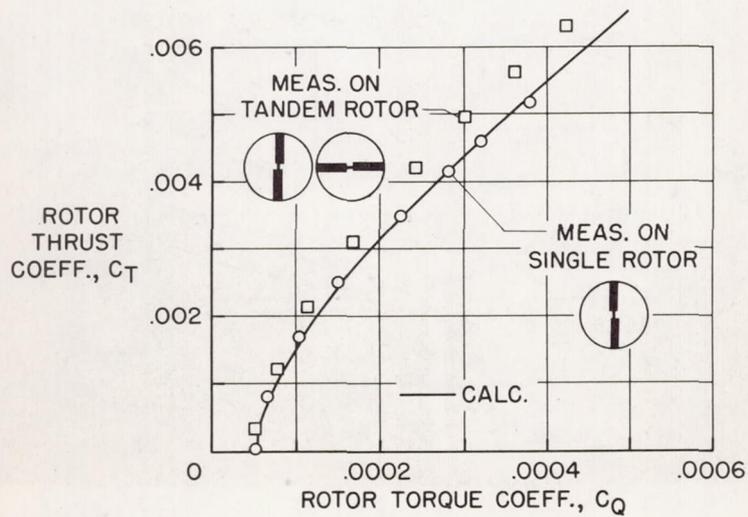## STATIC THRUST PERFORMANCE OF A TANDEM ROTOR
$\Omega R = 500$ FPS

Figure 4

LEVEL-FLIGHT PERFORMANCE WITH COAXIAL ROTOR
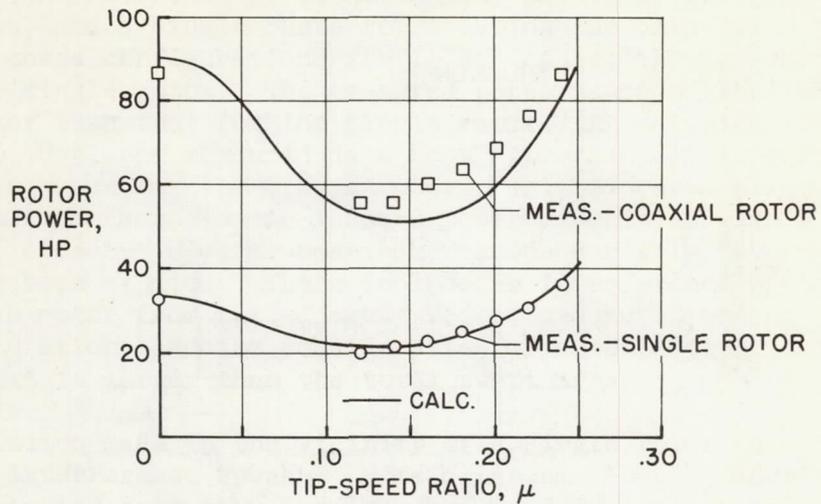$C_T = 0.0048$; $\Omega R = 469$ FPS

Figure 5

LEVEL-FLIGHT PERFORMANCE WITH TANDEM ROTOR
$C_T = 0.0034$; $\Omega R = 500$ FPS
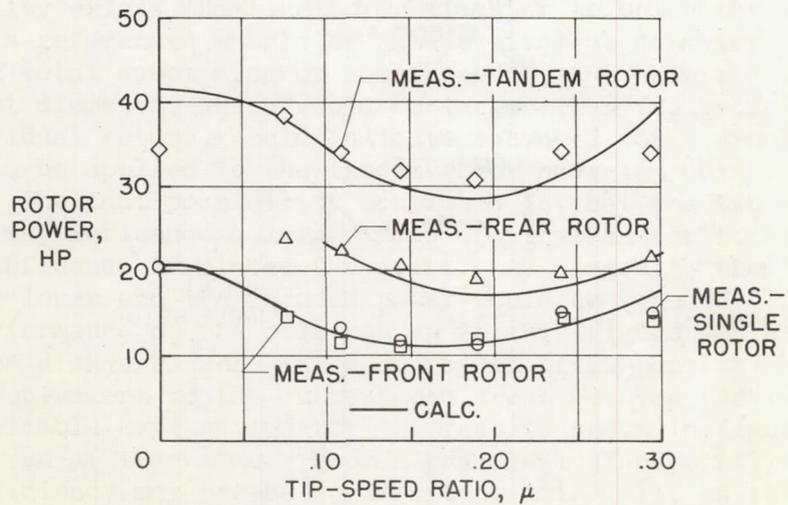
Figure 6