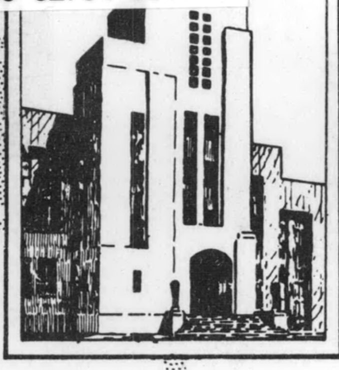

DEPARTMENT OF THE NAVY

DAVID TAYLOR MODEL BASIN

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EXPERIMENTAL PERFORMANCE OF A SIX-BLADED VERTICAL AXIS PROPELLER

by

B.V. Nakonechny

HYDROMECHANICS LABORATORY

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NOTATION

a	Radius of rolling circle
b_m	Mean chord length of blade
C	Steering point
D	Propeller orbit diameter (= 2r)
e	Efficiency ($= \frac{TV_a}{2\pi nQ} = \frac{K_t}{K_q} \cdot \frac{\lambda}{2}$)
K_q	Torque coefficient ($= \frac{Q}{\rho L n^2 D^4}$)
K_t	Thrust coefficient ($= \frac{T}{\rho L n^2 D^3}$)
l	Distance between steering point and point on blade orbit ($= \overline{CP}$)
L	Blade length
n	Revolutions per unit time
O	Center of vertical axis propeller
p	Pitch ratio ($= \frac{a\pi}{r}$)
P	Point on propeller blade orbit
Q	Torque
r	Propeller orbit radius ($= \overline{OP}$)
R_e	Reynolds number ($= b_m \cdot \frac{\sqrt{V_a^2 + (\pi nD)^2}}{\nu}$)
s	Solidity ($= \frac{zb_m}{\pi D}$)
T	Thrust
U	Orbital (tangential) velocity ($= \pi nD$)
V_a	Velocity of advance

V_r	Resultant velocity
z	Number of blades
α	Steering angle
β	Blade angle
θ	Blade orbit angle
λ	Advance coefficient $(= \frac{V_a}{U})$
ν	Kinematic viscosity
ρ	Density of water
ω	Angular velocity $(= \frac{U}{r})$

ABSTRACT

This report presents the results of experimental investigations of the performance of a 6-bladed vertical axis propeller (Voith-Schneider type). The investigations were conducted at different pitch ratios using modified cycloidal and sinusoidal blade motion. The tests were carried out at constant rpm of 600, 700, 800, and 900, respectively, for a range of speeds from zero to the speed of zero thrust. The results are presented in form of performance characteristic curves using new nondimensional coefficients of the K - λ type adapted to vertical axis propellers.

INTRODUCTION

The principle of a vertical axis propeller for ship propulsion appears to have been originated by Robert Hooke in the second half of the 17th century.[1] Somewhat later, about 1870, a device, consisting of a wholly submerged horizontal feathering paddle wheel, was proposed by Moody and Fowler[2,3,4] and installed on the U.S. torpedo boat ALARM. This propeller was a decided success as regards its capacity for maneuvering a vessel but it proved uneconomical with respect to power consumption as compared to a screw propeller. After a lapse of nearly fifty years, the principle was "rediscovered" almost simultaneously and independently by F.K. Kirsten in the United States and by E. Schneider in Austria and practical propellers were constructed. Kirsten's design, known as the Kirsten-Boeing propeller, was installed in 1922 on a speedboat and was tested in the U.S. Experimental Basin in 1923. Schneider's design developed by the J.M. Voith Company in Germany, known as the Voith-Schneider propeller, was installed in several river and lake vessels towards the end of the 1920-30 decade. The two propellers make use of the same principle but differ in the mode of operation; both permit changing the direction of thrust without changing the direction of rotation of the disc. In addition, the V.S.-propeller permits changing the magnitude of the thrust for constant RPM while the K.B.-propeller does not permit this. Perhaps due to this advantage or due to simpler mechanical construction or due to differences in geographical and economic conditions, the V.S.-propeller has found wide application on river and lake vessels in Europe and other parts of the world while the K.B.-propeller has been applied only in isolated cases in the United States.

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[1] References are listed on page 12.

The literature on cycloidal propellers is quite extensive and several excellent papers on the theory and the kinematical principles involved have been presented (References 2-40); however, the literature contains few data which permit the design of a vertical axis propeller in the well-known manner of designing a screw propeller. An exception is Reference 13 which contains a design chart for the K.B.-propeller derived from model tests carried out in the U.S. Experimental Model Basin but even this data is not very extensive. The most complete theoretical investigation of vertical axis propellers was carried out by Isay.[18 to 21] From Isay's theory, the propeller thrust, torque, and efficiency can be obtained. The work of Isay has been analyzed and computational work was carried out at the David Taylor Model Basin. It was found that certain basic assumptions of this theory appear to be oversimplified. In its present form, Isay's theory yields unreasonably high values of efficiency even at very low advance coefficients.

This report presents the results of experimental investigation in open water on an existing 6-bladed Voith-Schneider model propeller unit. The tests were carried out at the David Taylor Model Basin and included modified cycloidal and sinusoidal motions. The blade motion of the model propeller was simulated by different cams, each cam producing a particular type of motion.

INSTRUMENTATION AND TEST PROCEDURE

It was realized at the beginning of investigations that the open water experimental tests of vertical axis propeller cannot be conducted in a manner similar to those of conventional type which have a horizontal axis of rotation. Merits and drawbacks of different schemes were analyzed and it was finally decided to use the test arrangement shown in Figures 1 and 2.

The Voith-Schneider unit of 6.3-inch orbital diameter was fitted in a model and was rigidly attached to the two modular force gages for measuring the total thrust of the propeller. To permit deflection of the modular force gages, a free space of 1/4 inch between the propeller unit and the boat was provided. In the lower part of this free space a thin rubber diaphragm was fitted for the purpose of preventing air drawing into the propeller or water penetrating inside the boat (Figures 1 and 2). A transmission dynamometer for measuring the torque and rps was mounted in the propeller boat as shown in Figures 1 and 3.

The propeller boat was fixed to the carriage girder in such a fashion that, in the vicinity of the propeller, it touched the water level. At the forward perpendicular the boat had a clearance of about 1/32 inch with respect to the water level of the basin. In this manner, the wake and other possible boundary layer effects from the bottom of model boat were eliminated.

To prevent air drawing to the propeller from the sides, a flat boat bottom was used in the vicinity of vertical axis propeller.

The blades used in the tests were of rectangular outline, slightly tapered toward the tip, and had the cambered blade sections (Figure 4). The characteristics of the propeller are given in Table 1.

Figure 5 shows the propeller boat under the carriage during the tests in the basin. The housing of the propeller filled itself with water during the tests. Once filled, the water level in the housing remained constant for the entire test speed range (Figure 1). The following quantities were recorded during each test: total thrust, torque, speed of advance, and rps of the propeller. "No loads" were run before and after the test, with dummy shafts (shaft end flush with bottom of propeller housing) in place of propeller blades, so that the torque and the thrust could be corrected for the effect of the shaft friction and other rotative parts of the model propeller unit.

The steering angle* was set by rotating the propeller housing with respect to the fore-and-aft centerline of the propeller boat and is taken as positive when the housing is rotated clockwise viewing from top of the housing. For each blade motion, the steering angle was set in such a way as to give a resultant thrust in the fore-and-aft direction at a speed of advance of 9 fps and a rotational propeller speed of 10.5 rps.

To determine the effect of rps on K_t and K_q additional tests, covering a wide range of rps, were carried out at zero speed of advance.

Table 2 shows the summary of the test conditions with indication of the ranges of test speed of advance and rps. The test Reynolds numbers based on the mean chord length of the blade ranged from 1×10^5 to 2.75×10^5.

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* For description of terms see Appendix, page 9.

TEST RESULTS AND DISCUSSION

The measured values of thrust, torque, speed of advance, and rps are presented in the form of new nondimensional coefficients of the $K - \lambda$ type adapted to vertical axis propellers.

The relationship of K_t and K_q quantities with respect to a range of rps for zero speed of advance is presented in Figure 6. As can be seen from this figure, the K_t and K_q values remained essentially constant throughout the entire test range of rps showing only a small scatter which is within the limits of accuracy of the experiments.

Figures 7 through 12 present the performance curves obtained for different types of blade motion. The resulting blade motions, shown in Figures 7 to 12, were obtained by measuring the blade angle at various positions on the orbit and plotted as a function of the blade orbit angle.

In Figure 7 the performance curves for the modified cycloidal blade motion are presented. For this motion the maximum blade angle of 26.6 degrees in the forward semicircle occurred at a blade orbit angle of 105 degrees. The steering angle was kept at zero degrees, and the compensation taken as a difference between the maximum blade angles in the forward and after semicircles amounted to 5.6 degrees.

Figure 8 presents the performance curves for modified cycloidal blade motion with maximum blade angle equal to 39 degrees at a blade orbit angle of 120 degrees. The steering angle was 5 degrees and the compensation 1.2 degrees.

Figure 9 shows the performance curves for another modified type of cycloidal blade motion which had maximum blade angle of 28.1 degrees at blade orbit angle of 105 degrees. The steering angle was established to be 8 degrees and the compensation had a value of 0.7 degree.

In Figure 10 the performance curves for the similar motion as in Figure 9 but for a higher pitch ratio (i.e., a higher value of maximum blade angle) are presented. The maximum blade angle for this motion was 42.0 degrees and occurred at a blade orbit angle of 106 degrees. The steering angle was 6 degrees and the compensation 0.7 degrees

The performance curves for modified sinusoidal blade motion with maximum blade angle of 28.4 degrees at blade orbit angle of 80 degrees are presented in Figure 11. The steering angle for this blade motion was minus 4 degrees and the compensation was 4.5 degrees.

The sinusoidal motion for the higher pitch ratios was tested several times. However, the final performance curves are not presented here, since these curves exhibited a rather unusually irregular shape. This motion needs further analysis in order to establish the causes of this phenomenon. It is believed that separation effects and a subsequent thrust break which occurs at higher pitch ratios are responsible for this irregularity.

The highest value of efficiency obtained experimentally during these tests was for the modified cycloidal blade motion shown in Figure 12. The maximum blade angle for this motion was 43.5 degrees at blade orbit angle of 120 degrees. The steering angle for this motion had a value of 4 degrees and compensation of 2.2 degrees.

Figure 13 shows all the investigated motions with the corresponding efficiency curves. Examining the effect of the blade motion of the efficiency of a six-bladed vertical axis propeller we observe that the shape of the blade angle curve, the magnitude and position of a maximum of a blade angle with respect to orbit angle are of considerable importance. The blade angle curves with a sharp ascent and a maximum around 90 degrees of orbit angle are associated with relatively low values of efficiencies. This type of motion is characteristic mainly of modified sinusoidal (Figure 11) and to some extent of certain modified cycloidal (Figures 9 and 10) types of motion. A mild ascent of blade angle curve, particularly for high pitch ratios, with relatively narrow region of blade angle maximum shifted towards higher values of orbit angle, i.e., about 120 degrees in the forward portion of the propeller orbit, is characteristic of relatively higher efficiencies of vertical axis propellers. This feature is exemplified by modified cycloidal blade motion shown in Figure 8 and to even greater extent by the modified cycloidal type of motion given in Figure 12. These modified cycloidal blade motions approximate to some degree the ideal cycloidal blade motion for idling condition (see Figure 15).

As can be expected, each type of motion of vertical axis propeller shows the similar trend with regard to pitch diameter ratio as do the screw propellers. Namely, with an increase of pitch diameter ratio the values of K_t and K_q increase and the location of maximum efficiency curve is shifting in the direction of the higher λ values.

CONCLUSIONS

In general, the experimental open water efficiency curves for the model vertical axis propeller exhibited somewhat lower values than screw propellers. It appears from the results that for low pitch ratios (i.e., low values of maximum blade angle), the efficiencies both for modified cycloidal and sinusoidal motions are practically of comparable order. However, with increasing pitch ratios, the modified cycloidal blade motion which tends to approximate closely the ideal cycloidal motion appears to be more efficient than modified sinusoidal motion. With increased pitch ratio each type of motion yields higher values of K_t and K_q. Also, for higher pitch ratios the position of maxima of the efficiency curves is shifted in the direction of higher values of advance coefficient.

Further experimental investigations on new types of modified cycloidal blade motions, with still higher pitch ratios, in open water as well as in water tunnel, are recommended. They should include investigations using a larger model and studies of cavitation phenomena of vertical axis propellers.

TABLE 1

PROPELLER CHARACTERISTICS

Propeller blade orbit diameter (D)	0.525 ft
Number of blades	6
Blade Length (L)	0.263 ft
Blade section	airfoil
Blade length diameter ratio (L/D)	0.5
Swept area of the propeller (D · L)	0.138 sq ft
Solidity (s)	0.347
Propeller rotation	R.H.*

* When viewing from top of the propeller housing.

TABLE 2

Test Conditions

Item	Blade Motion	Magnitude and Position of β_{max}				Steering Angle α	Compen- sation in Degrees	Number of Blades	Test n in rps	Test V_a in fps
		β_{max}	θ	β_{max}	θ					
1	Modified cycloidal	26.6	105	-32.2	248	0	5.6	6	8 to 15.0	0 to 15
2	Modified cycloidal	39.0	120	-40.2	254	5	1.2	6	8 to 14.5	0 to 17
3	Modified cycloidal	28.1	105	-28.8	254	8	0.7	6	6 to 11.7	0 to 12
4	Modified cycloidal	42.0	106	-42.7	240	6	0.7	6	6 to 15.0	0 to 17
5	Modified sinusoidal	28.4	80	-32.9	266	-4	4.5	6	6 to 11.7	0 to 17
6	Modified cycloidal	43.5	120	-45.7	246	4	2.2	6	4.7 to 11.7	0 to 14

Note:

The values of β_{max}, θ, and α are given in degrees.

APPENDIX

DESCRIPTION OF TERMS RELATED TO VERTICAL AXIS PROPELLERS

GENERAL REMARKS

When a vertical axis propeller, mounted in a model or a ship, rotates at uniform angular velocity about its center and advances at uniform rectilinear translational velocity through the water, the center of each blade shaft follows a cycloidal path. Depending on the advance coefficient, the relative motion of the blade shaft center may follow the path of

(a) a curtate cycloid (trochoid) - for $\lambda < 1$

(b) a common cycloid - for $\lambda = 1$ (Figure 14)

(c) a prolate cycloid (trochoid) - for $\lambda > 1$

Based on this fact, any vertical axis propeller can also be called a cycloidal propeller as, for example, any screw propeller might also be called a helical propeller.

BLADE ANGLE

The instantaneous angle between the chord of a blade and the tangent to the propeller blade orbit through the blade axis is called the blade angle. Blade angles are taken in this report as positive when the leading edge is pointing away from the rotor centerline during its circular motion. In the case when the leading edge is directed toward the rotor centerline the blade angle is taken as negative (see Figure 15).

BLADE ORBIT ANGLE

The blade orbit angle is defined as the angular position of blade shaft center (i.e., the axis of rotation of the blade) and is measured in the direction of rotation, having a value of 90 degrees in the direction of the forward motion (Figures 15 and 16).

CYCLOIDAL BLADE MOTION

Cycloidal blade motion is defined as that blade motion for which the chord of a symmetric blade section is tangent (at the blade axis) to the cycloidal path at every instant of its motion.

To obtain cycloidal blade motion, kinematics requires that the perpendicular to the profile chord of each blade passes through the same point C, called the steering point (Figures 15 and 17). The cycloidal blade motion for three different positions of steering point and hence three different values of advance coefficient is shown in Figure 15.

Referring to Figure 14 it is seen that for $\lambda < 1$ the direction of the blade experiences a continuous change during the entire orbiting cycle. For $\lambda = 1$ there occurs a sudden change in direction of the blade at a blade orbit angle $\theta = 180^{\circ}$. At this blade orbit angle the direction of the blade is instantaneously changed by 180 degrees. For $\lambda > 1$ the blade direction again changes continuously during the orbiting cycle. The discontinuity in the blade motion curve of Figure 16 for $\lambda > 1$ is only apparent since $\beta_{180} = \beta_{-180}$.

SINUSOIDAL BLADE MOTION

Sinusoidal blade motion is defined as that blade motion for which the blade angle varies sinusoidally with respect to blade orbit angle.

ECCENTRICITY, PITCH, AND PITCH RATIO

The eccentricity $\overline{OC}$ of the vertical axis propeller (Figure 15) is equal to the radius of the rolling circle, a, (Figure 17), and can be expressed in form of a simple relation

$$a = r \cdot \frac{V_a}{U}$$

The eccentricity, a, determines the amplitude of the oscillating motion of the blade and when multiplied by 2π gives the magnitude of advance of the propeller per revolution at no-load operation (Figure 17). In other words, the eccentricity of a vertical axis propeller has the same significance as the effective pitch of a screw propeller, i.e., the advance per revolution at which the thrust is zero. We note that the angle β is also the angle included between the distance $\overline{CP}$ and blade orbit radius $\overline{OP}$ (Figures 15 and 17). This angle is determined by the values of the eccentricity and represents the pitch angle corresponding to idling condition of the propeller.

The pitch ratio, p, is defined as the ratio of the propeller advance per revolution (at zero slip) to blade orbit diameter. Based on this definition, the pitch ratio determines also the type of cycloid that is traced by the blade axis. Thus the pitch ratio for

(1) the curtate cycloid range $p = \frac{a\pi}{r} < \pi$, i.e., for $r > a$, Figure 17

(2) the common cycloid $p = \pi$, i.e., for $r = a$

(3) the prolate cycloid range $p = \frac{a\pi}{r} > \pi$, i.e., for $r < a$

For the range of pitch ratios smaller and larger than π, it is possible to include control mechanisms which will vary the total thrust in magnitude and direction. For pitch equal to π only the direction of total thrust can be varied. The Voith-Schneider propeller is an example of a controllable pitch vertical axis propeller operating in the curtate cycloid range. A fixed pitch ($p = \pi$) vertical axis propeller is exemplified by the Kirsten-Boeing propeller.

To the author's knowledge there is, at present, no single vertical axis controllable pitch propeller in operation with range of pitch ratios greater than π (i.e., the prolate cycloid range).

COMPENSATION AND STEERING ANGLE

The difference in the maxima of blade angle in rear and forward half of the propeller blade is called compensation. Compensation is added to the blade motion to equalize the loading in the fore-and-aft parts of the orbit.

The angle included between the direction of the resultant (total) thrust and the centerline of the propeller boat or ship is called steering angle.

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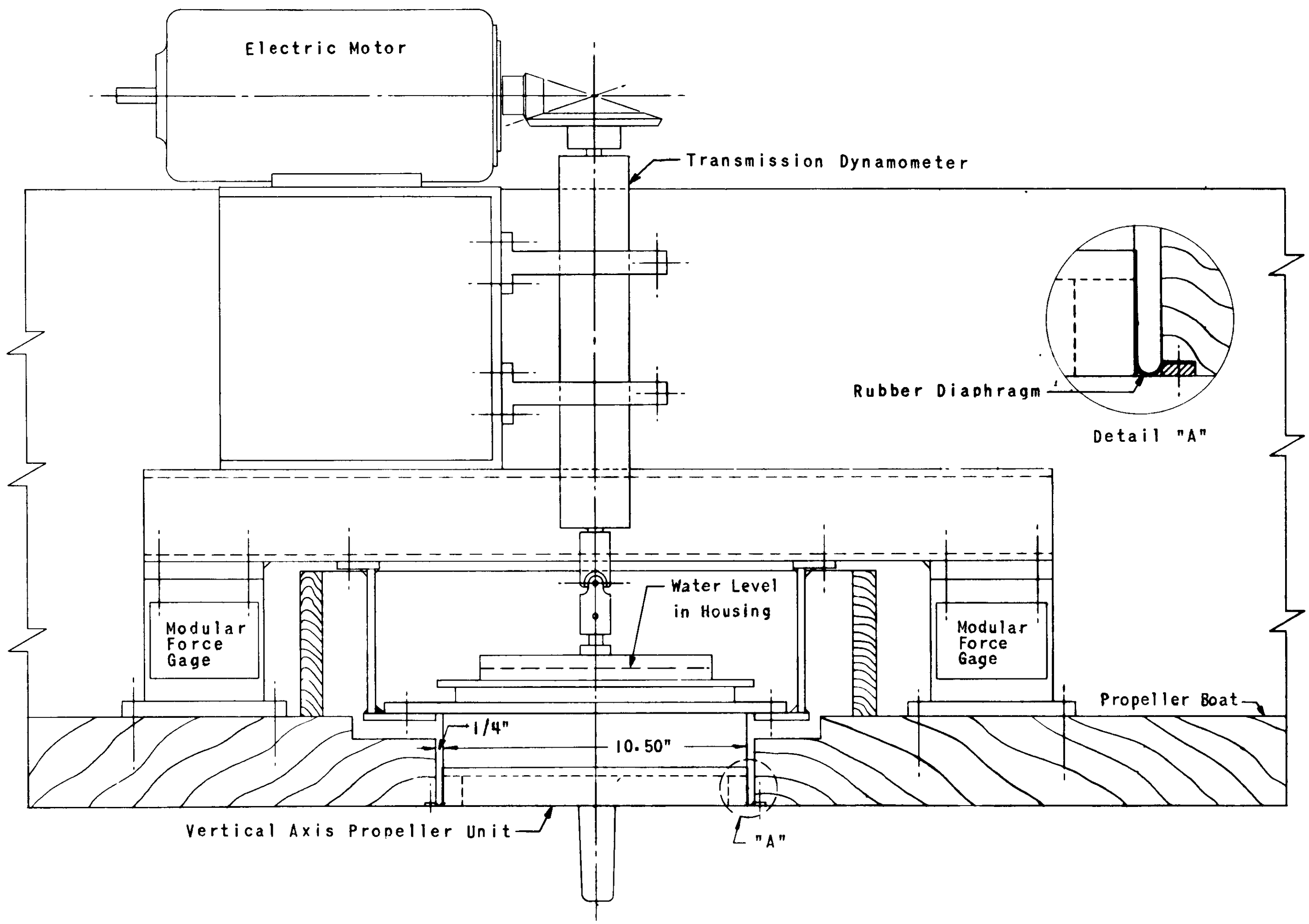
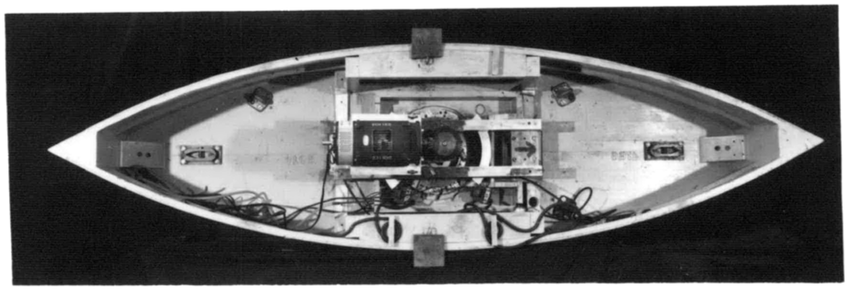
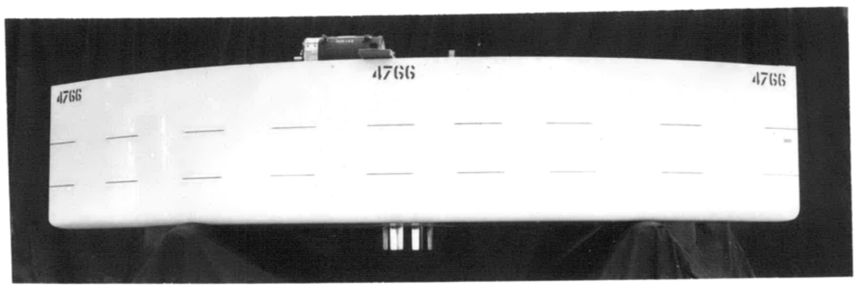


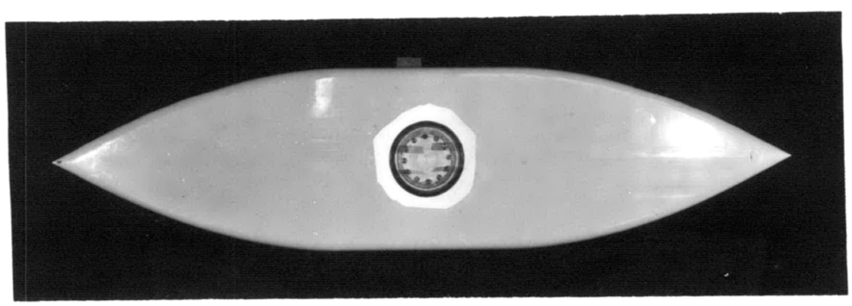
Figure 1 - Sketch of Test Arrangement of Vertical Axis Propeller



Top View

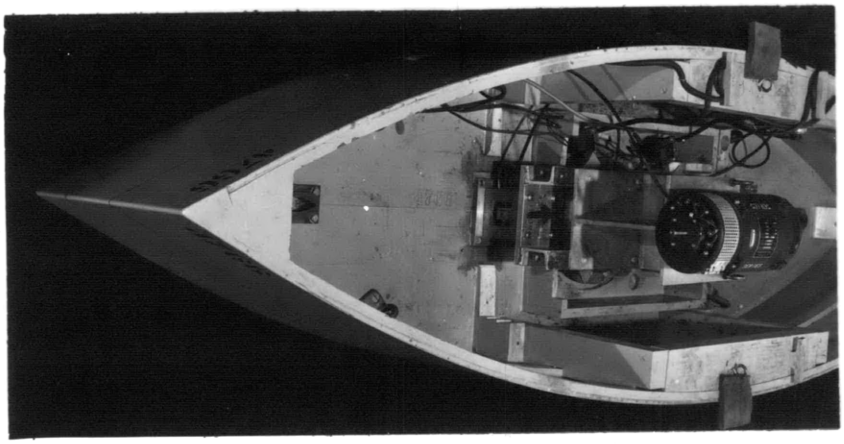


Side View

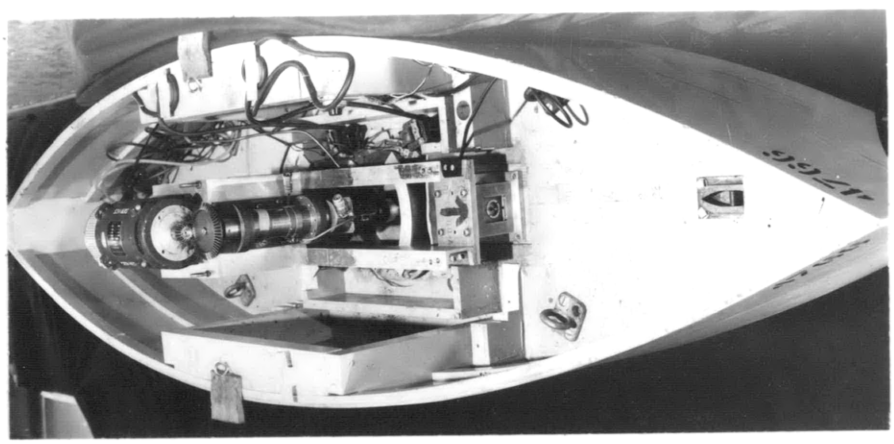


Bottom View

Figure 2 - Arrangement of Vertical Axis Propeller Boat



Top View Aft



Top View Fore

Figure 3 - Arrangement of Vertical Axis Propeller Boat

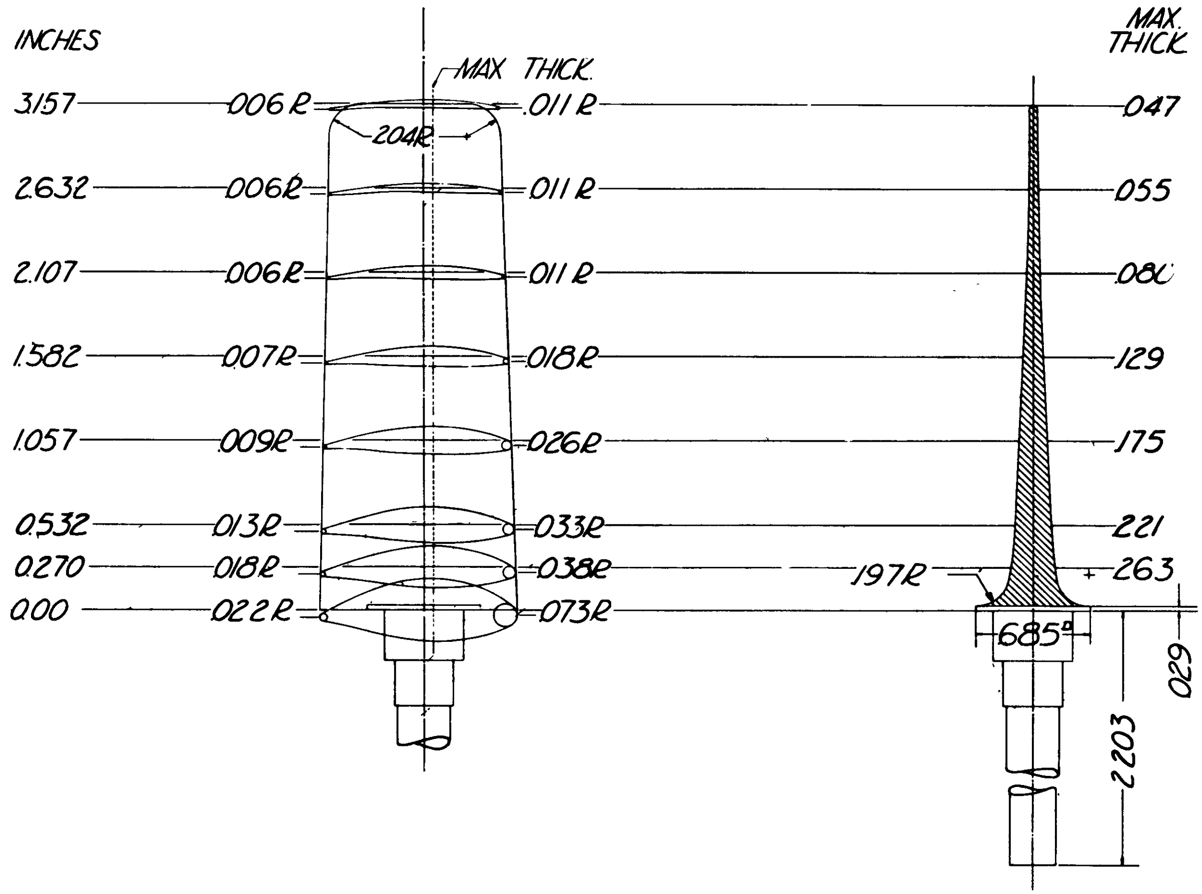
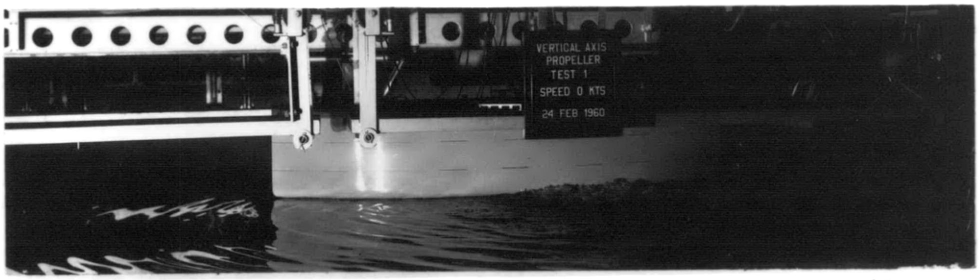
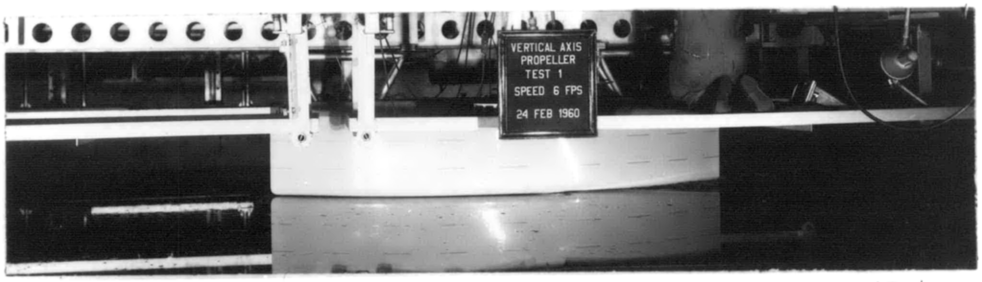


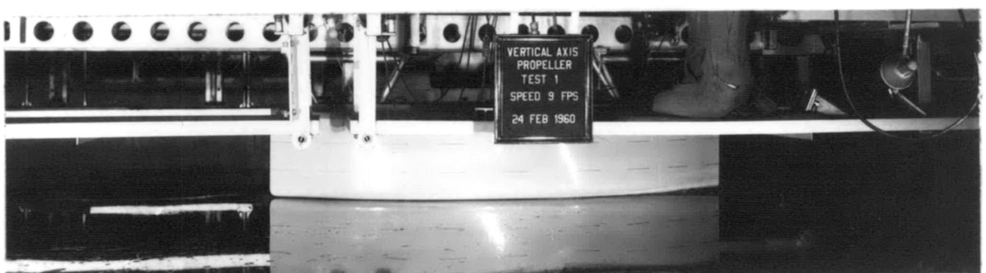
Figure 4 - Outline of Propeller Blades



13.4 rps



13.5 rps



13.7 rps

14.2 rps

(Mod. Cycl. $\beta_m = 39^o$ at $\theta = 120^o$)

Figure 5 - Propeller Boat under Carriage during the Test

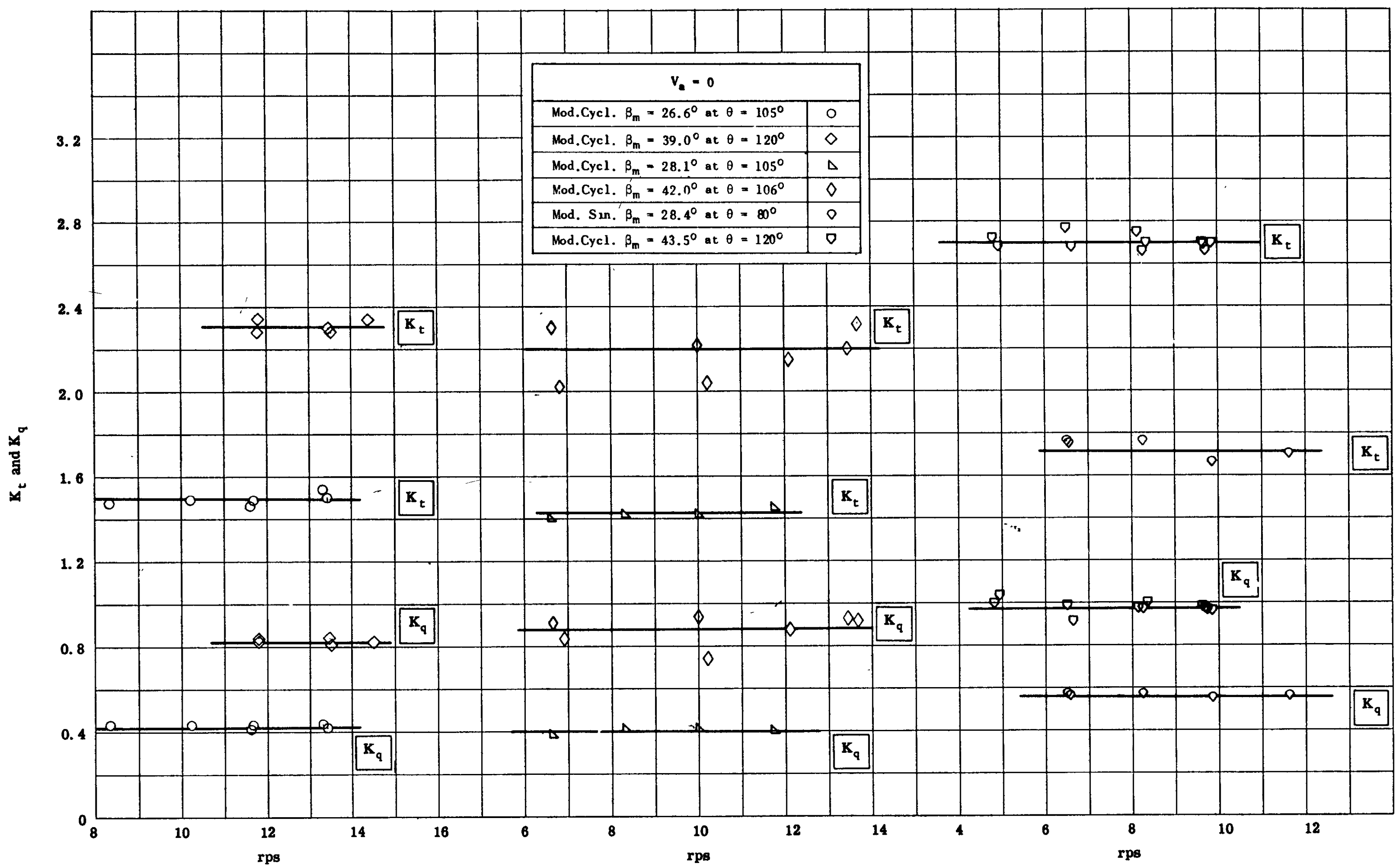


Figure 6 - K_t and K_q Values at Zero Speed of Advance

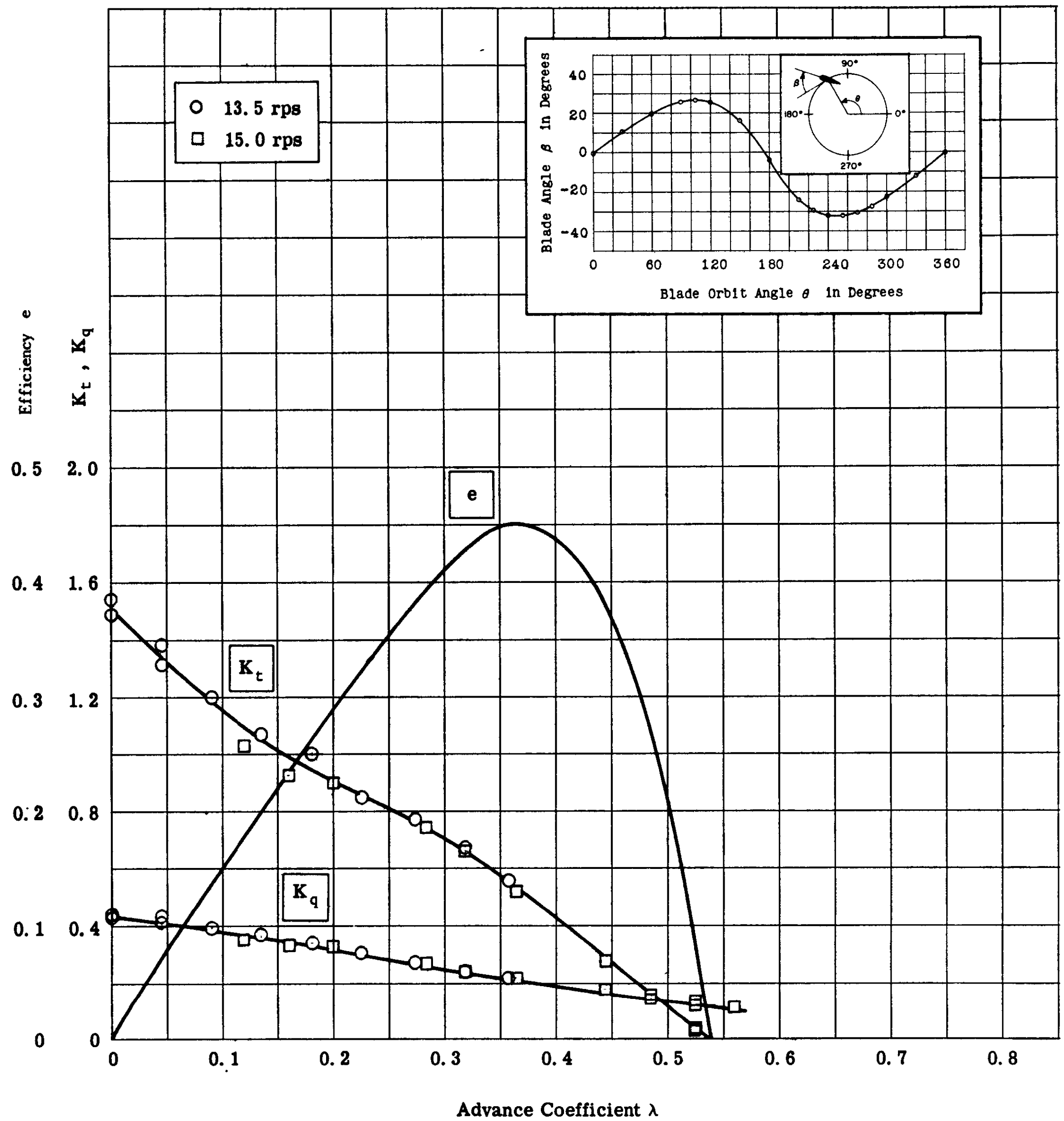


Figure 7 - Performance Curves for Vertical Axis Propeller with Modified Cycloidal Blade Motion (β_{max} = 26.6 degrees at θ = 105 degrees)

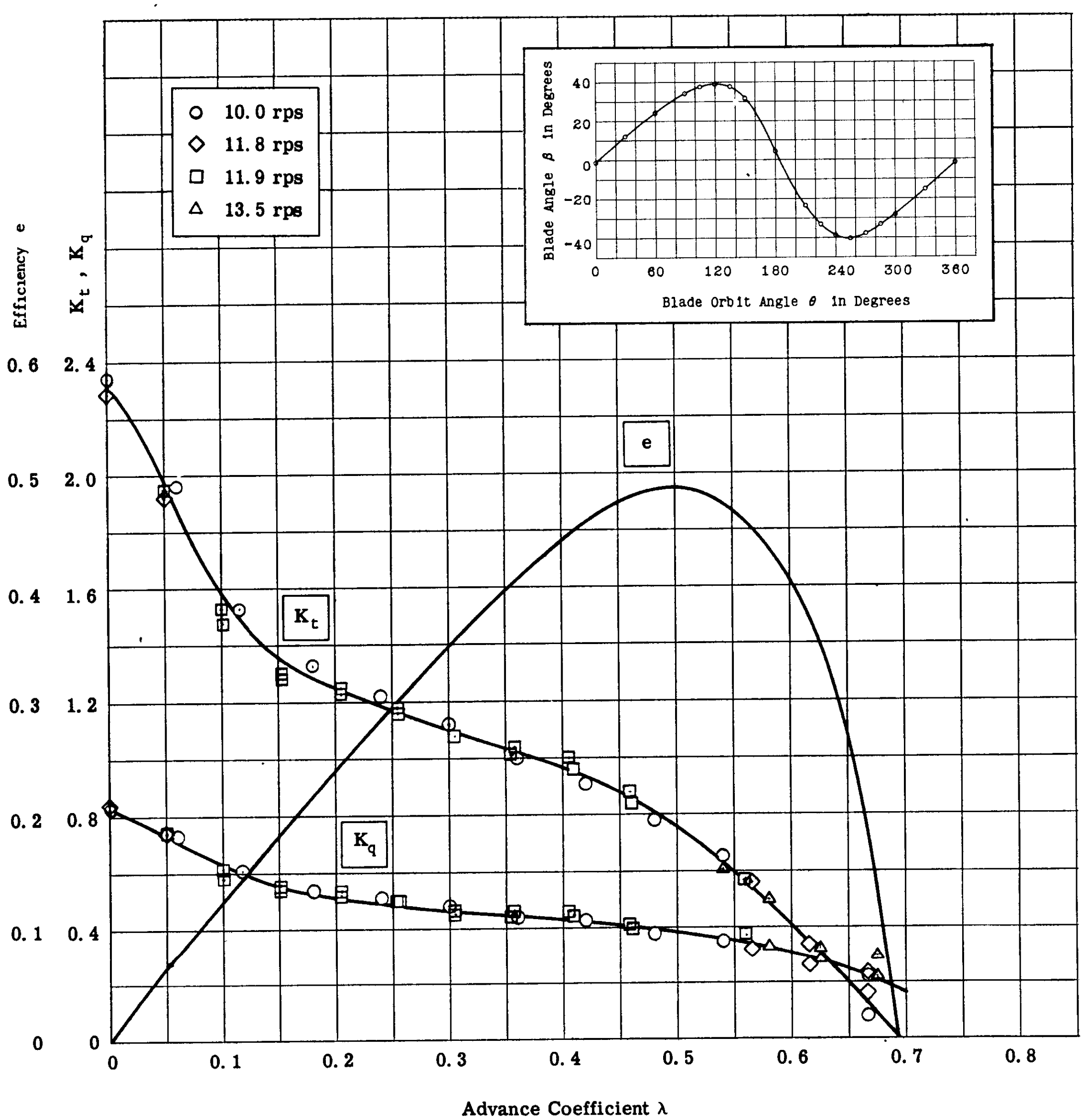


Figure 8 - Performance Curves for Vertical Axis Propeller with Modified Cycloidal Blade Motion
(β_{max} = 39.0 degrees at θ = 120 degrees)

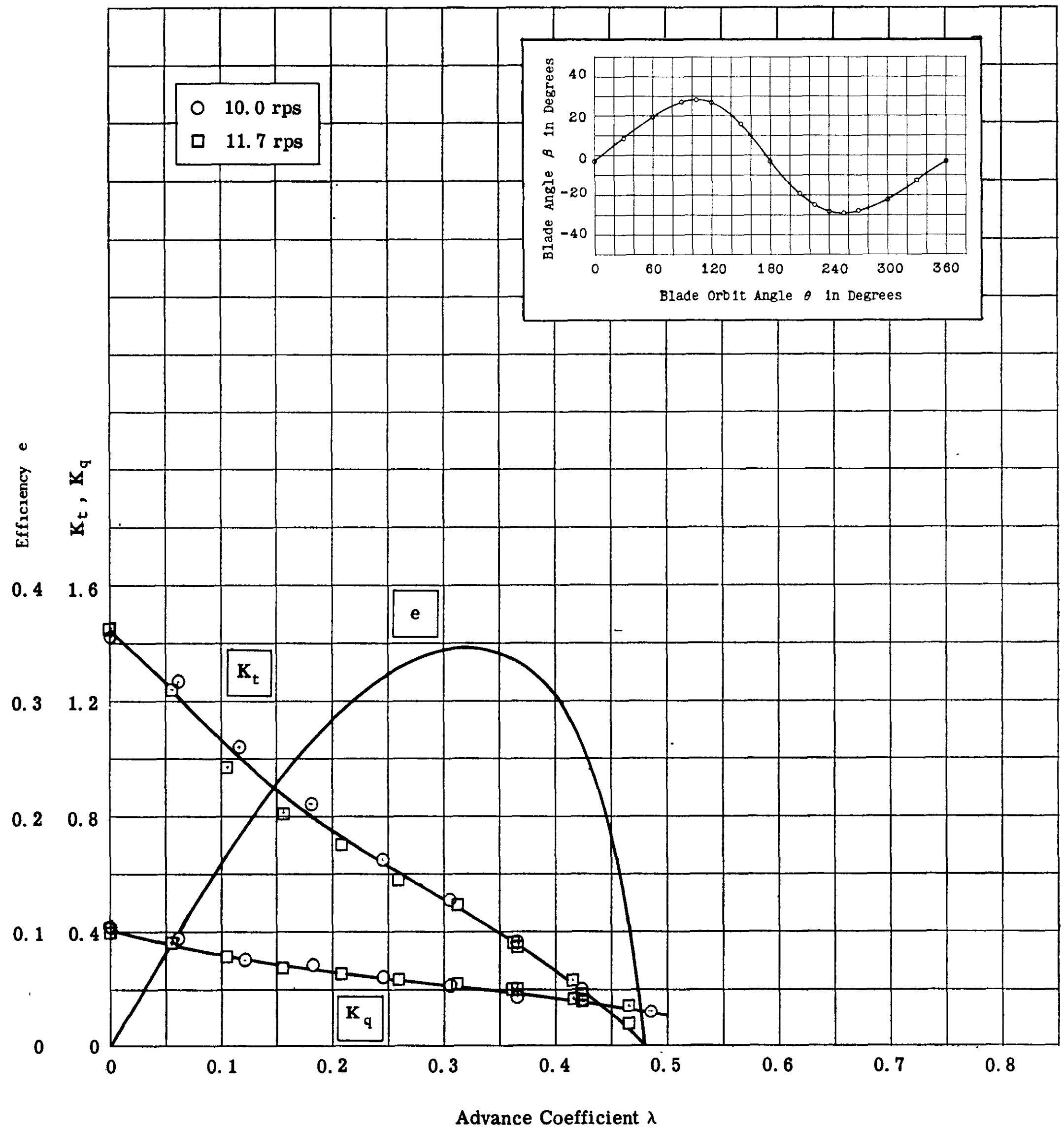


Figure 9 - Performance Curves for Vertical Axis Propeller with Modified Cycloidal Blade Motion
(β_{max} = 28.1 degrees at θ = 105 degrees)

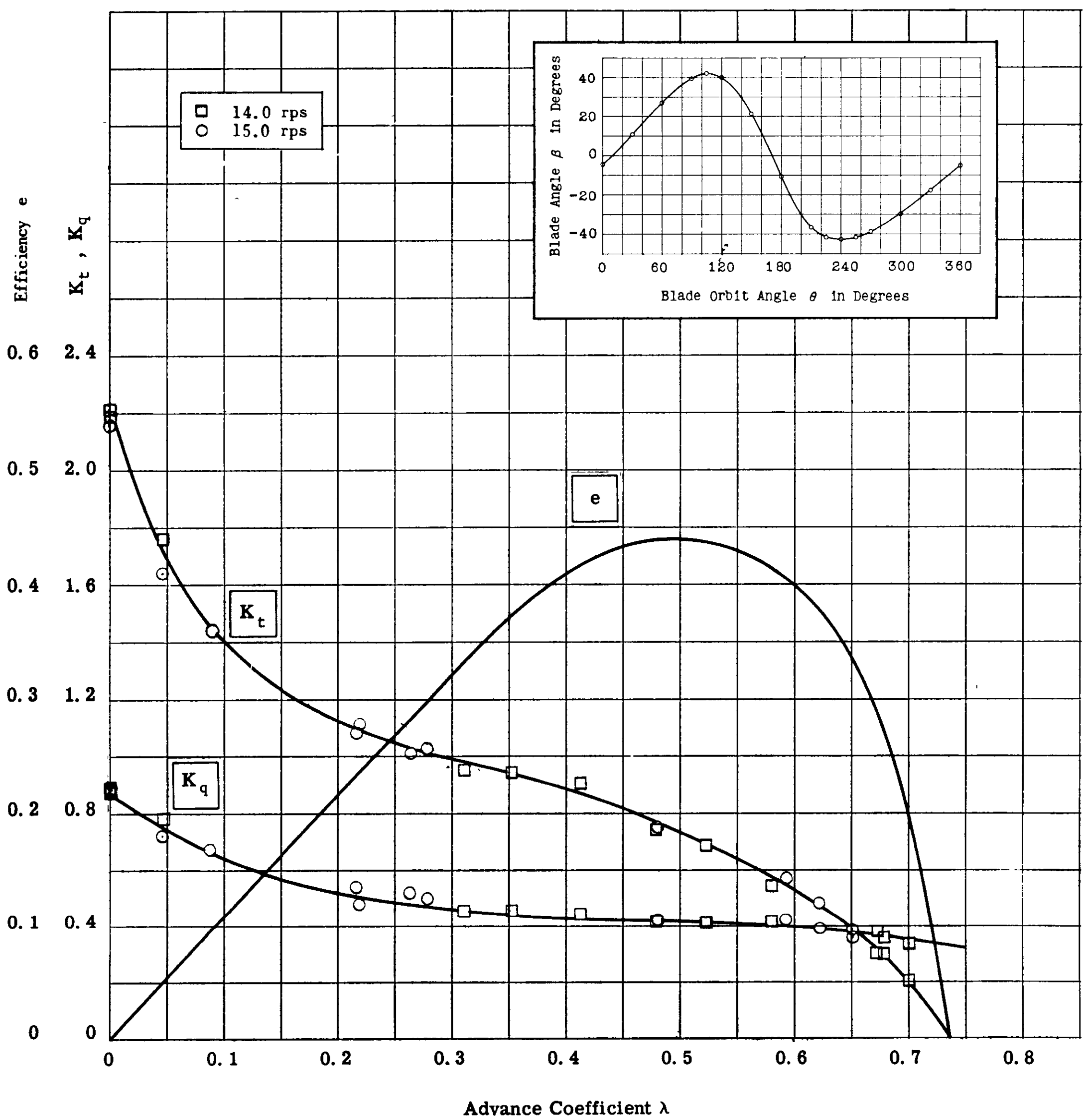


Figure 10 - Performance Curves for Vertical Axis Propeller with Modified Cycloidal Blade Motion

(β_{max} = 42.0 degrees at θ = 106 degrees)

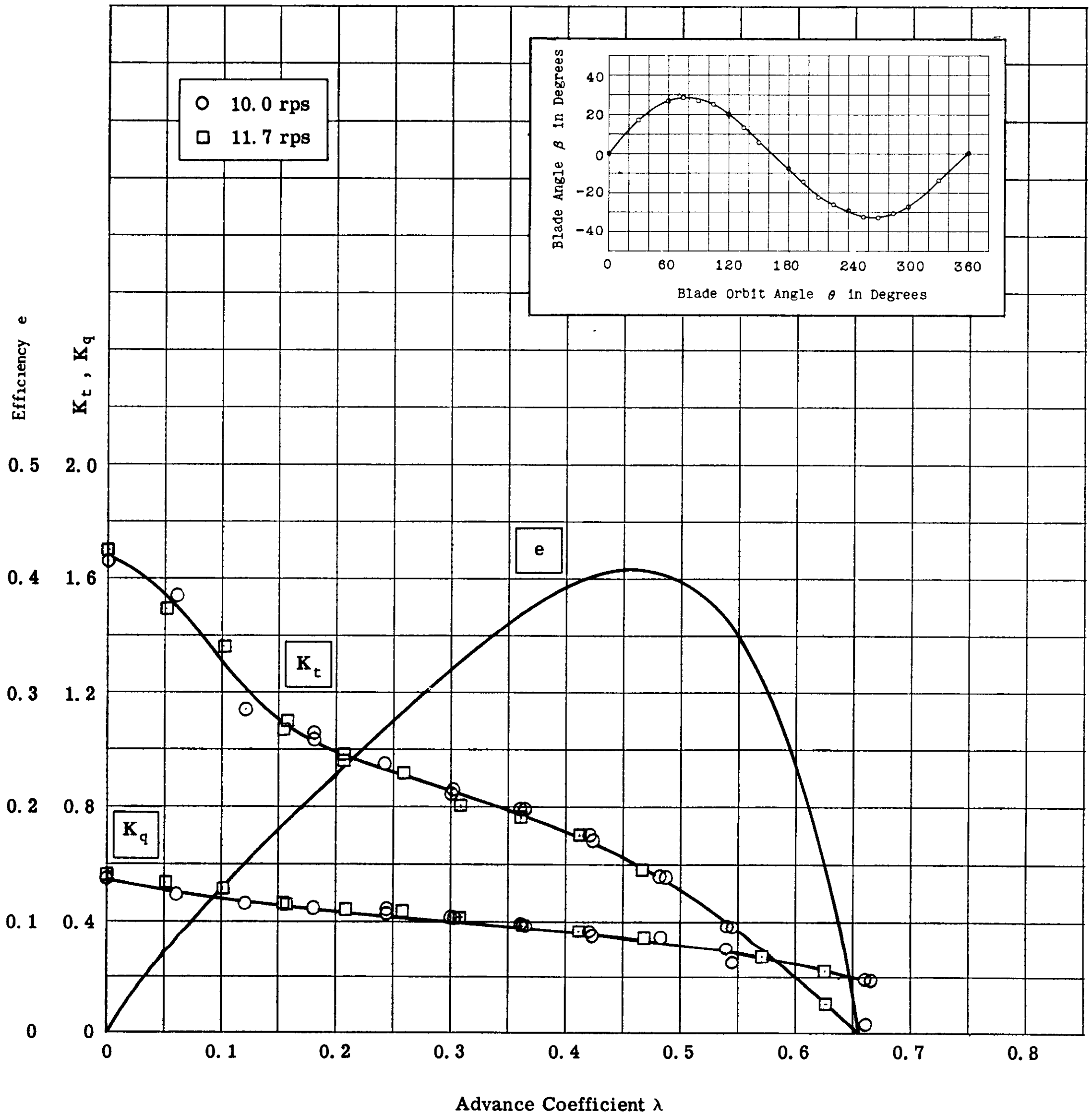


Figure 11 - Performance Curves for Vertical Axis Propeller with Modified Sinusoidal Blade Motion
(β_{max} = 28.4 degrees at θ = 80 degrees)

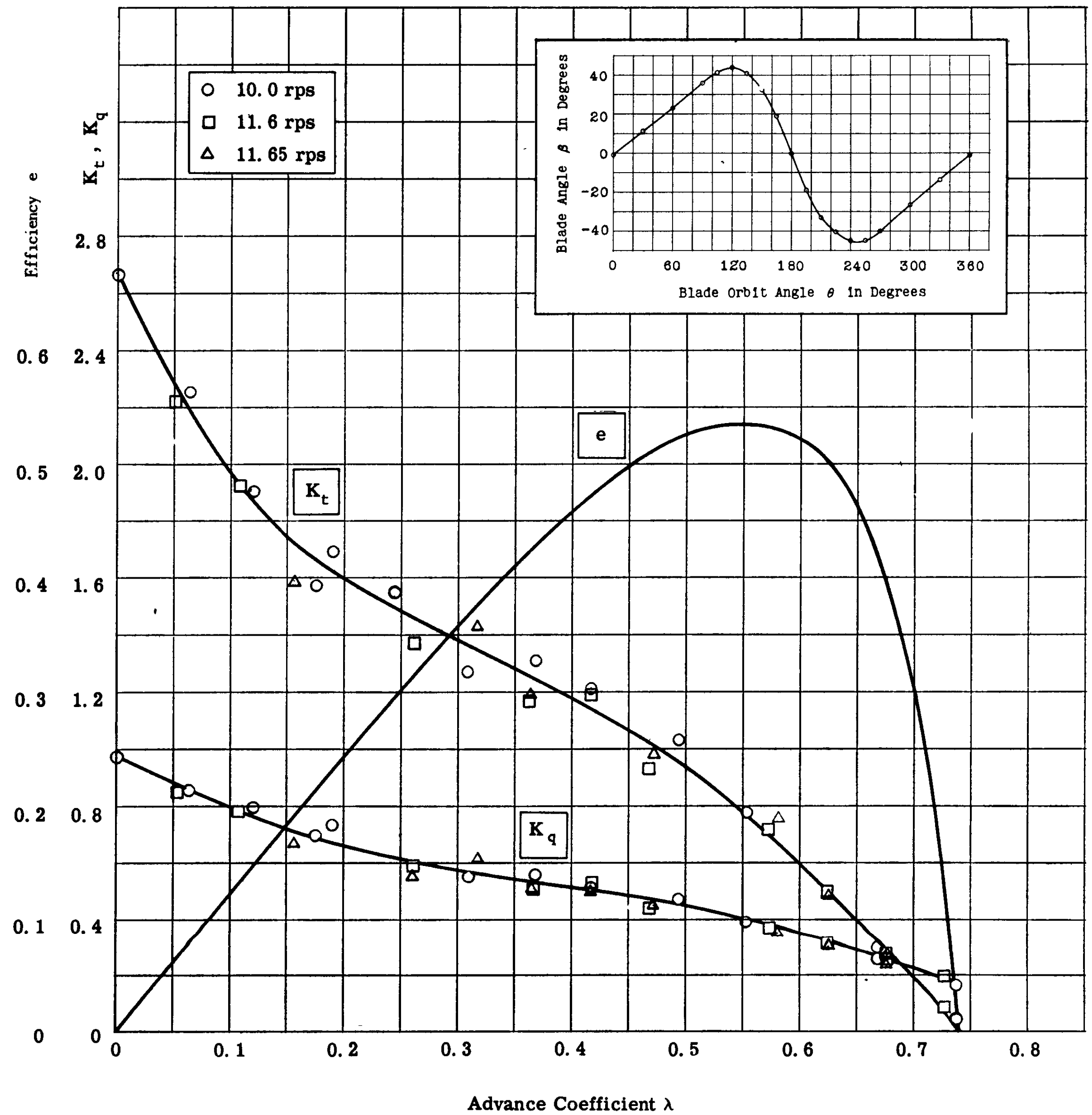


Figure 12 - Performance Curves for Vertical Axis Propeller with Modified Cycloidal Blade Motion
(β_{max} = 43.5 degrees at θ = 120 degrees)

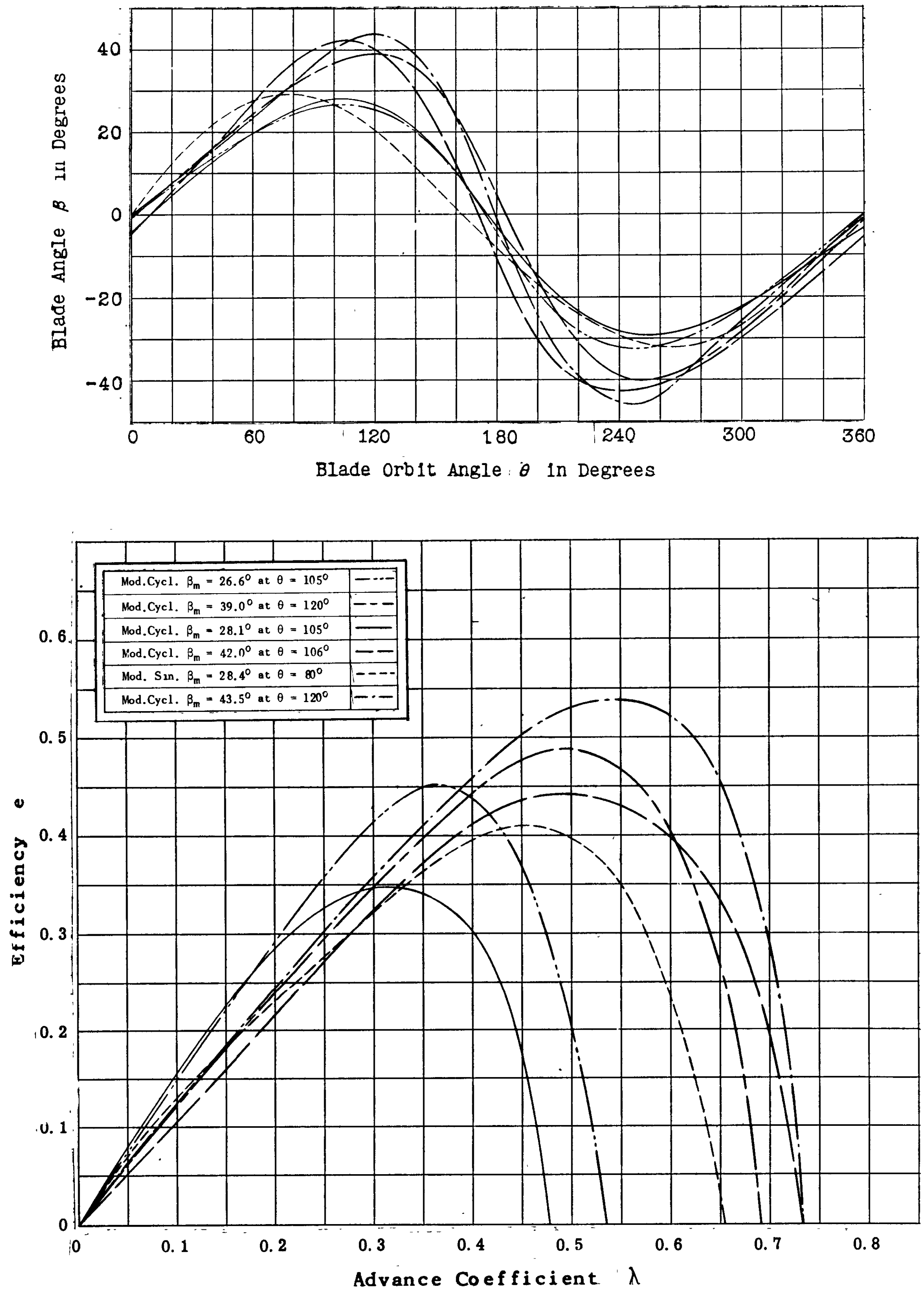
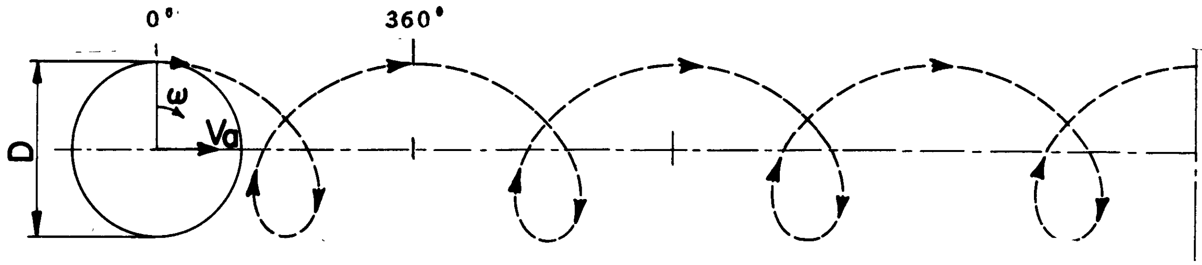
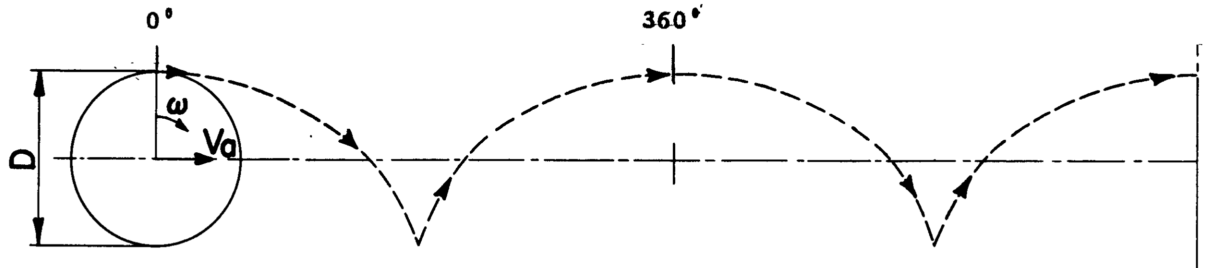


Figure 13 - Comparison of Efficiency Curves for Different Types of Blade Motion



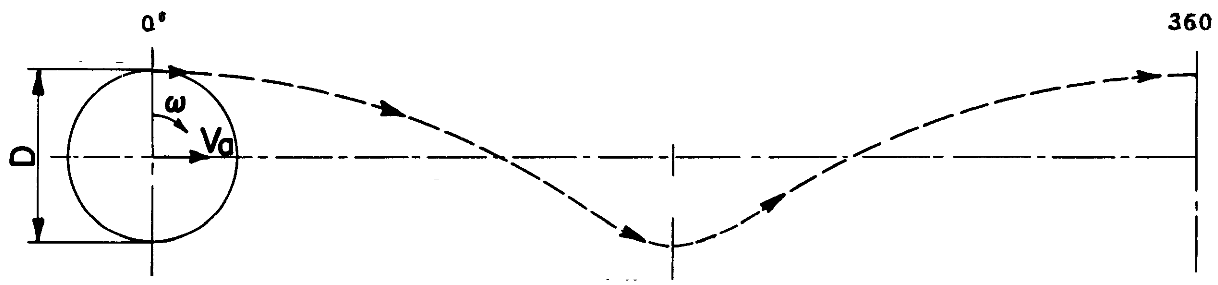
λ = ½

Curtate Cycloid



λ = 1

Common Cycloid



λ= 2

Prolate Cycloid

Figure 14 - Blade Path at Different Advance Coefficients

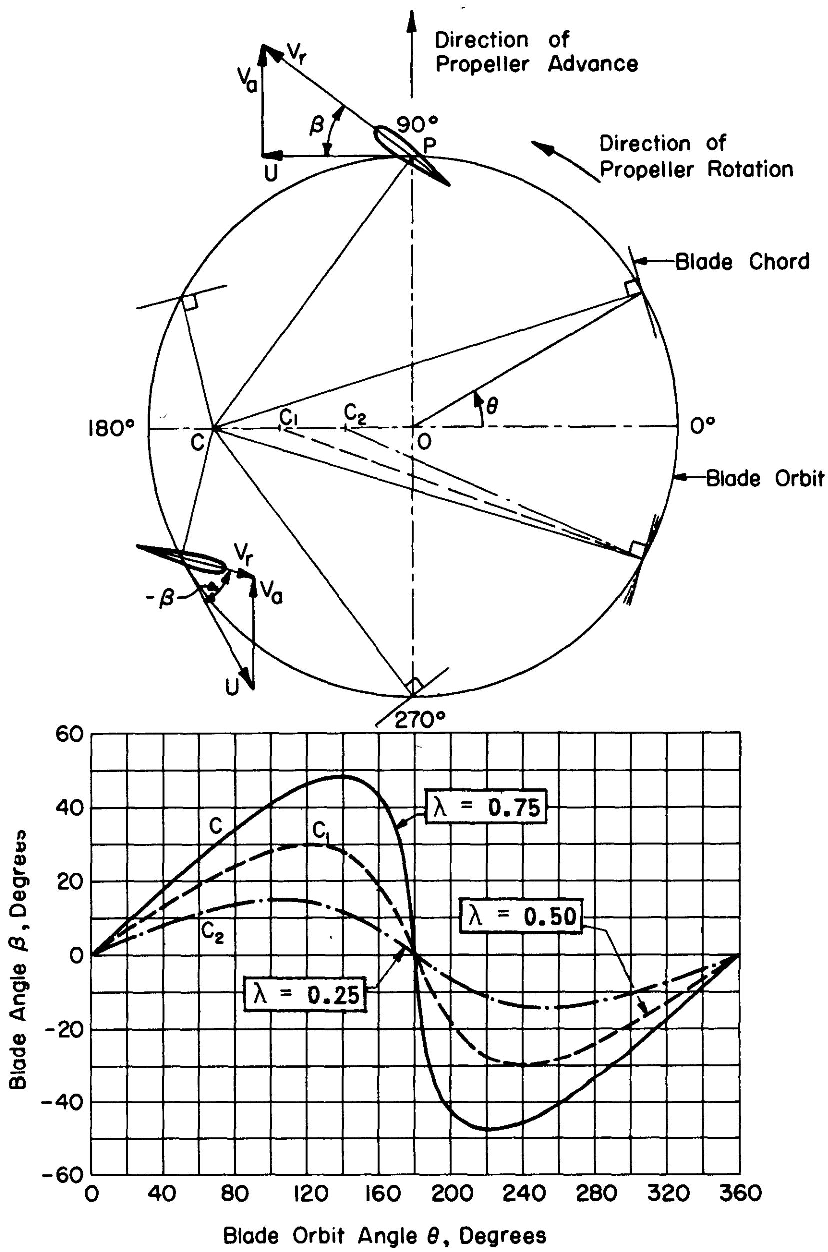


Figure 15 - Cycloidal Blade Motion at Various Advance Coefficients

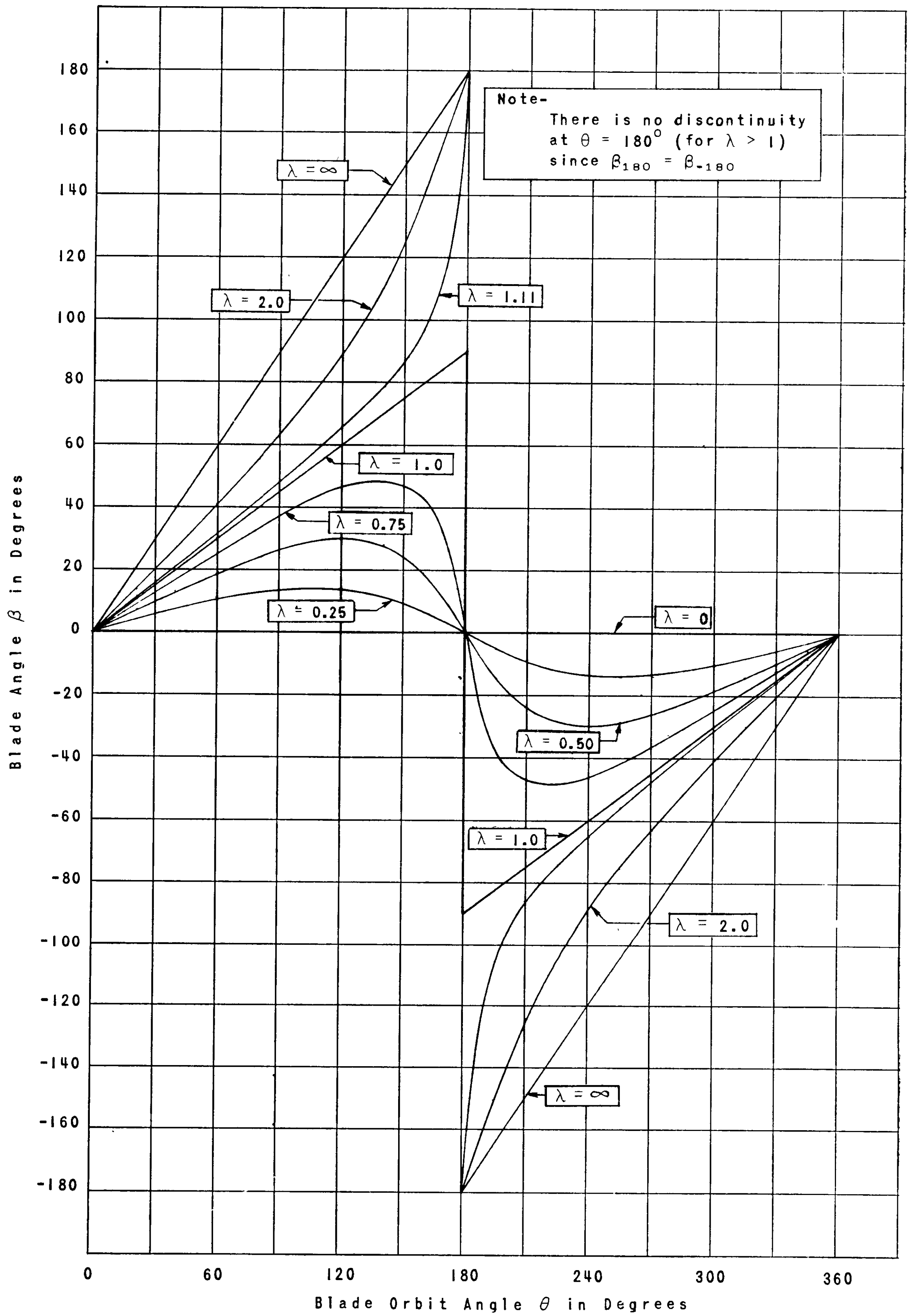


Figure 16 – Examples of Cycloidal Blade Motion over Entire Range of Advance Coefficients

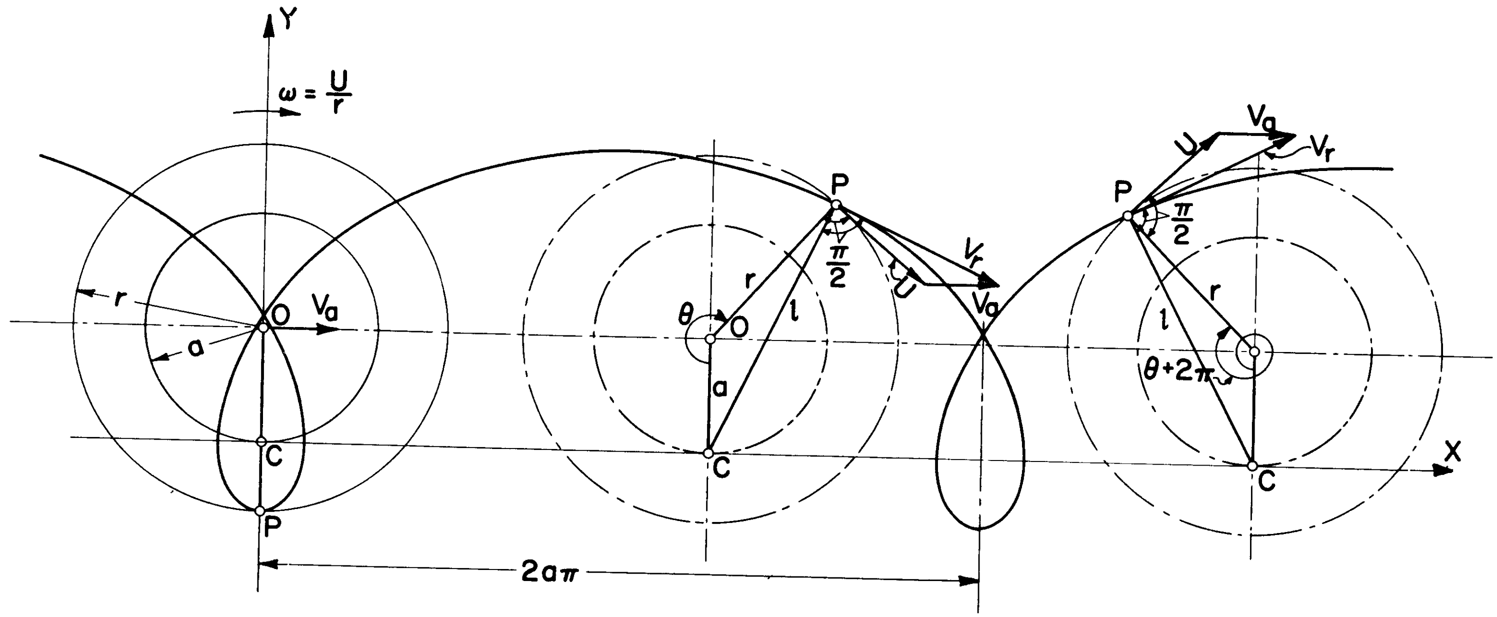


Figure 17 - Curtate Cycloid Associated with Pitch Ratios Smaller than One

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This report presents the results of experimental investigations of the performance of a 6-bladed vertical axis propeller (Voith-Schneider type). The investigations were conducted at different pitch ratios using modified cycloidal and sinusoidal blade motion. The tests were carried out at constant rpm of 600, 700, 800, and 900, respectively, for a range of speeds from zero to the speed of zero thrust. The results are presented in form of performance characteristic curves using new nondimensional coefficients of the K - λ type adapted to vertical axis propellers.

1. Vertical-axis propellers--Performance--Model tests
I. Nakonechny, Basil V.

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