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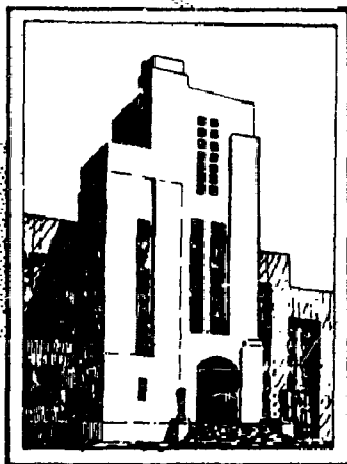
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DEPARTMENT OF THE NAVY
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HYDROMECHANICS

PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PROPELLERS
CALCULATED BY TANIGUCHI'S METHOD

by

AERODYNAMICS

W.L. Haberman and E.E. Harley

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PERFORMANCE OF VERTICAL AXIS (CYCLOIDAL) PROPELLERS
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NOTATION

a_o	Blade section lift-curve slope
b	Blade length
c	Blade chord
c_s	Blade chord at root
c_d	Blade section drag coefficient
c_{do}	Blade section drag coefficient at zero lift
c_l	Blade section lift coefficient
d	Blade section drag
D	Orbit diameter ($= 2R$)
e	Propeller efficiency ($= \frac{K_T}{K_Q} \frac{\lambda}{2}$)
I_1, I_2, I_3	Integrals, defined on page 5
k	Constant in expression for blade section drag coefficient
K_T	Propeller thrust coefficient ($= \frac{T}{\rho n^2 D^5 b}$)
K_Q	Propeller torque coefficient ($= \frac{Q}{\rho n^2 D^5 b}$)
l	Blade section lift (in direction perpendicular to resultant velocity v)
m	Moment about orbit origin acting on each blade section
n	Revolutions per unit time
Q	Total torque of propeller
R	Orbit radius
t	Blade section thrust
$T(\theta)$	Instantaneous thrust of blade
T_{av}	Average thrust of blade of propeller
T	Total thrust of propeller
u_i	Induced velocity component in direction of advance
u_o	Speed of advance of propeller

v	Resultant velocity of fluid past blade section
z	Number of propeller blades
α	Angle of attack of blade section measured from angle of zero lift
η	Eccentricity setting of propeller
θ	Blade orbit angle
κ	Correction factor in momentum relation
λ	Advance coefficient ($= \frac{u_o}{n\pi D}$)
λ_i	Induced velocity factor
ρ	Density of fluid
σ	Solidity ($= \frac{z C_b}{\pi D}$)
ϕ	Blade angle
ω	Angular velocity ($= n\pi D$)

ABSTRACT

A method proposed by Taniguchi has been used to compute the performance characteristics of vertical axis propellers having cycloidal blade motion and semi-elliptic blades. Numerical results of thrust and torque coefficient and efficiency are presented for a wide range of advance coefficients, maximum blade angle, and blade solidity.

Good agreement between the experimental performance and the computed results is obtained for two, three, and six-bladed cycloidal propellers.

INTRODUCTION

In a series of three papers, Taniguchi presented a method for numerically evaluating the performance characteristics of vertical axis propellers.^{1,2,3} In the first paper he derived expressions for the thrust, torque, and efficiency of a vertical axis propeller based on certain simplifying assumptions and estimates. After conducting experiments with a six-bladed vertical axis propeller he modified the earlier expressions for the propeller performance. The final form of the computational method proposed by Taniguchi was presented in detail as a doctoral thesis.³

To assess the validity of Taniguchi's method over a wide range of conditions, computations were carried out at the David Taylor Model Basin using his method. The results of the DTMB computations were compared with available data from DTMB experimental investigations on two, three, and six-bladed cycloidal propellers. In addition, numerical evaluation of propeller performance characteristics were carried out over a large range of propeller eccentricity and blade solidity. The results of all the computations and the comparison are presented in graphical form.

OUTLINE OF TANIGUCHI'S METHOD

The method proposed by Taniguchi for computing the performance characteristics of vertical axis propellers is based on the assumption that quasi-steady state motion exists.* The total thrust and torque of the propeller

¹ References are listed on page 10.

* An attempted unsteady theory for vertical axis propellers was analyzed in a recent report.⁴

is evaluated by integrating the lift and drag forces exerted on each blade section. For this purpose numerical values of lift and drag coefficients of the blade sections are required. In addition, an estimate of the magnitude and direction of the induced velocity at every blade section must be made. Taniguchi assumed (1) that only the longitudinal velocities induced by the trailing vortex system (i.e., those in the direction of propeller advance) contribute to the thrust and torque of the propeller, (2) that they are of constant magnitude over the length of blade, (3) that the induced velocity is not a function of the orbital position of the blade. The value of the induced velocity is obtained from momentum considerations with modifications based on experimental performance of a six-bladed vertical axis propeller.

The details of the derivation of Taniguchi's method are as follows:

Each propeller blade is assumed to rotate with constant angular velocity about the center "O" which advances at constant speed u_0 (Figure 1). As a consequence of the motion, the fluid exerts a force on each section of the blade. This force can be resolved into two components: the section lift force and the section drag force. These forces can be expressed in terms of the force coefficient and dynamic head, namely

$$l = c_l \frac{\rho}{2} v^2 c$$

$$d = c_d \frac{\rho}{2} v^2 c$$

where the lift is in a direction perpendicular to the resultant field velocity past each blade section, while the drag is parallel to the resultant velocity.

Taking the components of the lift and drag force on the blade section in the direction of forward motion of the propeller, the thrust force due to each blade section is obtained:

$$t = l \cos(\theta - \phi + \alpha) + d \sin(\theta - \phi + \alpha)$$

where θ is the blade orbit angle, ϕ is the blade angle, and α is the angle of attack of blade section. For most of the orbital positions of the blade, the drag contribution to the section thrust will be small in comparison to the lift contribution. An exception occurs at orbit angles in the neighborhood of 90 and 270 degrees. Since the integrated effect over the entire orbit is of concern here, Taniguchi neglected the drag term. Thus

$$t = c_l \frac{1}{2} v^2 c \cos(\theta - \varphi + \alpha)$$

The moment about the propeller origin acting on each blade section is (see Figure 2)

$$m = l \cos(\theta - \varphi + \alpha) R \sin \theta - l \sin(\theta - \varphi + \alpha) R \cos \theta \\ + d \cos(90 - \theta + \varphi - \alpha) R \sin \theta + d \sin(90 - \theta + \varphi - \alpha) R \cos \theta$$

Using trigonometric simplification, we obtain

$$m = l R \sin(\varphi - \alpha) + d R \cos(\varphi - \alpha) \\ m = \frac{1}{2} v^2 c R [c_l \sin(\varphi - \alpha) + c_d \cos(\varphi - \alpha)]$$

To obtain quantitative evaluation of propeller performance, values must now be assigned to these coefficients. In his earlier paper,¹ Taniguchi used the following values for the drag and lift coefficient:

$$c_l = a_0 \alpha = 5.34 \alpha \quad (\alpha \text{ in radians}) \\ c_d = c_{d0} + k \alpha^4 = 0.10 + 6 \alpha^4$$

These values were based on averages obtained from wind tunnel tests on airfoil sections. In his second paper,² Taniguchi revised the expression for the drag coefficient based on the experiments conducted by him on six-bladed cycloidal propellers with semi-elliptic blade outline. The revised expression is as follows:

$$c_d = c_{d0} + k \alpha^2 = 0.019 + 2.24 \alpha^2$$

Substituting into the expression for thrust and moment of the blade section we obtain

$$t = \frac{1}{2} v^2 c a_0 \alpha \cos(\theta - \varphi + \alpha)$$

$$\text{and} \quad m = \frac{1}{2} v^2 c R [a_0 \alpha \sin(\varphi - \alpha) + (c_{d0} + k \alpha^2) \cos(\varphi - \alpha)]$$

To evaluate the thrust and torque of a given propeller, the following relationships must be known:

(1) The variation of resultant velocity (v) at each blade section with blade orbit angle (θ).

(2) The variation of blade angle (φ) with blade orbit angle (θ).

From a knowledge of v and φ at every blade orbit position, we can derive a relationship between angle of attack of blade (α) and orbit angle (θ).

In evaluating the resultant velocity v past each blade section, Taniguchi included only the induced velocity in the direction of forward motion of the propeller. Thus he takes

$$v^2 = (n\pi D)^2 + (u_o + u_i)^2 - 2(u_o + u_i) n\pi D \sin \theta$$

Dividing by $(n\pi D)^2$ we obtain

$$\left(\frac{v}{n\pi D}\right)^2 = 1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta$$

He further assumed that the induced velocity is constant over the entire length of blade and is independent of blade orbit position.

For cycloidal blade motion, the tangent of the blade angle varies with the orbit angle in the following manner:

$$\tan \phi = \frac{\eta \cos \theta}{1 - \eta \sin \theta}$$

where η is the eccentricity setting of the propeller and is related to the maximum blade angle as indicated in Figure 3.

By appropriate substitution we obtain an expression for $\cos(\theta - \phi + \alpha)$ in terms of θ , λ , and λ_i , namely

$$\cos(\theta - \phi + \alpha) = \pm \frac{\cos \theta}{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}$$

Where the positive signs applies to values of θ between $-\pi/2$ and $\pi/2$, while the negative sign applies to values of θ between $\pi/2$ and $3/2\pi$. By further substitution, we obtain the following relation between angle of attack (α) of the blade section and blade orbit angle (θ):

$$\tan \alpha = \pm \frac{(\eta - \lambda - \lambda_i) \cos \theta}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta}$$

where the same sign convention as given above holds. For small angles α i.e., for angles of attack below the stall angle (12 to 16 degrees), $\tan \alpha \cong \alpha$. Thus the section thrust at a given orbit position is

$$t = \frac{\rho}{2} a_o c (\pi n D)^2 (\eta - \lambda - \lambda_i) \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta$$

The thrust of each blade at a given orbital position is then obtained by integrating over the blade length. Thus

$$T(\theta) = \int_0^b t \, db$$

For blades with semi-elliptic outline, the thrust of each blade becomes

$$T(\theta) = \frac{\pi^3}{8} \rho a_o c b n^2 D^2 (\eta - \lambda - \lambda_i) \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta$$

With the assumption of constant induced velocity and symmetry of blade motion (Figure 3), the thrust of each blade is symmetric in the forward and aft half of the orbit. To obtain the average thrust of each blade (T_{av}), we need to average over half of the orbit only. Thus

$$T_{av} = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} T(\theta) d\theta = \frac{\pi^2}{8} \rho a_0 C_s b n^2 D^2 (\eta - \lambda - \lambda_i) \int_{-\pi/2}^{\pi/2} \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta d\theta$$

The total thrust of the propeller is then obtained by multiplying by the number of blades

$$T = z T_{av}$$

The moment of the blade section about the propeller origin becomes

$$m = \frac{\rho}{2} c \frac{D}{2} (\pi n D)^2 [a_0 (\lambda + \lambda_i) (\eta - \lambda - \lambda_i) \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta + c_{d0} \{1 - (\lambda + \lambda_i) \sin \theta\} \sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta} + k (\eta - \lambda - \lambda_i)^2 \{1 - (\lambda + \lambda_i) \sin \theta\} \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{\{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta\}^2} \cos^2 \theta]$$

The total torque of the propeller is then given by

$$Q = z \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \int_0^b m db d\theta$$

For brevity, let

$$I_1 = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \frac{\sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta} \cos^2 \theta d\theta$$

$$I_2 = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \{1 - (\lambda + \lambda_i) \sin \theta\} \sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta} d\theta$$

$$I_3 = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \frac{\{1 - (\lambda + \lambda_i) \sin \theta\} \sqrt{1 + (\lambda + \lambda_i)^2 - 2(\lambda + \lambda_i) \sin \theta}}{\{1 + \eta(\lambda + \lambda_i) - (\eta + \lambda + \lambda_i) \sin \theta\}^2} \cos^2 \theta d\theta$$

The thrust and torque of the propeller therefore become

$$T = \frac{\pi^3}{8} z \rho C_s b n^2 D^2 a_0 (\eta - \lambda - \lambda_i) I_1$$

$$Q = \frac{\pi^3}{16} z \rho C_s b n^2 D^3 [a_0 (\lambda + \lambda_i) (\eta - \lambda - \lambda_i) I_1 + c_{d0} I_2 + k (\eta - \lambda - \lambda_i)^2 I_3]$$

Define the thrust and torque coefficients as follows:

$$K_T = \frac{T}{\rho n^2 D^3 b}$$

$$\text{and } K_Q = \frac{Q}{\rho n^2 D^4 b}$$

In addition, let $\sigma = \frac{z C_s}{\pi D}$ be the solidity of the blades. We, therefore, obtain the following expressions for the thrust and torque coefficient:

$$K_T = \frac{\pi^4}{8} a_0 \sigma (\eta - \lambda - \lambda_i) I_1$$

$$K_Q = \frac{\lambda + \lambda_i}{2} K_T + \frac{\pi^4}{16} \sigma [c_{d0} I_2 + k (\eta - \lambda - \lambda_i)^2 I_3]$$

Further the propeller efficiency is given by

$$e = \frac{K_T}{K_Q} \frac{\lambda}{2}$$

The integrals I_1 , I_2 , and I_3 can be evaluated numerically for values of eccentricity, advance coefficient and induced velocity factor. There now remains the problem of estimating values of the induced velocity factor. To obtain this estimate, Taniguchi used a momentum relation, namely

$$T = 2 \rho D b \frac{u_o + u_i}{\kappa} \left[\frac{u_o + u_i}{\kappa} - u_o \right]$$

Nondimensionalizing we obtain

$$K_T = 2 \pi^2 \frac{\lambda + \lambda_i}{\kappa} \left[\frac{\lambda + \lambda_i}{\kappa} - \lambda \right]$$

where κ is a correction factor to account for non-uniformity of induced velocity over the blade length. In Reference 1, Taniguchi estimated the value of κ as 1.176. After conducting experiments on a six-bladed propeller, and obtaining a large discrepancy between computed and experimental values of advance coefficient at zero thrust, Taniguchi modified the momentum relation for K_T to

$$K_T = \frac{2 \pi^2}{\kappa} (\lambda + \lambda_i) \lambda_i$$

The factor κ is now a projected area reduction factor. This modification resulted in a revised value of κ , namely 1.321.

Values of induced velocity factor as a function of propeller thrust coefficient for various advance coefficient are given in Figure 4.

To obtain performance characteristics of a propeller, of specified solidity over a range of advance coefficients, the two expressions for K_T must be solved simultaneously. This is done by graphical solution as indicated by the example shown in Figure 5, where the two expressions for thrust coefficient have been plotted for an eccentricity of 0.7 over a range of solidity and advance coefficient. The intersection of the $\sigma = \text{constant}$ and $\lambda = \text{constant}$ curves gives the value of thrust coefficient desired.

Using his revised values for section drag coefficient and κ , Taniguchi computed² the performance characteristics of vertical axis propellers with semi-elliptic blade outline and solidity of 0.40.

RESULTS OF DTMB NUMERICAL EVALUATIONS

Using the procedure outlined above and the revised values of section drag coefficient and induced velocity factor, the thrust coefficient, torque coefficient and efficiency of vertical axis propellers with cycloidal blade motion and semi-elliptic blade outline were evaluated by the David Taylor Model Basin over a range of advance coefficients, maximum blade angles (eccentricities), and solidities. The results of these computations are given in Figures 6 and 7. Propeller performance at values of eccentricity and solidity other than those given in the figures can easily be obtained by cross plotting.

As seen in the figures, the performance characteristics were evaluated at eccentricities up to 0.95. It is clear, however, that in some cases the angles of attack will be large and the angle of stall will be exceeded. Since small angles of attack were assumed in the derivation and since reduced lift characteristics of the blade sections are obtained for angle of attack exceeding the stall angle, reliable predictions of the performance characteristics cannot be expected for those cases. To illustrate this limitation, a typical variation of the angle of attack with blade orbit angle is shown in Figure 8. From the expression for α given in the preceding section, it is seen that for a given eccentricity, the maximum angle of attack always occurs at zero advance coefficient. Thus, values of maximum α at zero advance were computed over a range of eccentricity and solidity and are given in Figure 9.

From Figures 6 and 7 it is further seen that the total thrust, torque and maximum efficiency of the cycloidal propellers increase with increase in maximum blade angle. For increase in blade solidity, the total thrust and torque increases. However, the thrust and torque of each blade and the maximum efficiency of the propeller decrease with increase in number of blades of same dimensions. Such decrease in thrust per blade and efficiency is also characteristic of screw propellers (see e.g. Reference 5).

COMPARISON WITH DIMB EXPERIMENTS

A comparison was made between the results of the DIMB computations using Taniguchi's method and DIMB experimental measurements of the performance of vertical axis propellers with blades having semi-elliptic outline. The experiments were conducted with propellers having two, three, and six identical blades. Cycloidal blade motion was used in the experiments with eccentricity settings of 0.4 and 0.6.* The aspect ratio of the DIMB blades was the same as Taniguchi used in his experiments. The comparison between experimental and computational results is shown in Figures 10 and 11. It is seen from the figures that good agreement is obtained between the computed and experimental values of propeller performance. Of particular interest is the good prediction of the effect of varying the number of blades on the propeller.

The correction factor (κ) and section drag characteristics (c_{d0} , k) were evaluated by Taniguchi at the zero advance condition. He obtained an average value of 1.321 based on his experimental results of a six-bladed propeller at four different eccentricity settings. Table 1 gives values of κ evaluated from the results of the DIMB experiments.

TABLE 1
Evaluation of κ

η z	0.4			0.6		
	2	3	6	2	3	6
$K_T(\text{exp})$	0.70	0.86	1.13	1.22	1.56	2.13
$\lambda_i(\text{exp})$	0.212	0.240	0.277	0.287	0.323	0.375
κ	1.264	1.312	1.340	1.332	1.312	1.303
Av. κ	1.305			1.315		

* The results of the DIMB experimental investigation, in which blade motion and blade outline was varied, will be reported in detail in a forthcoming report.

In Table 2, the quantities used to evaluate the section drag characteristics are given. A plot of these quantities is also shown in Figure 12.

TABLE 2
Evaluation of Section Drag Coefficient

η z	0.4			0.6		
	2	3	6	2	3	6
$K_T(\text{exp})$	0.70	0.86	1.13	1.22	1.56	2.13
$K_Q(\text{exp})$	0.12	0.16	0.219	0.32	0.40	0.58
$\lambda + \lambda_i(\text{comp})$	0.212	0.240	0.277	0.287	0.323	0.375
$I_2(\text{comp})$	1.034	1.043	1.057	1.062	1.077	1.105
$I_3(\text{comp})$	0.506	0.500	0.492	0.535	0.520	0.497
$16 \frac{K_Q - \frac{1}{2}(\lambda + \lambda_i)K_T}{\pi^4 \sigma I_2}$	0.0547	0.0445	0.0243	0.1685	0.1124	0.06711
$(\eta - \lambda - \lambda_i)^2 I_3 / I_2$	0.0173	0.0123	0.00703	0.0494	0.0370	0.0229

CONCLUSIONS

The computational procedure proposed by Taniguchi for evaluating the performance characteristics of vertical axis propellers is adequate for propellers with cycloidal blade motion and semi-elliptic blades. For this type of propeller the procedure gives satisfactory prediction of the effect of number of blades on propeller performance.

For each blade motion other than cycloidal motion, experimental results are required to obtain new values of the correction factor κ . In addition, large changes in aspect ratio of the blade will affect the magnitude of the correction factor. Further, significant variation in blade motion would probably result in different values of the section characteristics.

In summary, the most serious limitation of Taniguchi's method lies in the way the induced velocities are estimated; specifically, in the assumption that only the longitudinal components contribute to propeller

performance, in the assumption that the induced velocity is constant over the entire length of the blade, and finally in the fact that the induced velocity cannot be computed without resorting to determination by experiment.

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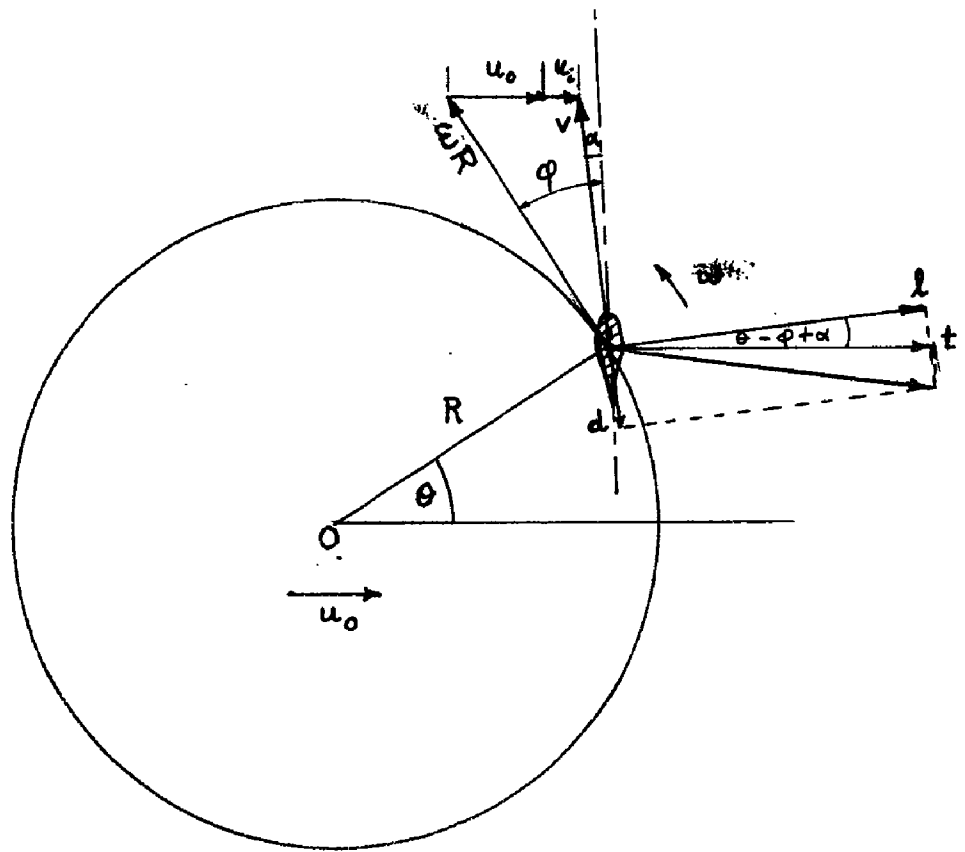


Figure 1 - Sketch of Blade Section Showing Forces Exerted

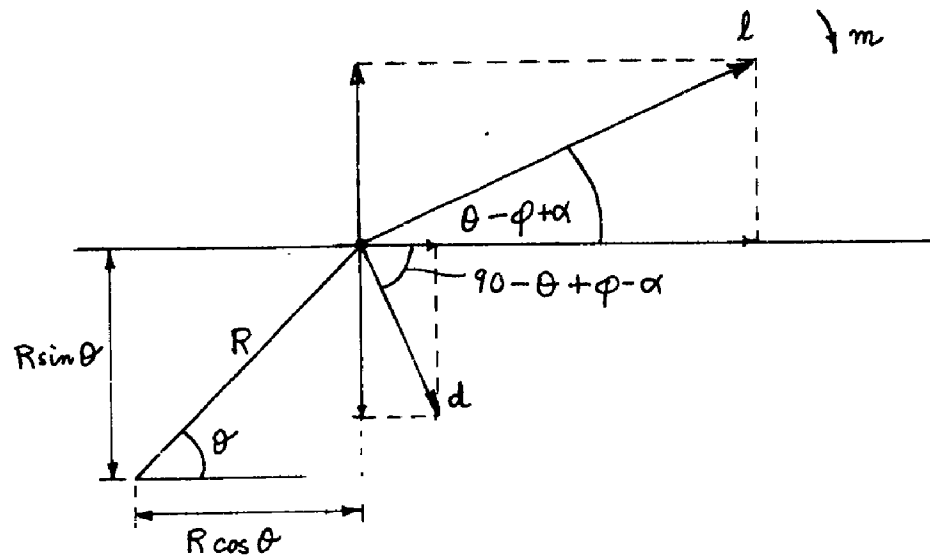


Figure 2 - Sketch of Blade Force System

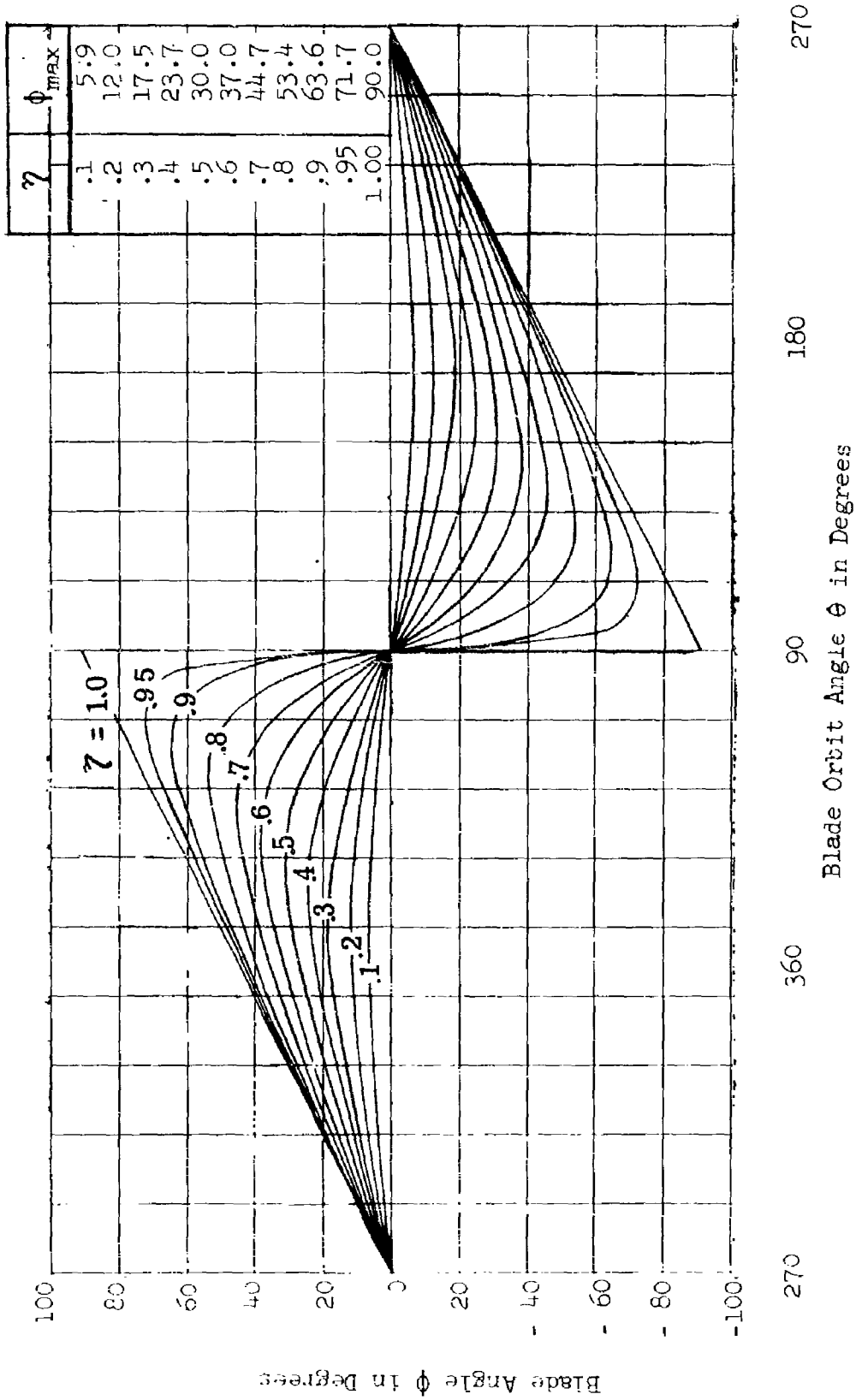


Figure 3 - Variation of Blade Angle with Blade Orbital Position for Various Eccentricities

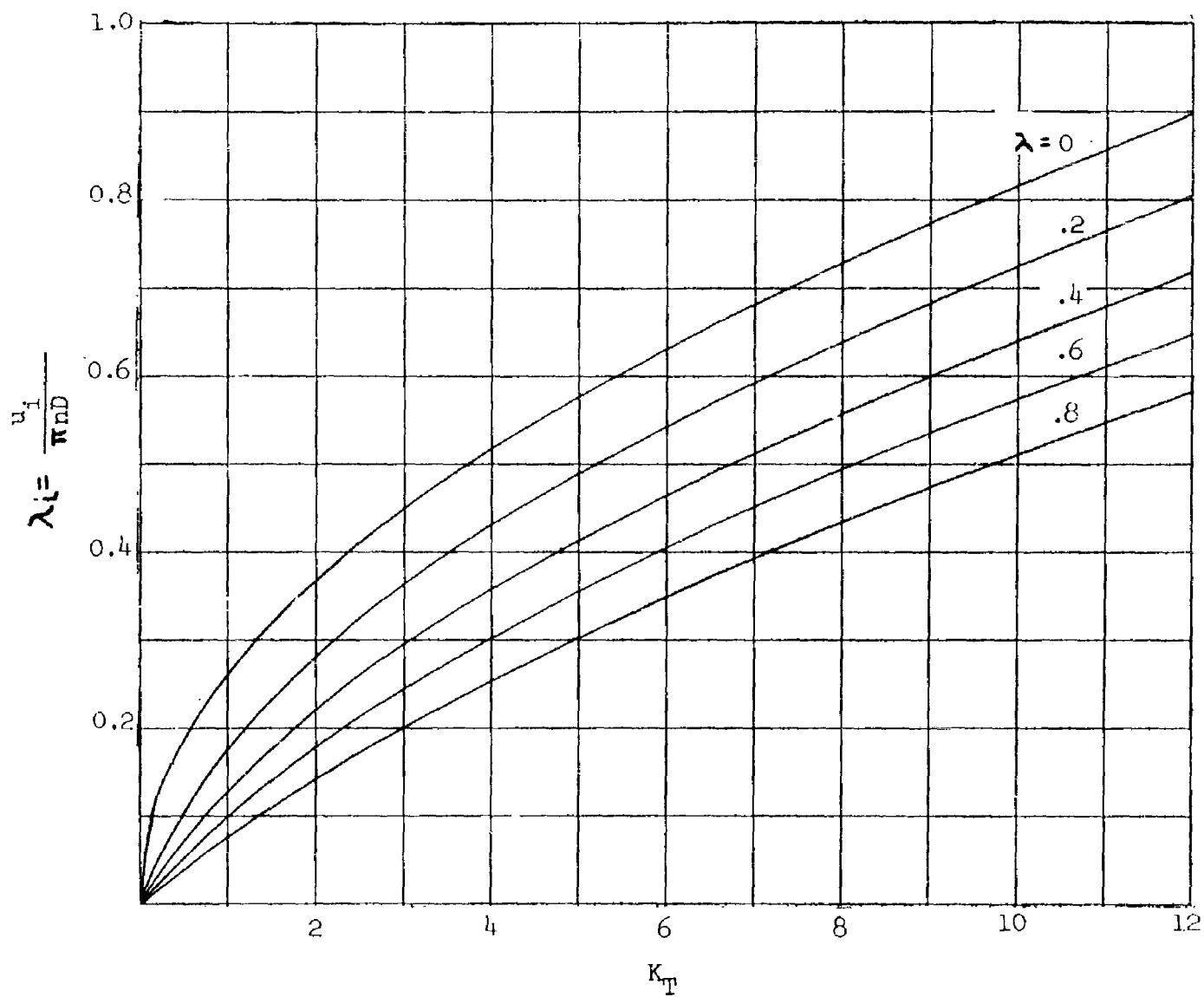


Figure 4 - Longitudinal Induced Velocity as a Function of Thrust Coefficient
for Various Advance Coefficients

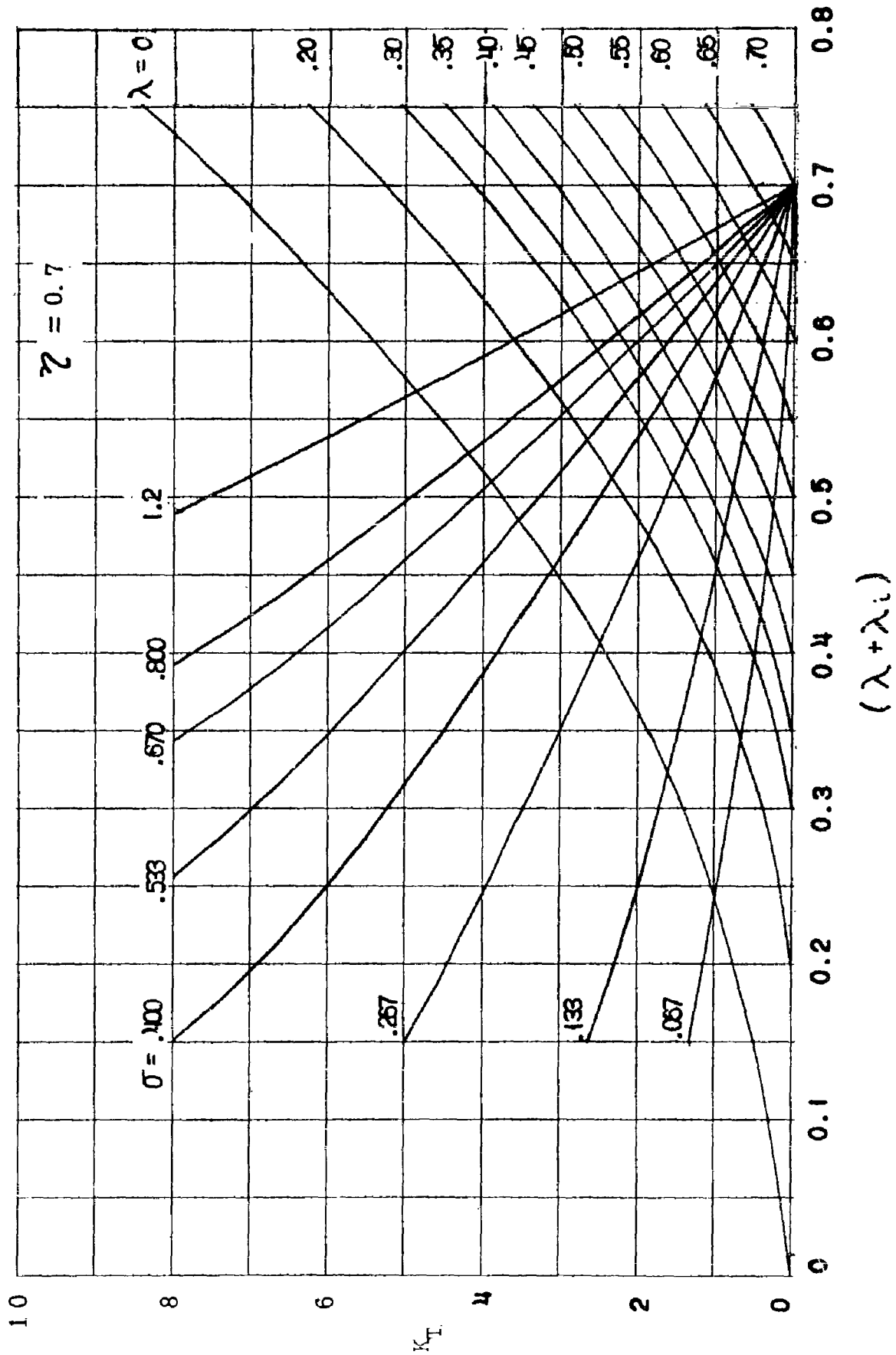


Figure 5 - Thrust Coefficient as a Function of Advance Coefficient and Induced Velocity Factor for Various Blade Solidities

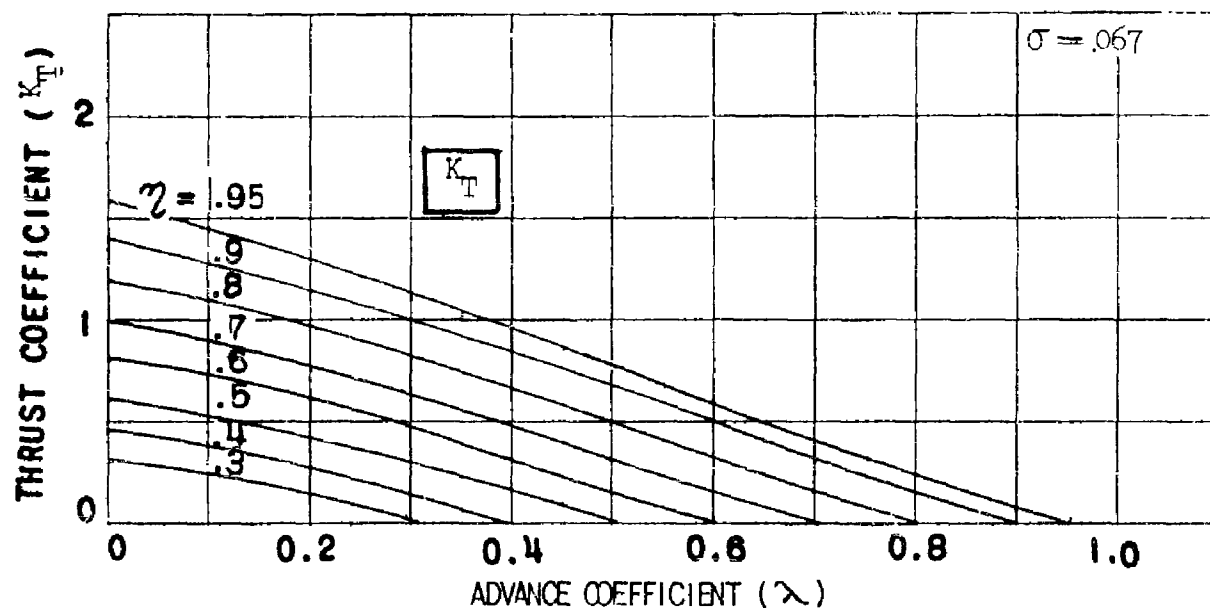


Figure 6(a) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .067$

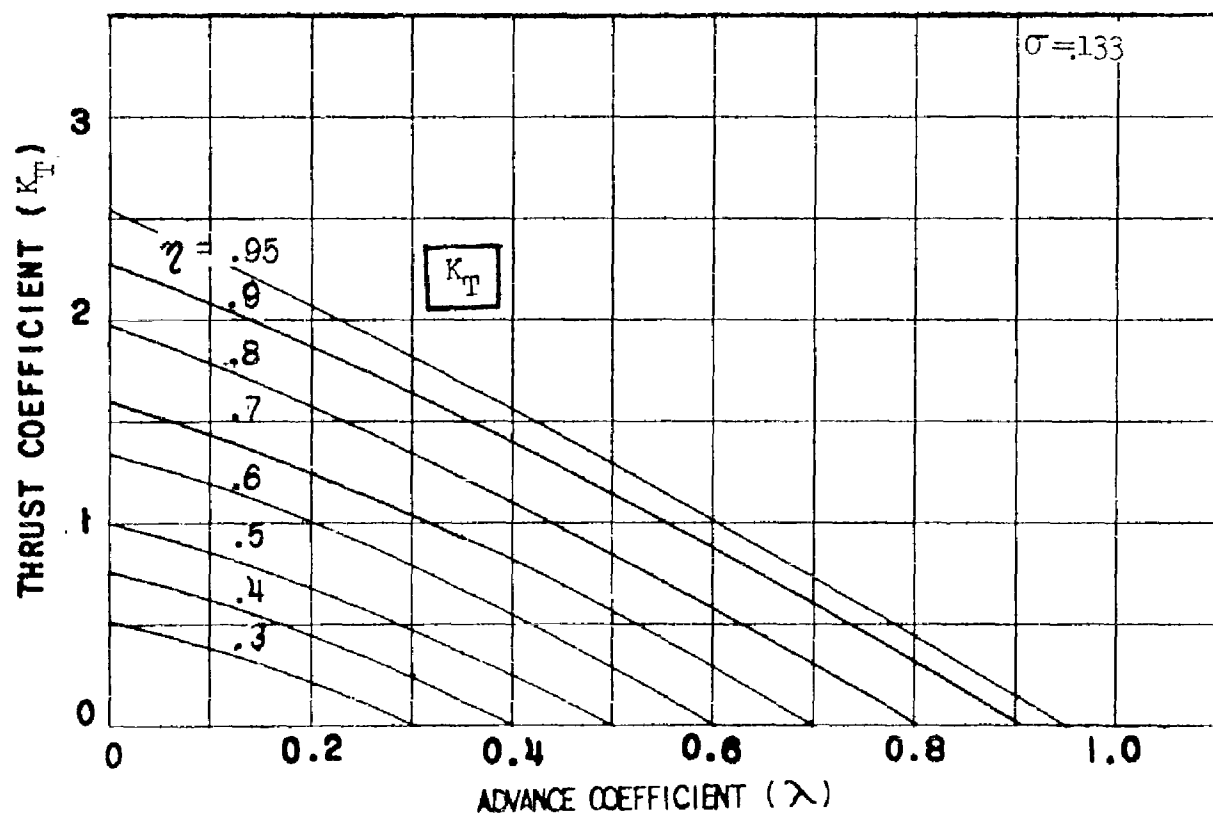


Figure 6(b) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .133$

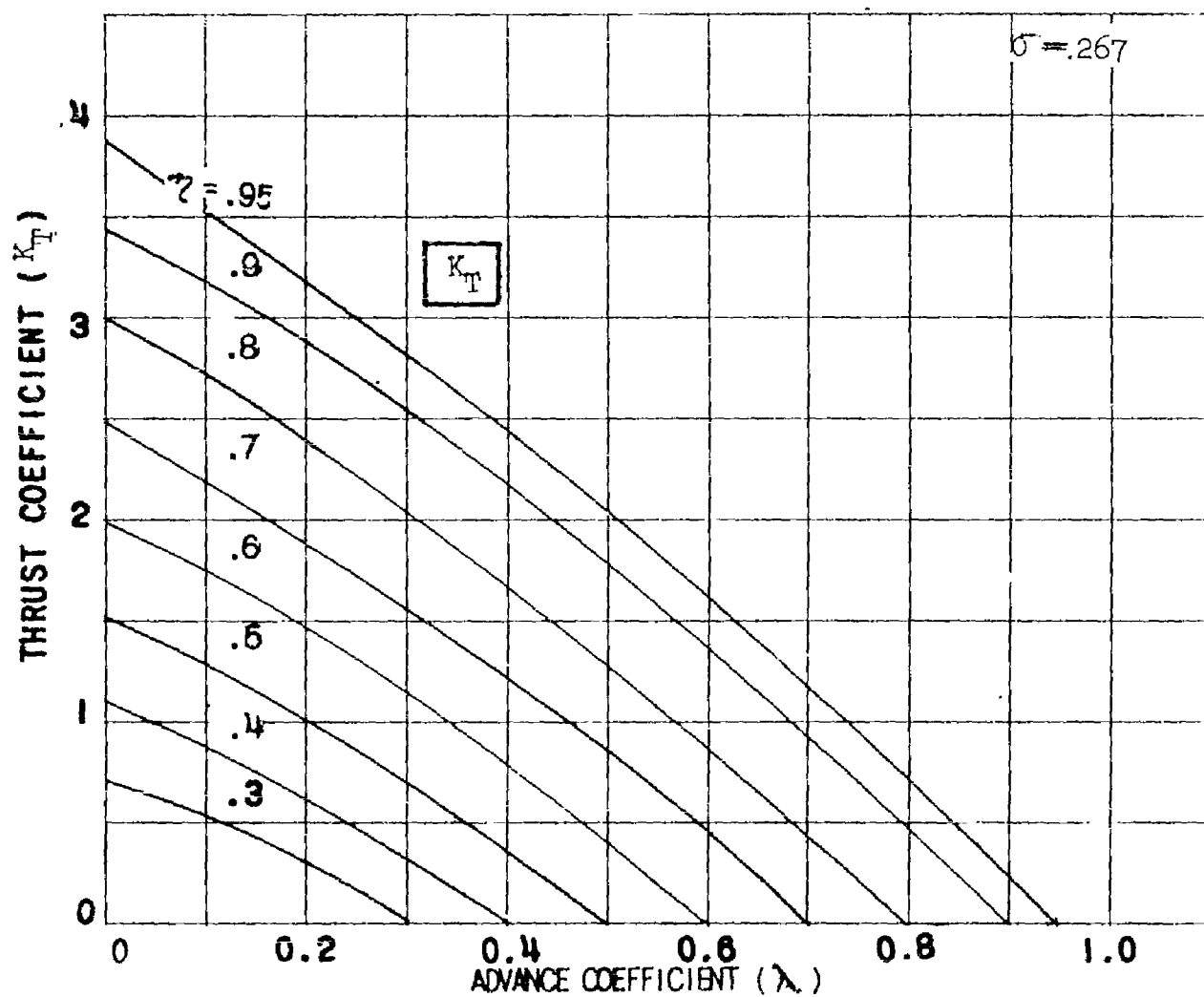


Figure 6(c) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .267$

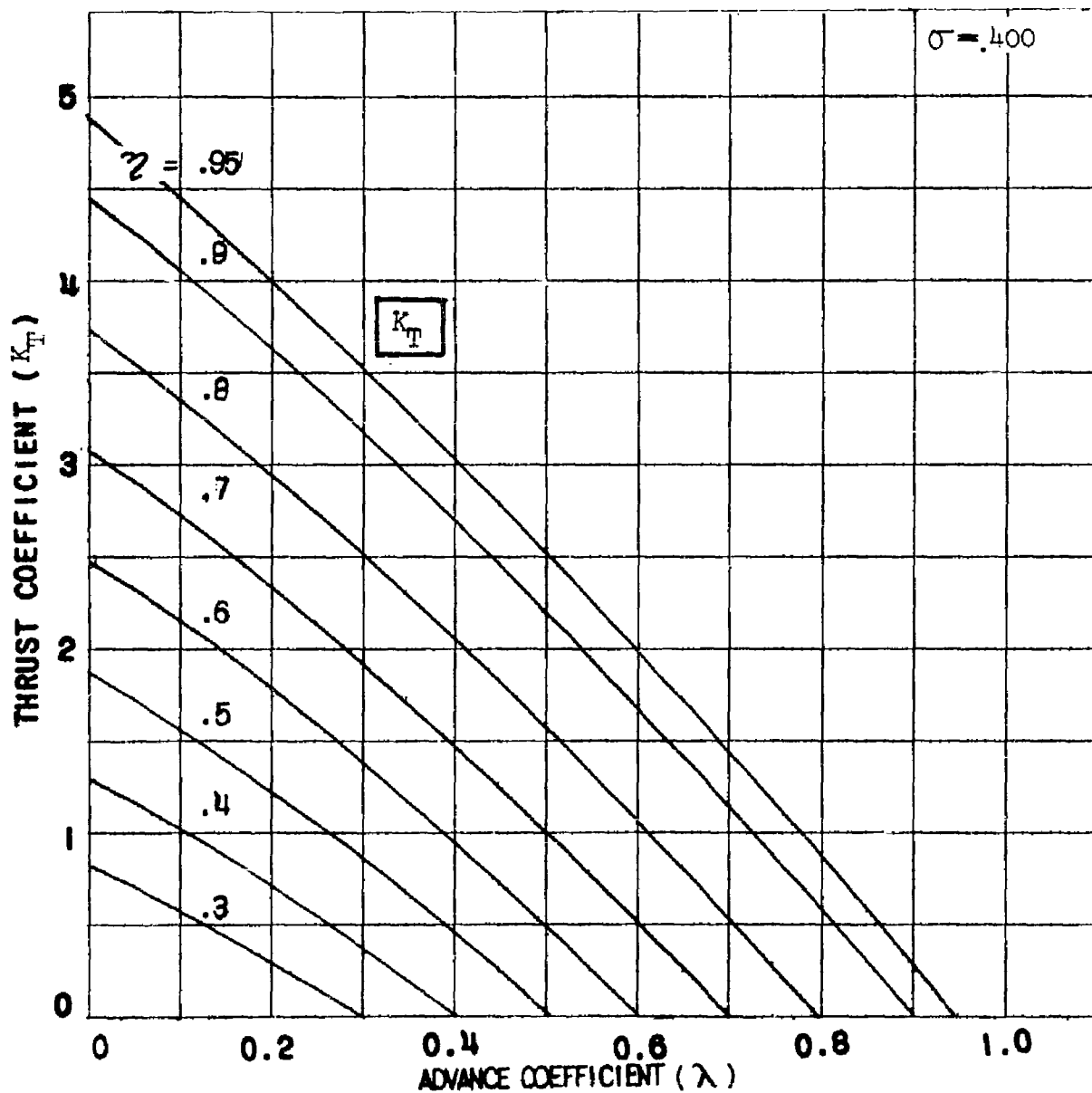


Figure 6(d) - Variation of thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .400$

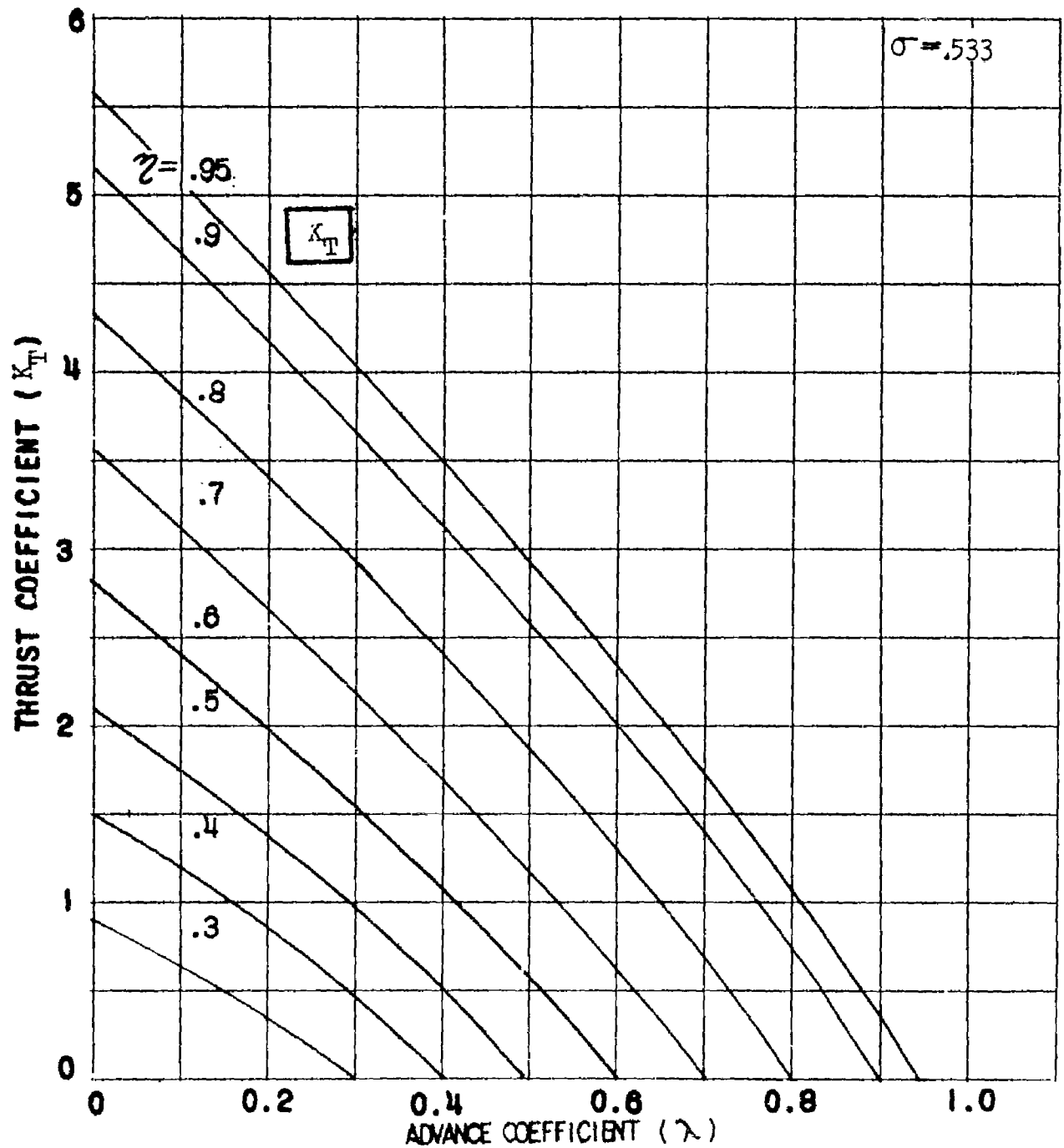


Figure 6(e) • Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .533$

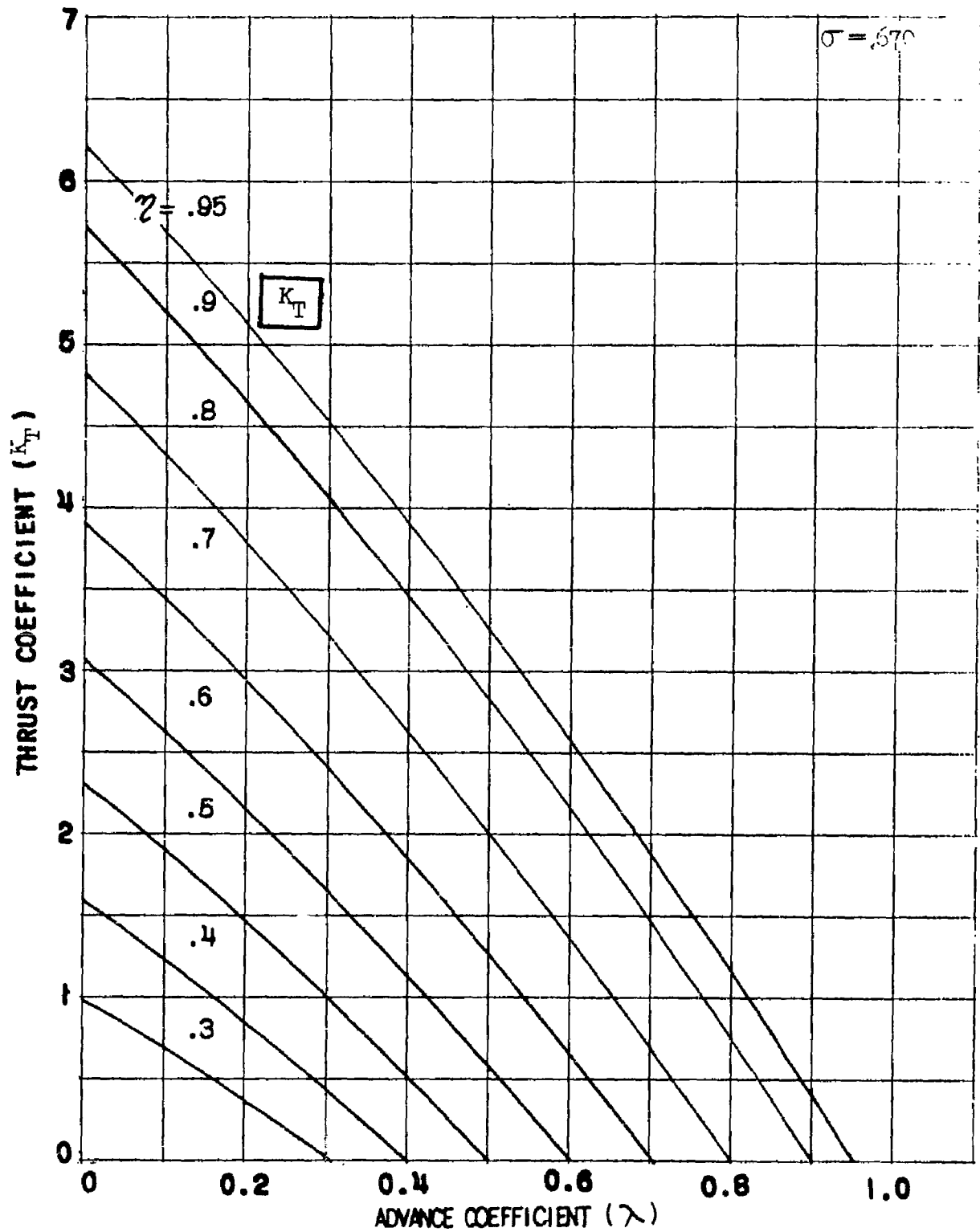


Figure 6(f) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .670$

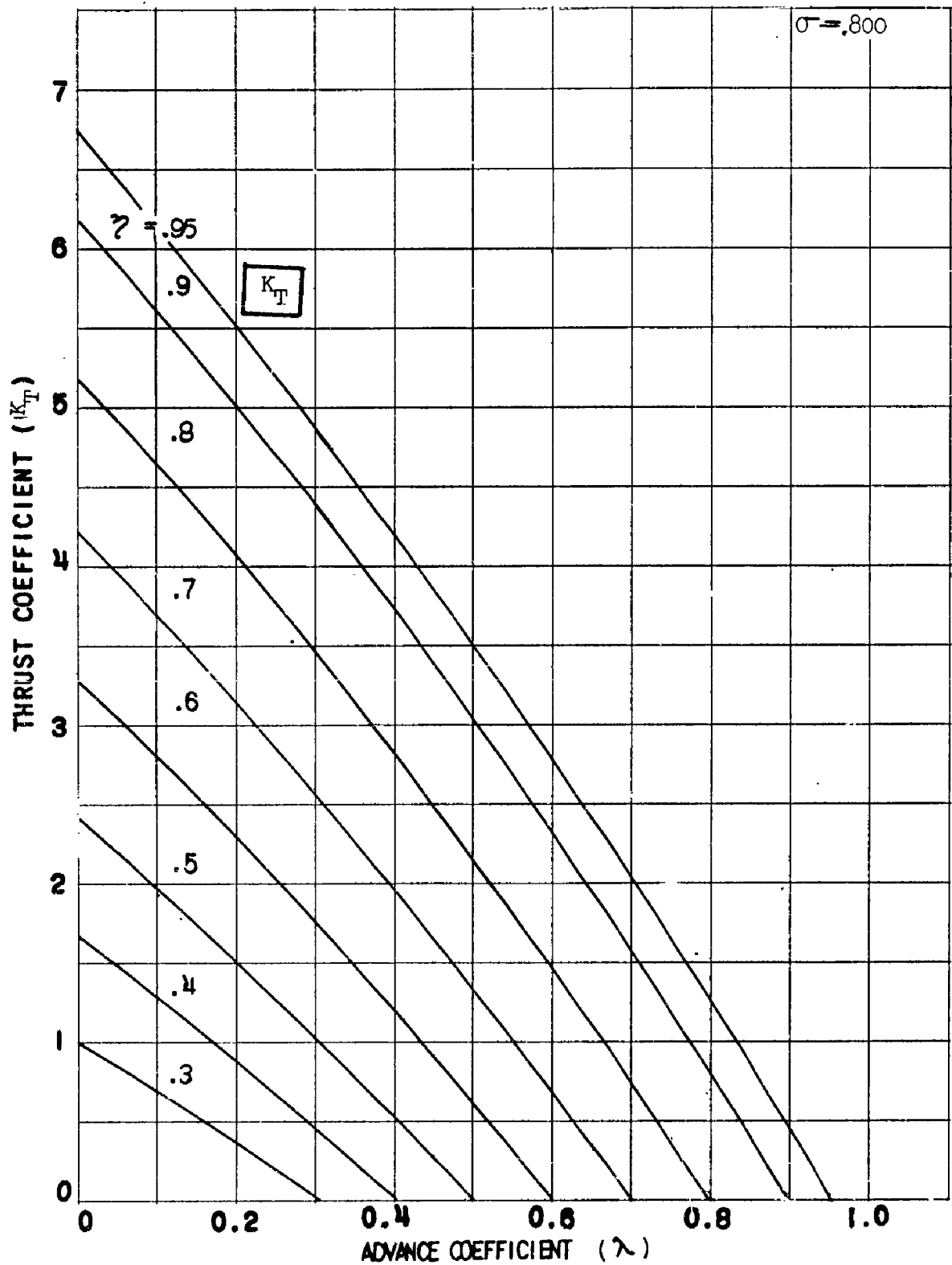


Figure 6(g) - Variation of Thrust Coefficient with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .800$

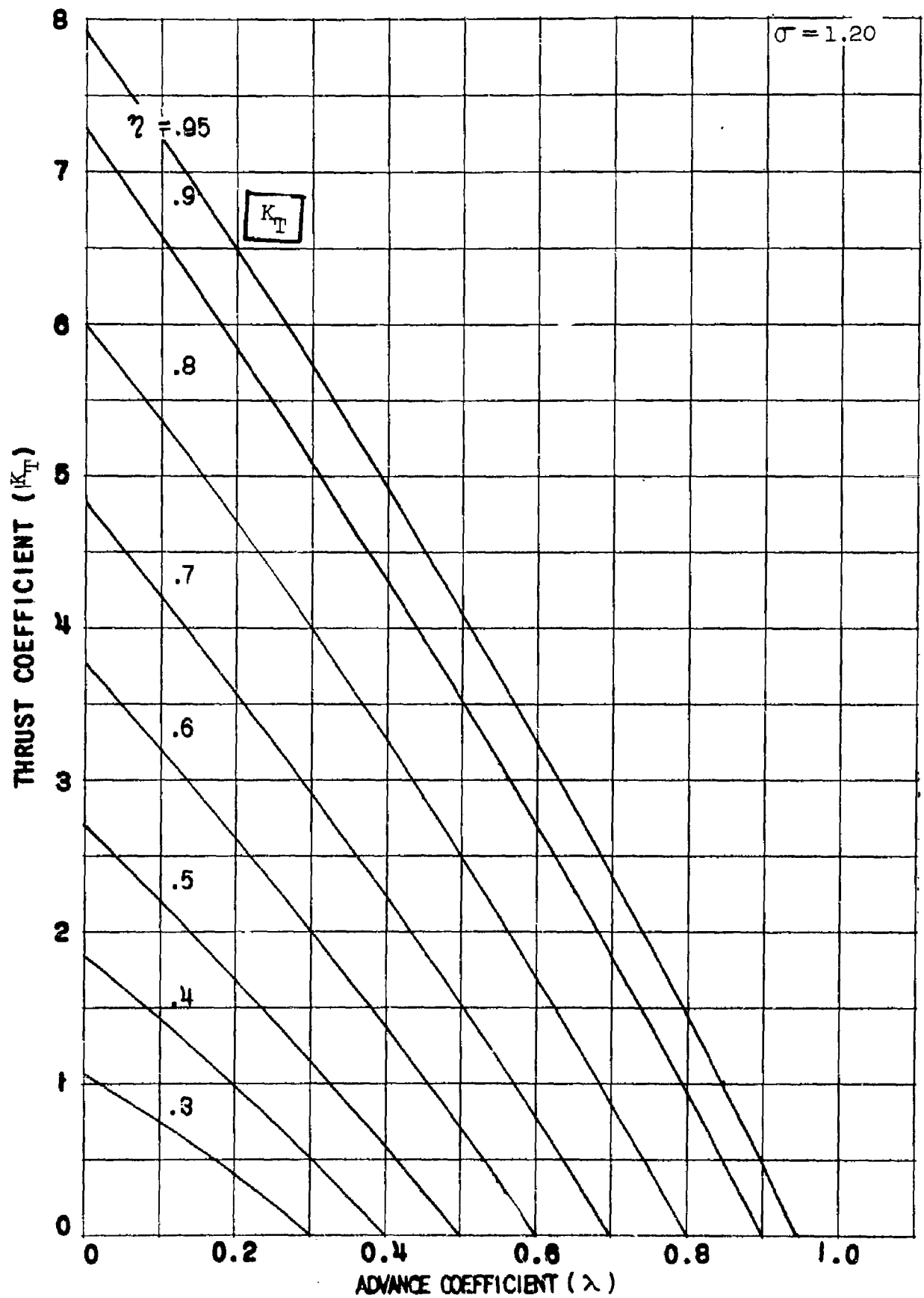


Figure 6(h) - Variation of Thrust Coefficient with Advance Coefficient
and Eccentricity for Various Values of Blade Solidity, $\sigma = 1.200$

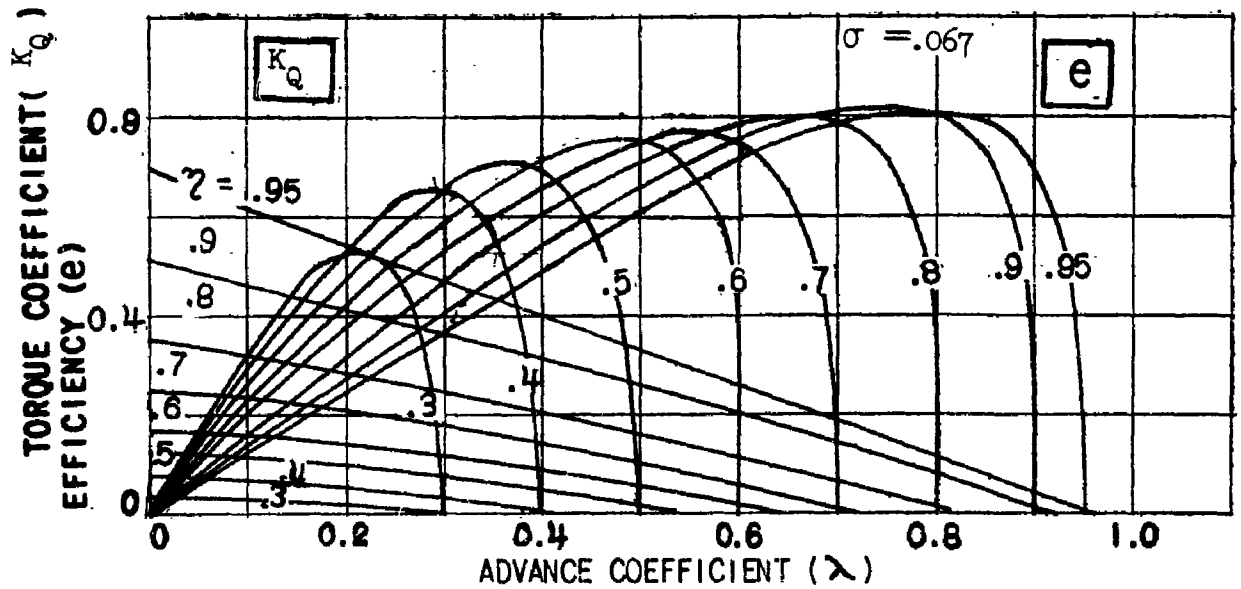


Figure 7(a) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .067$

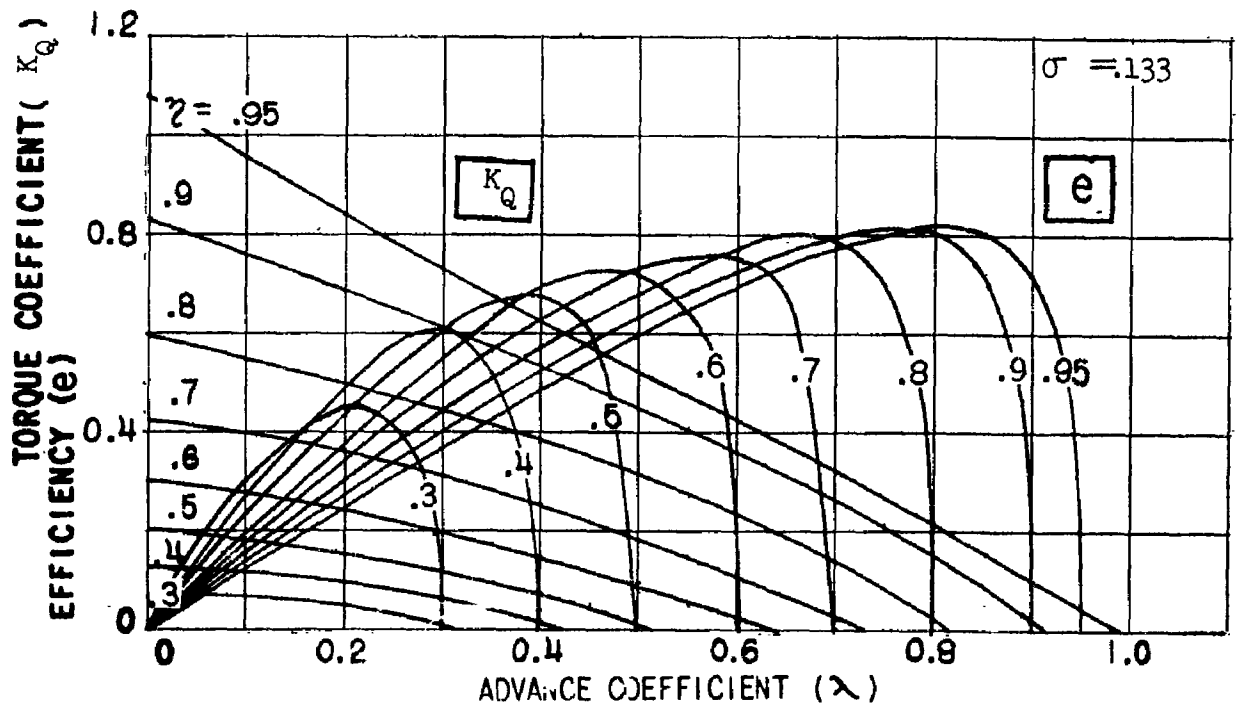


Figure 7(b) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .133$

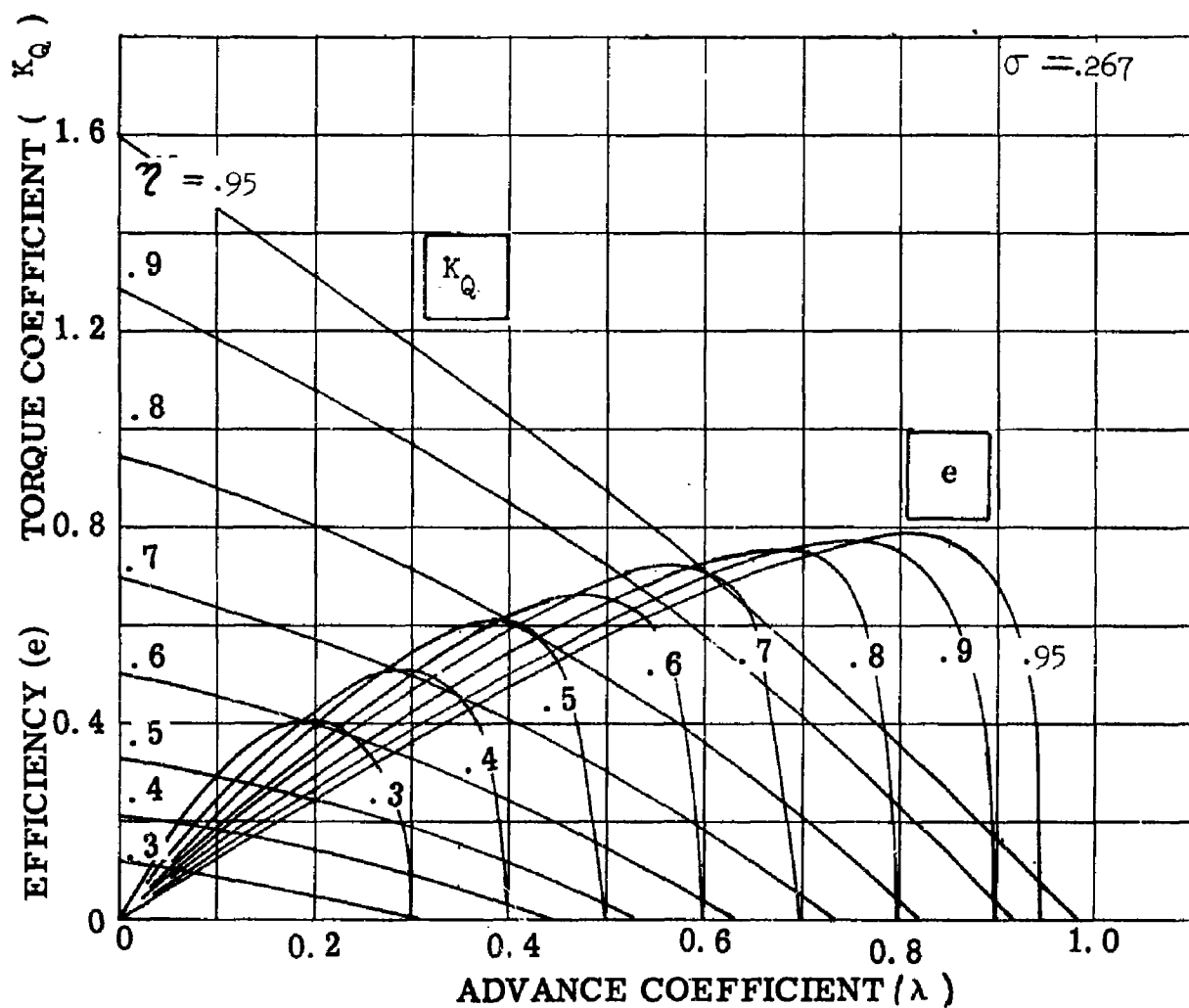


Figure 7(c) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .267$

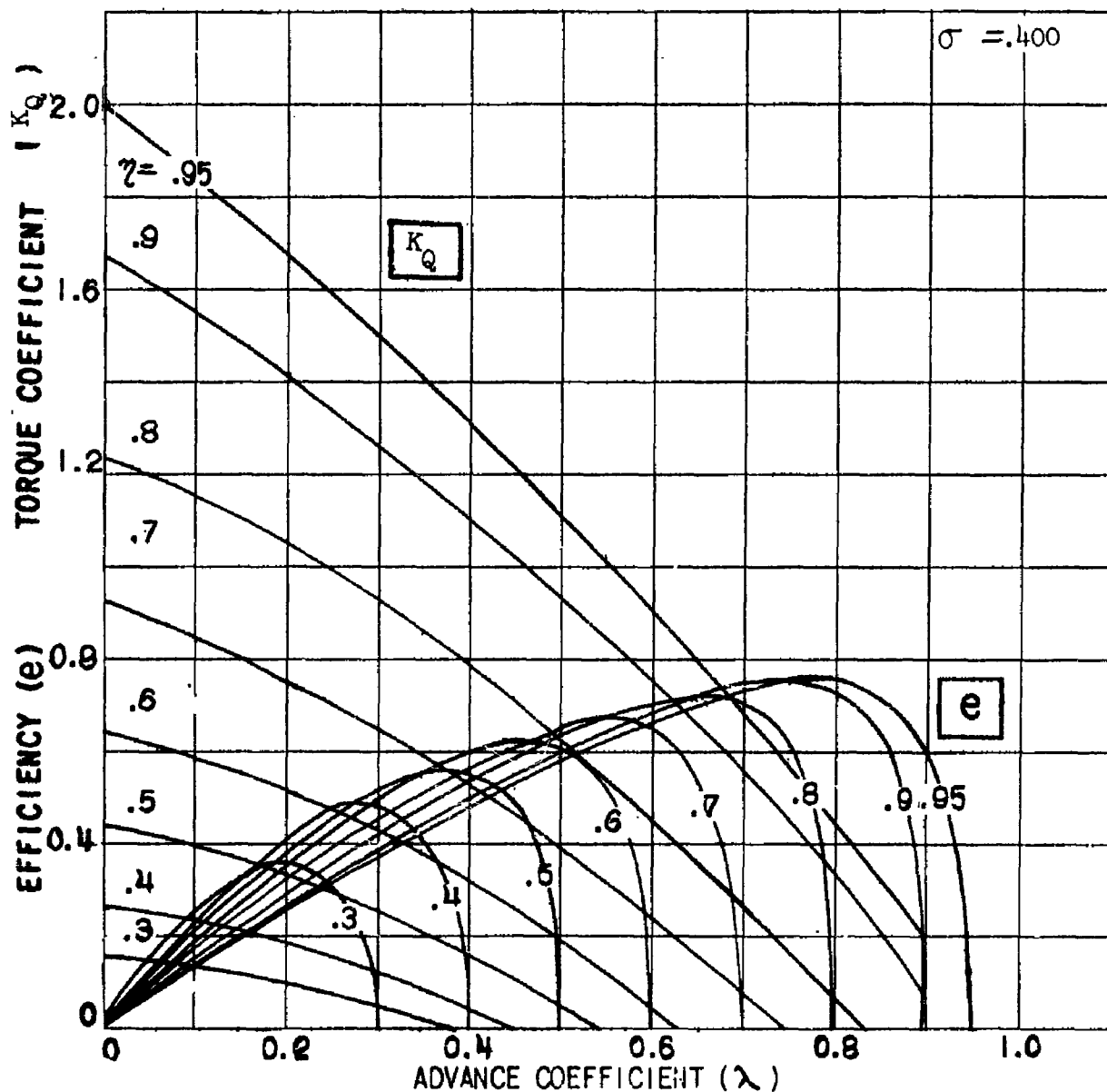


Figure 7(d) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .400$

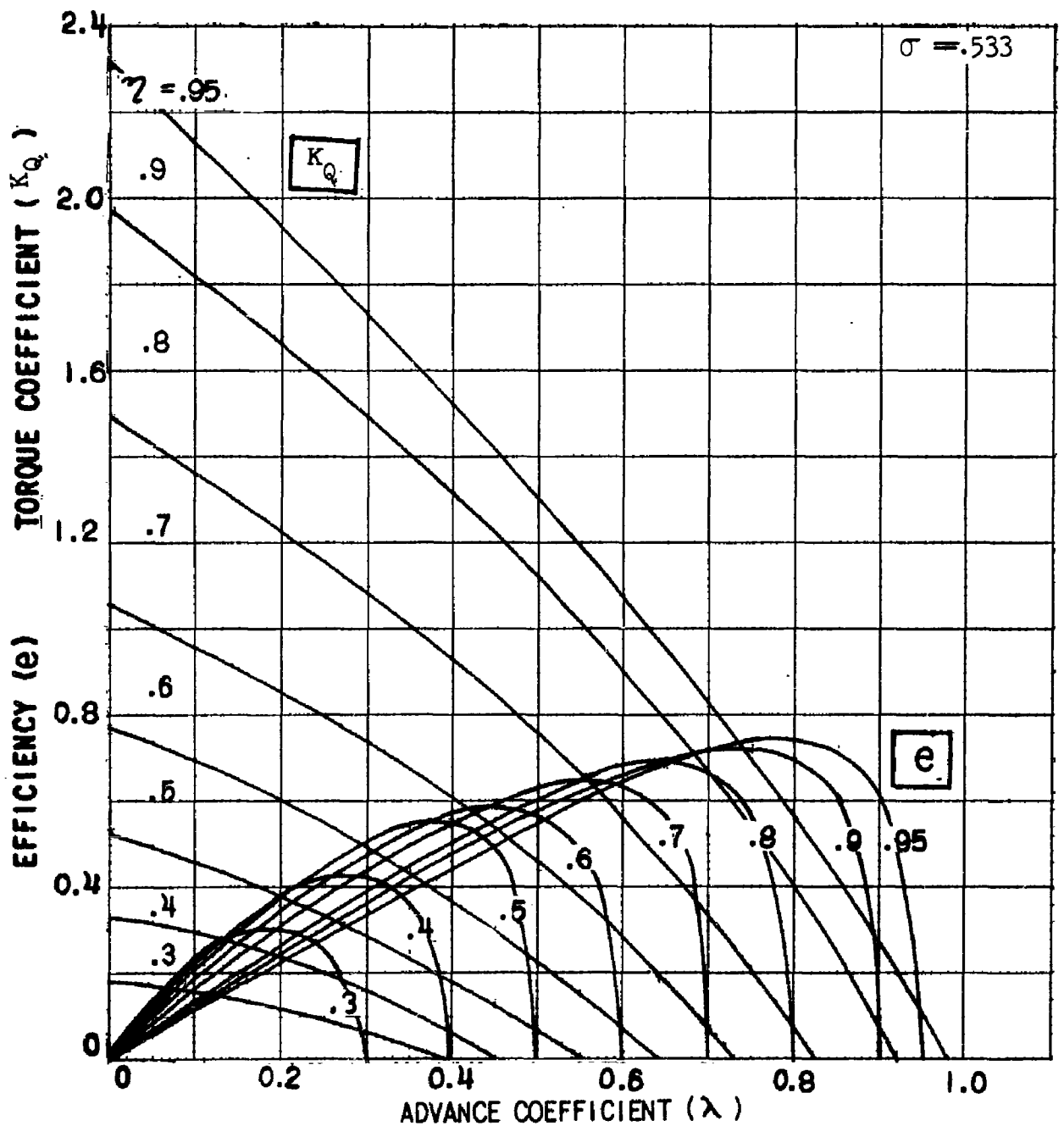


Figure 7(e) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .533$

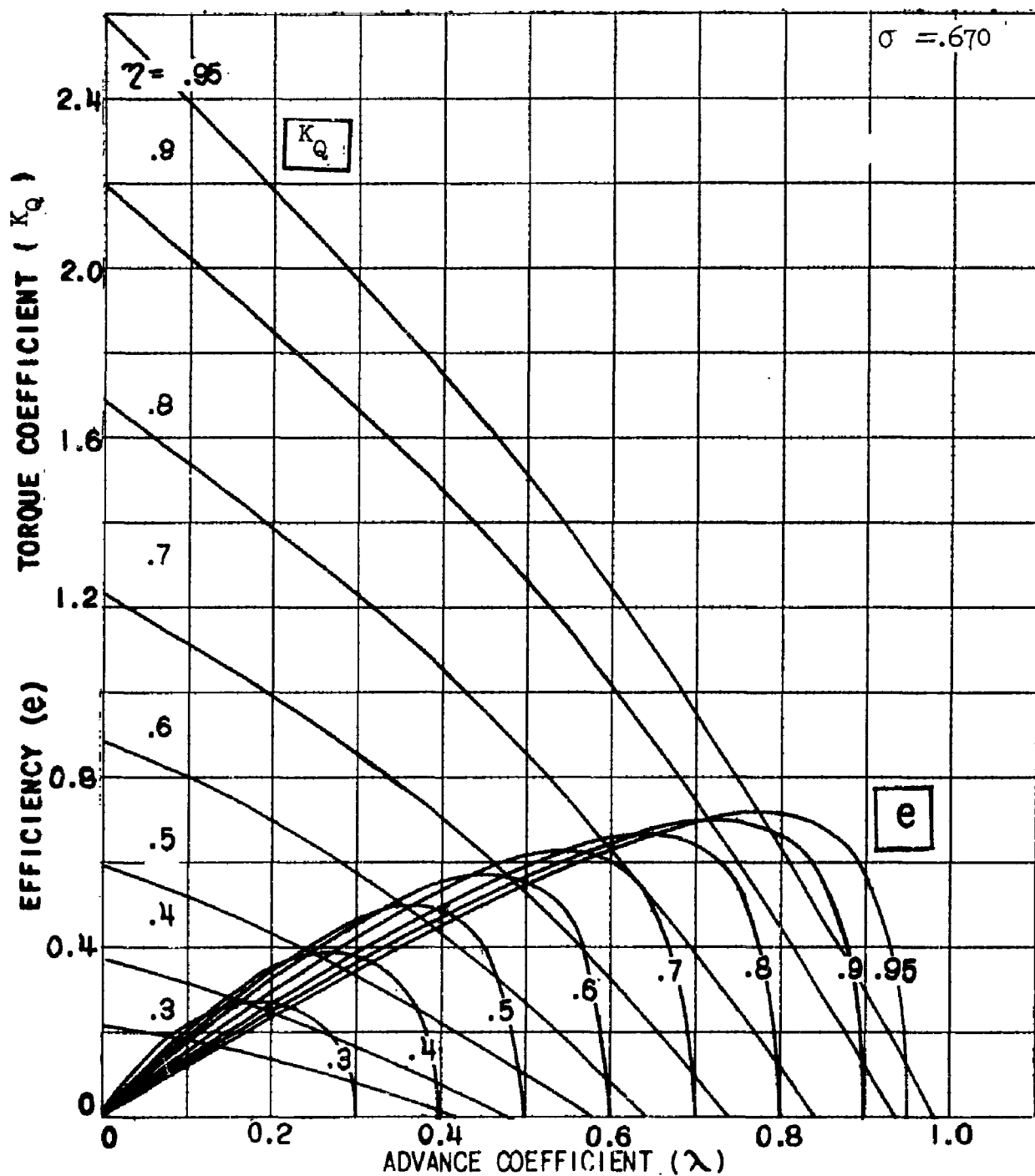


Figure 7(f) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .670$

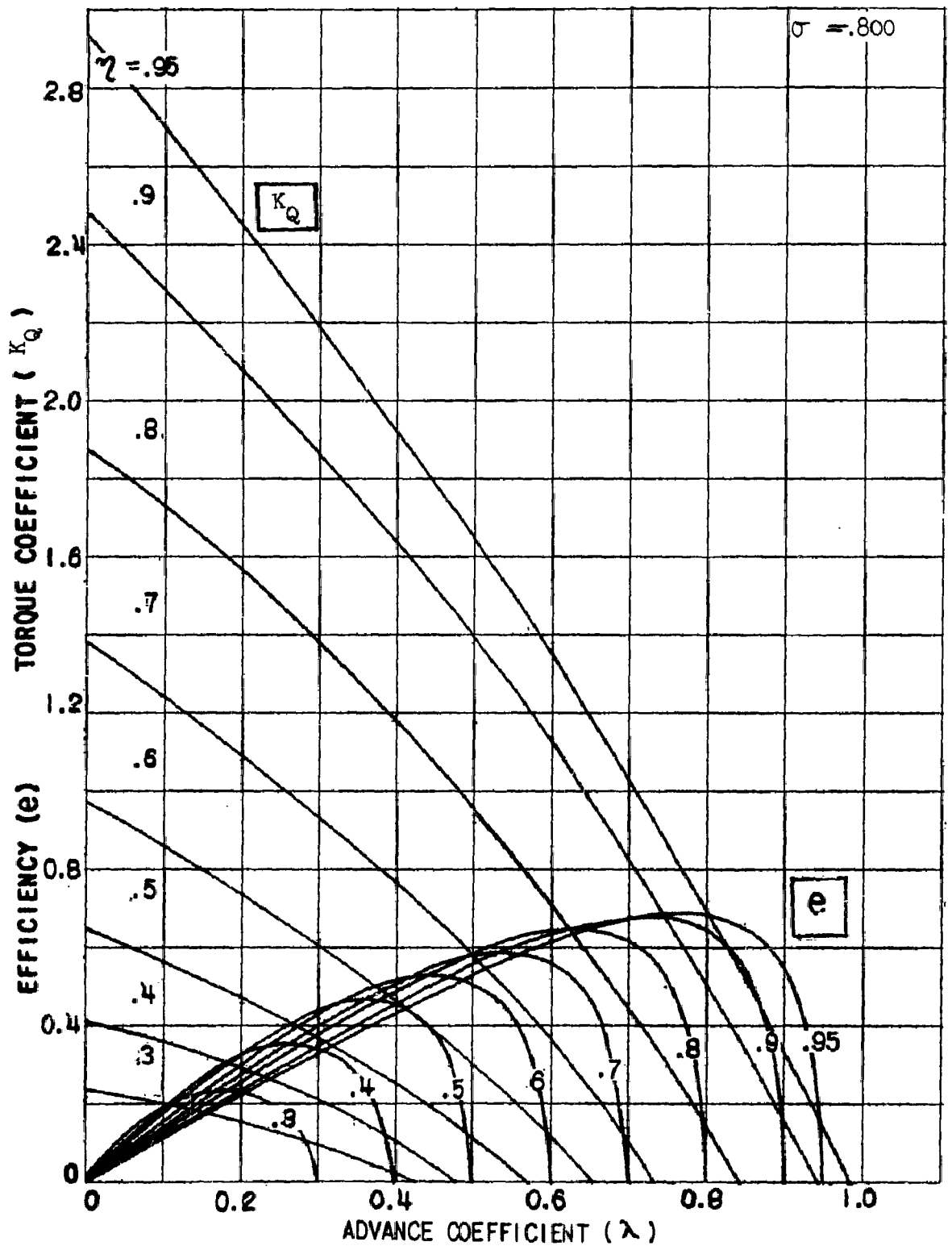


Figure 7(g) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = .800$

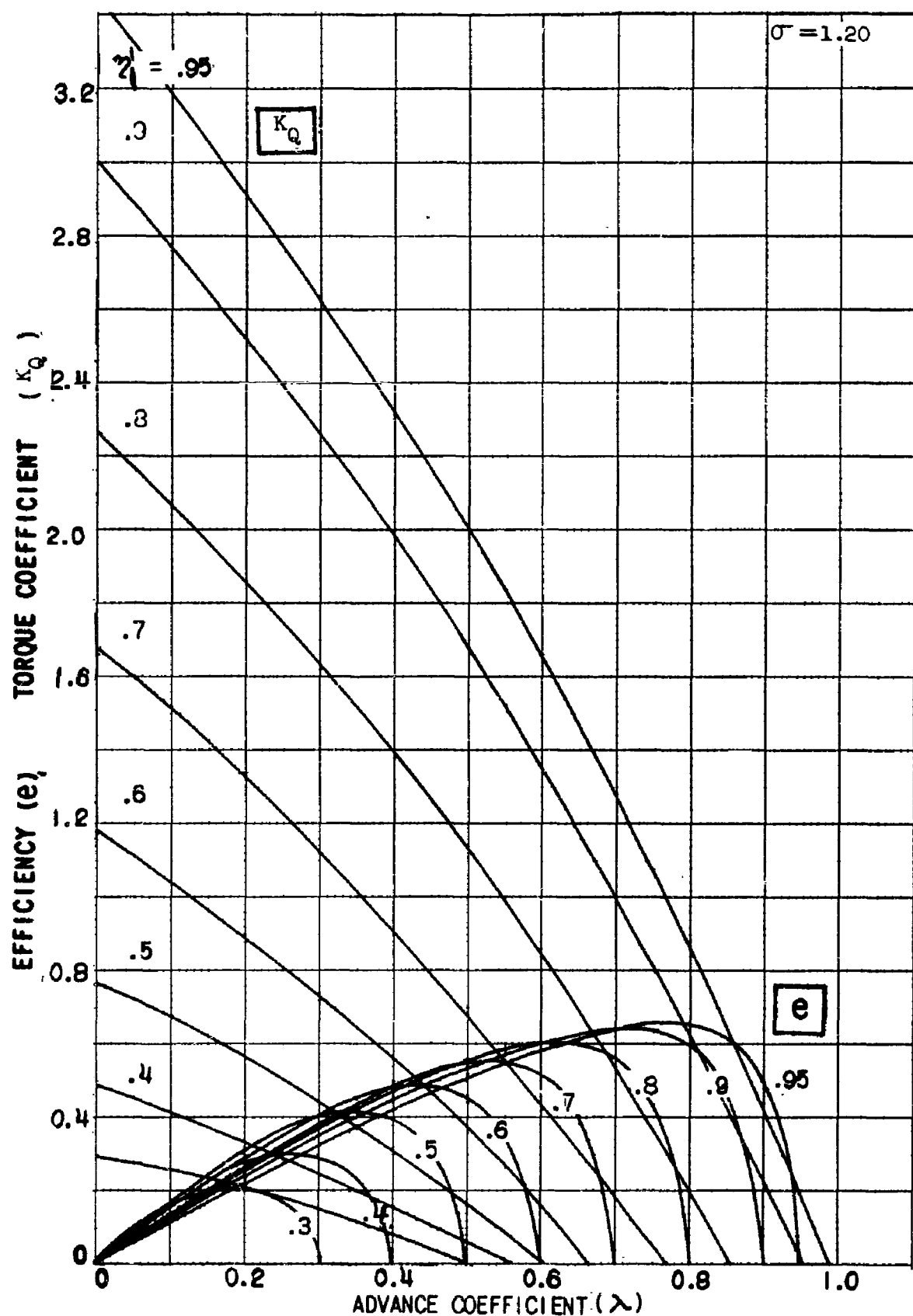


Figure 7(h) - Variation of Torque Coefficient and Efficiency with Advance Coefficient and Eccentricity for Various Values of Blade Solidity, $\sigma = 1.20$

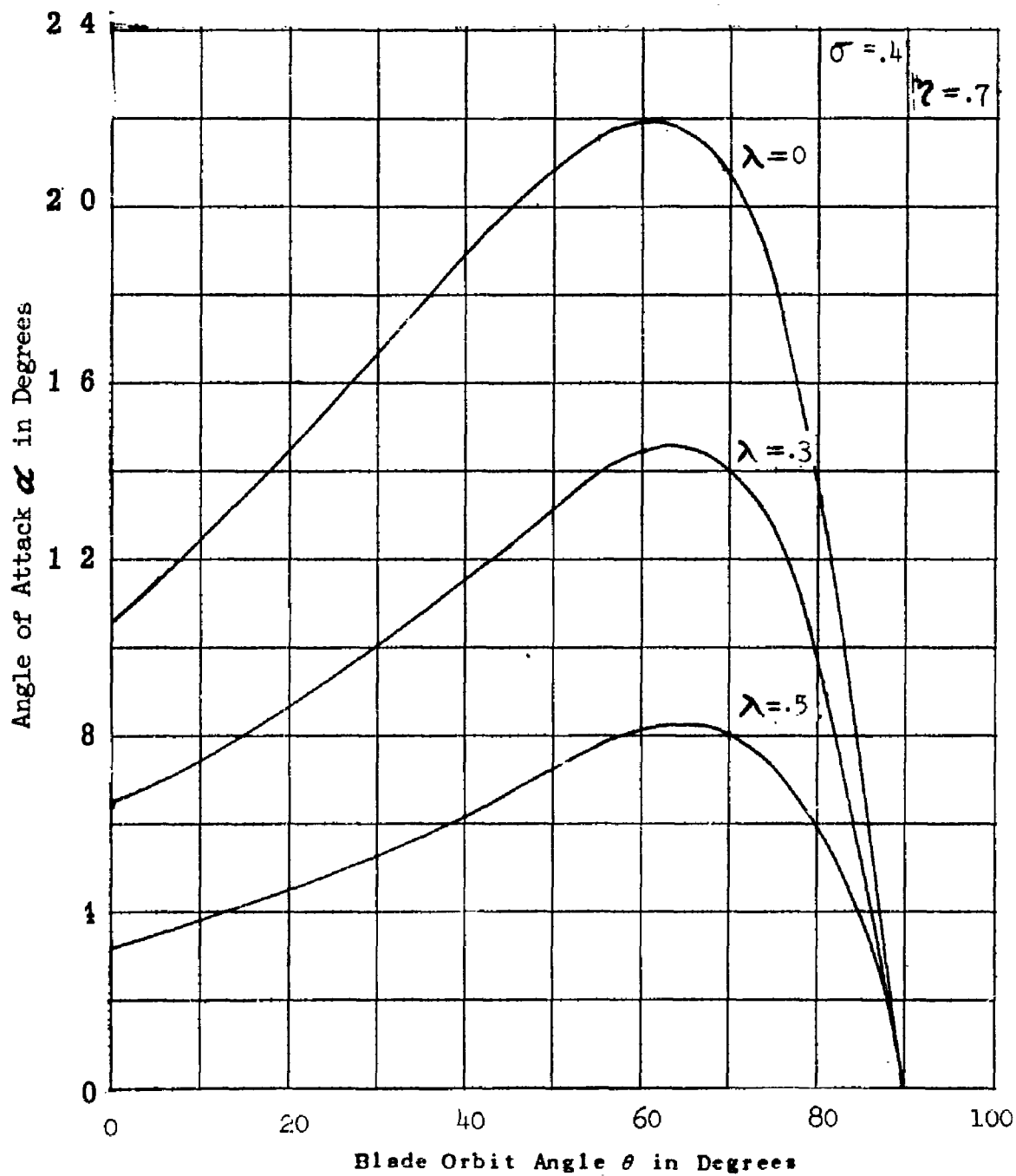


Figure 8 - Typical Variation of Angle of Attack of Blade Section with Orbital Position

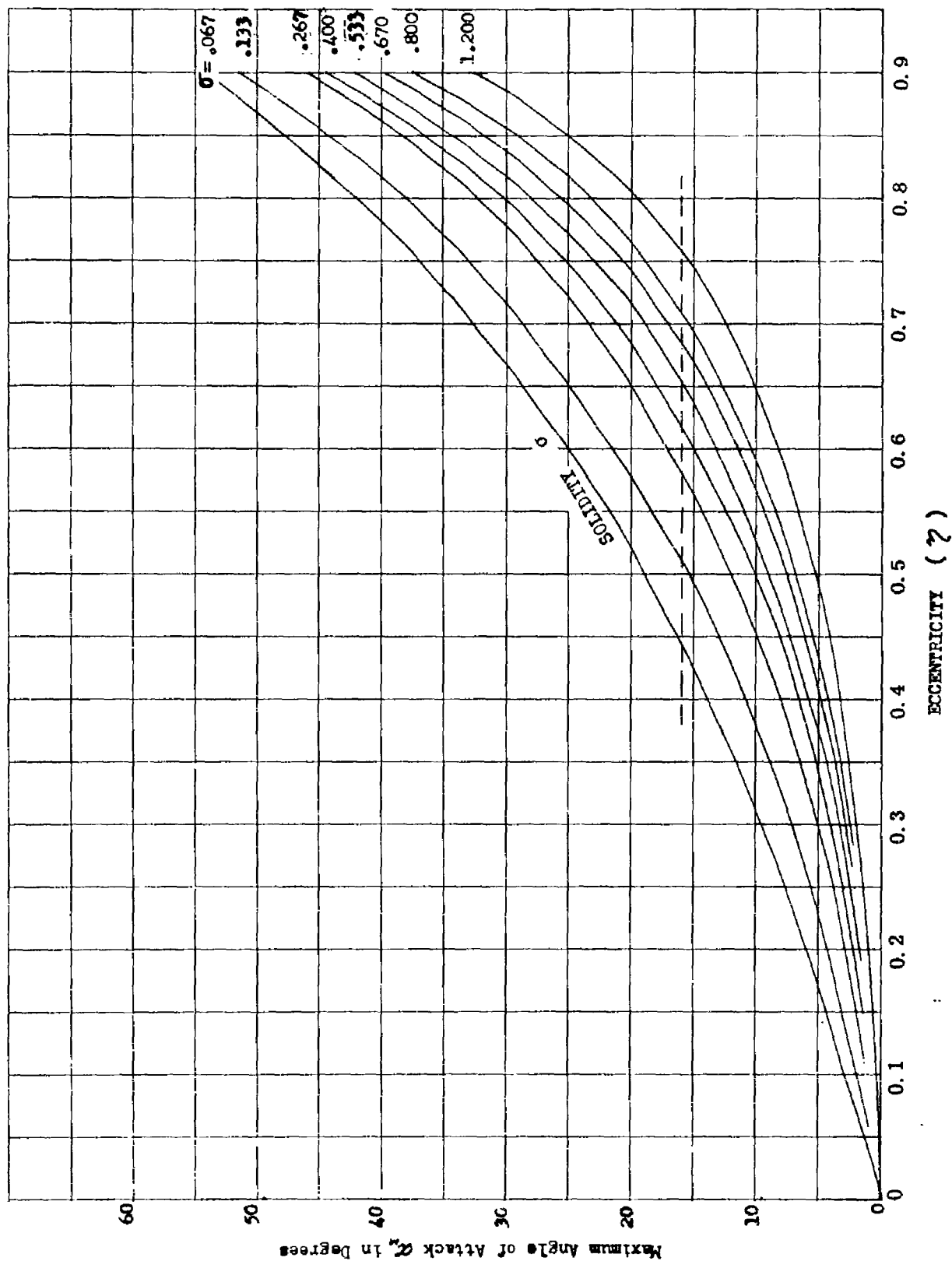


Figure 9 -- Maximum Angle of Attack as Function of Eccentricity and Solidity

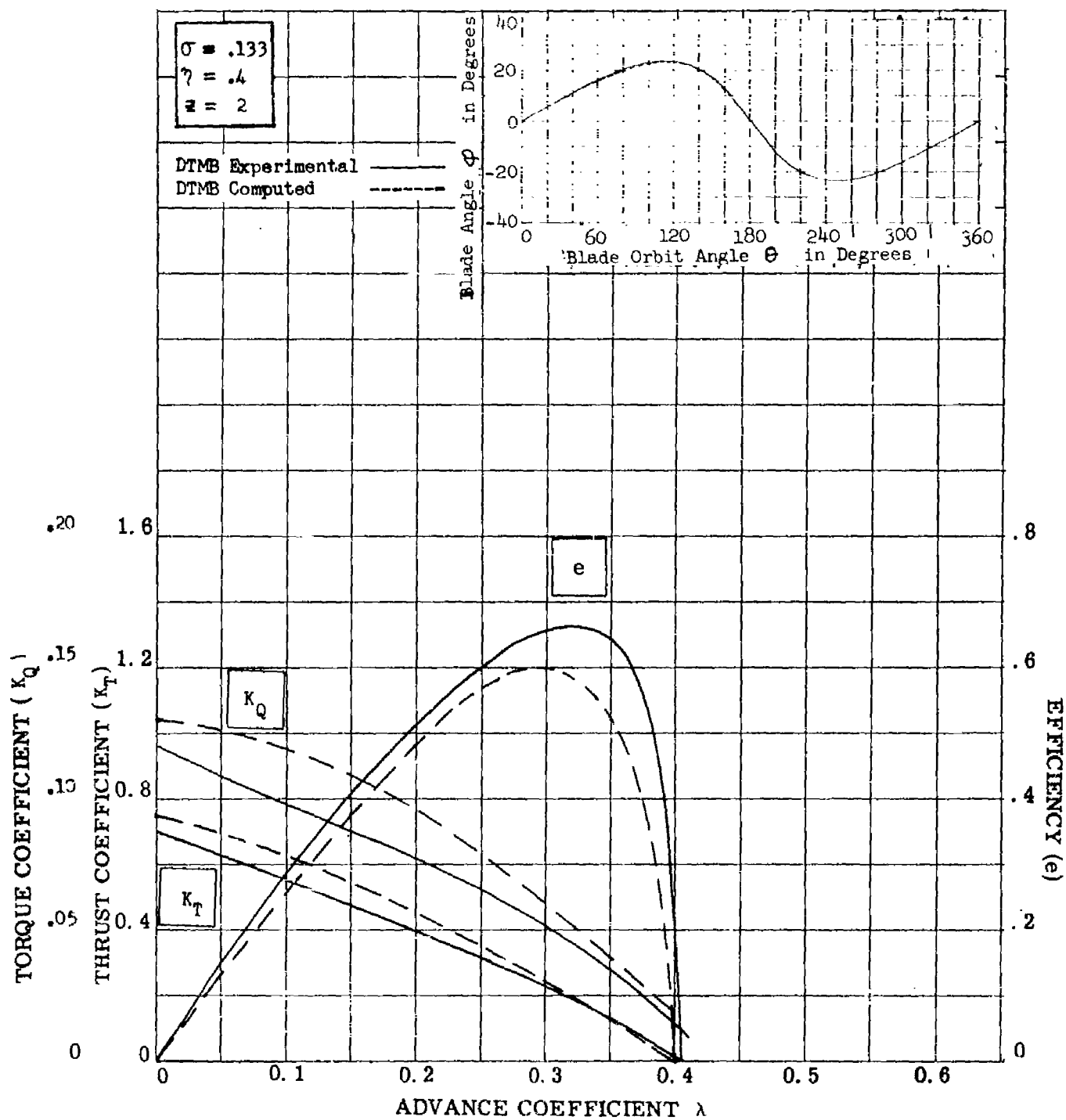


Figure 10(a) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4

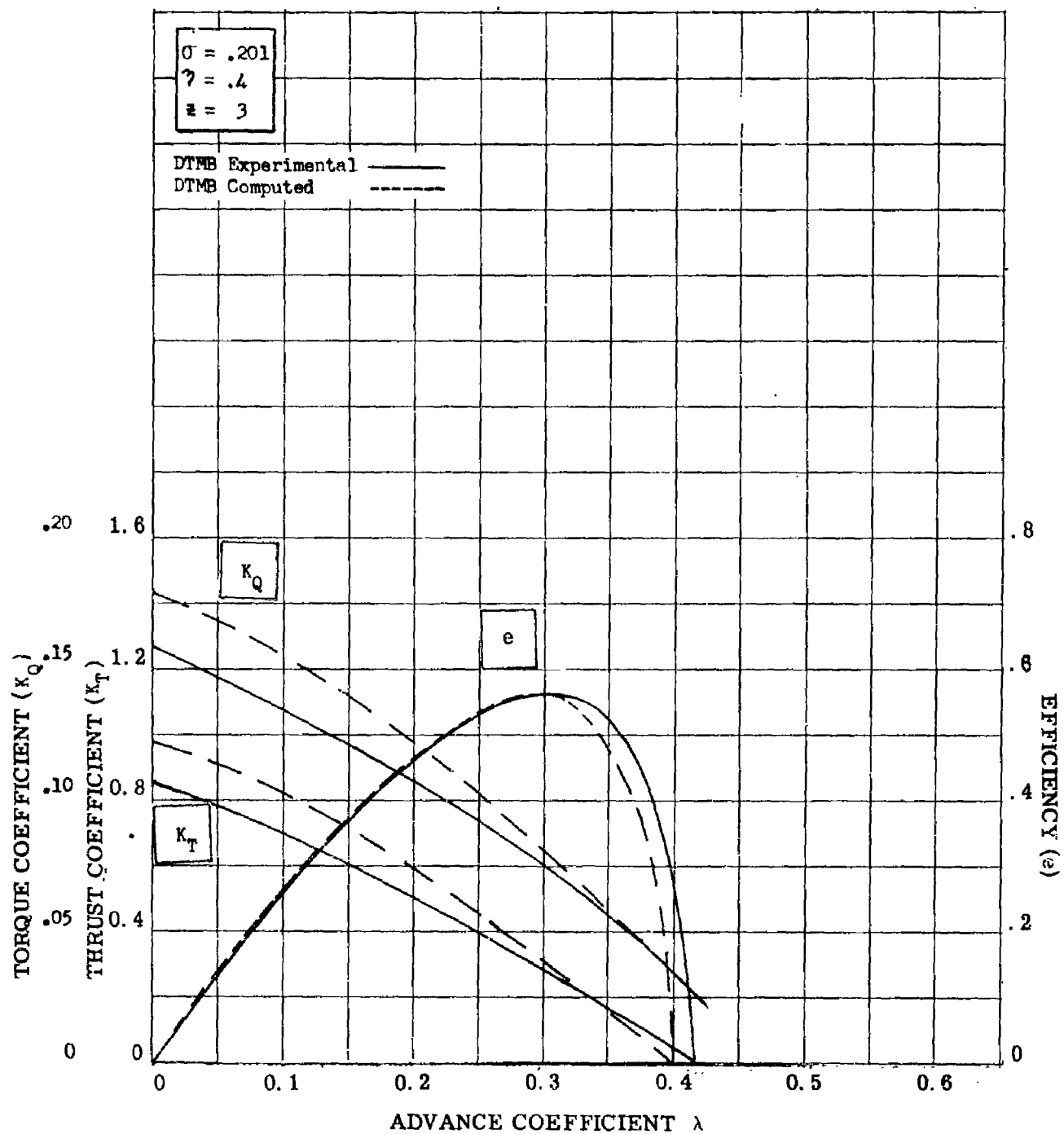


Figure 10(b) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4

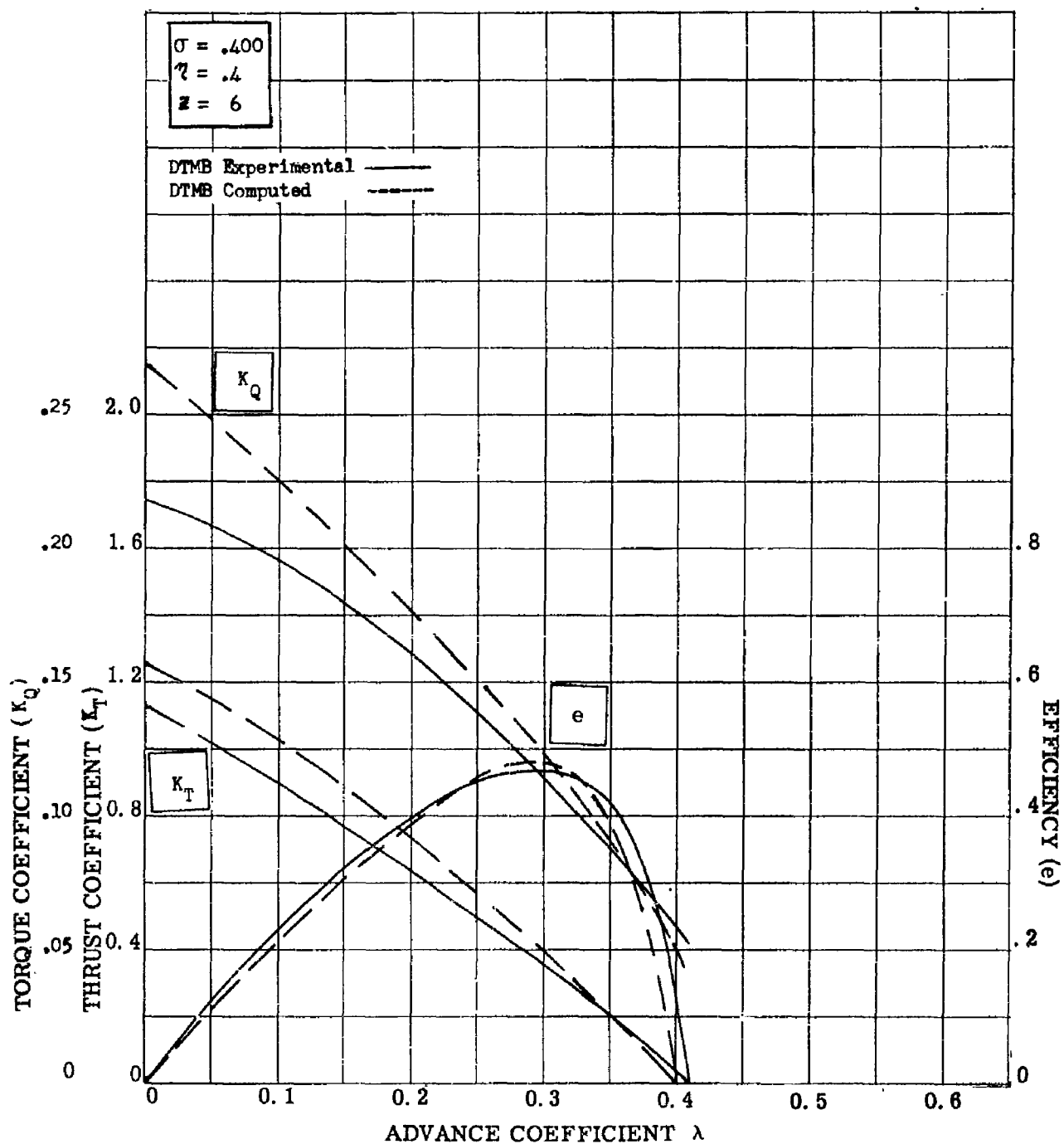


Figure 10(c) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propeller with Semi-elliptic Blades; Eccentricity = 0.4

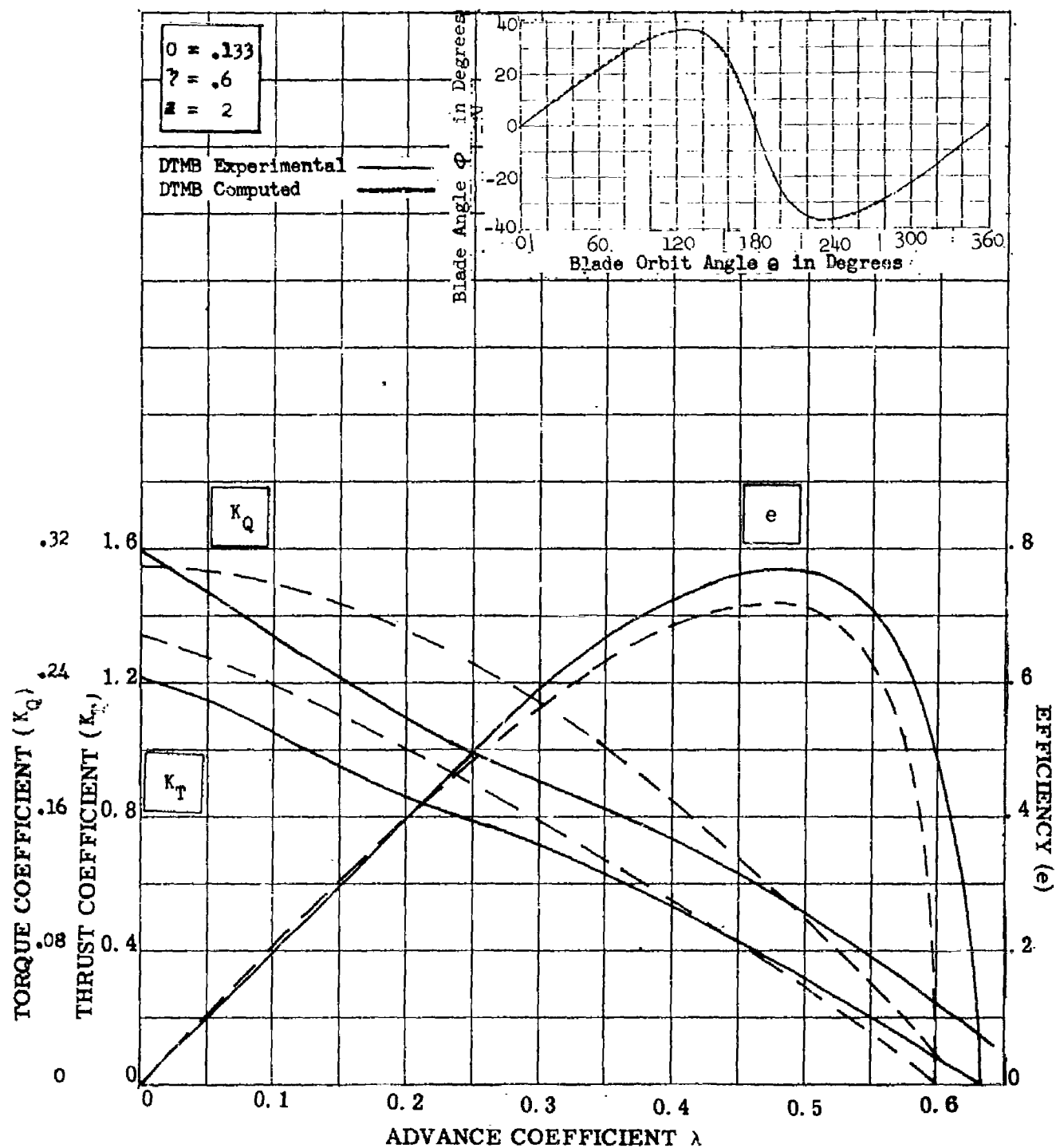


Figure 11(a) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6

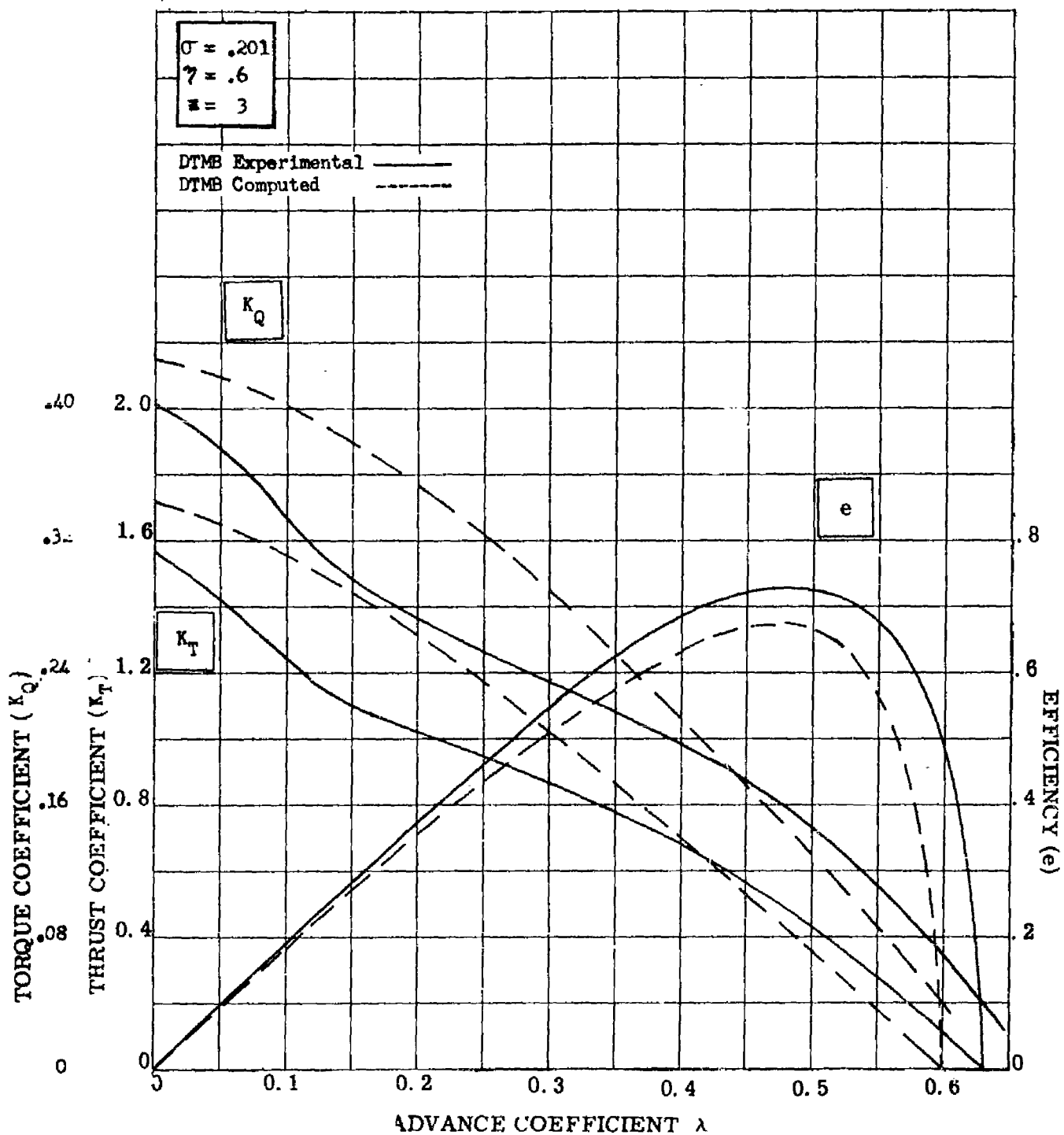


Figure 11(b) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6

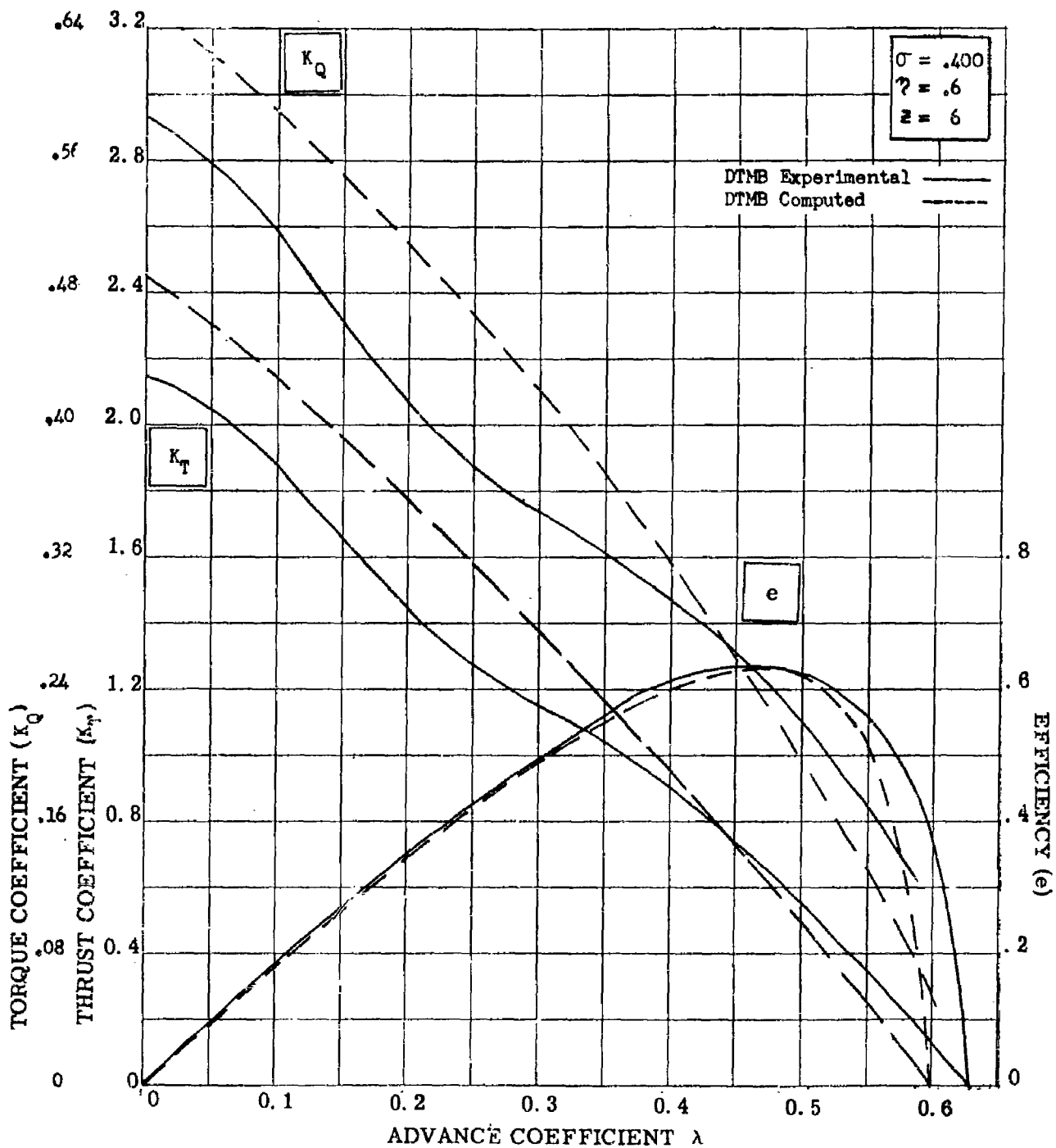


Figure 11(c) - Comparison of Computed and Experimental Performance Characteristics of a Vertical Axis Propellers with Semi-elliptic Blades; Eccentricity = 0.6

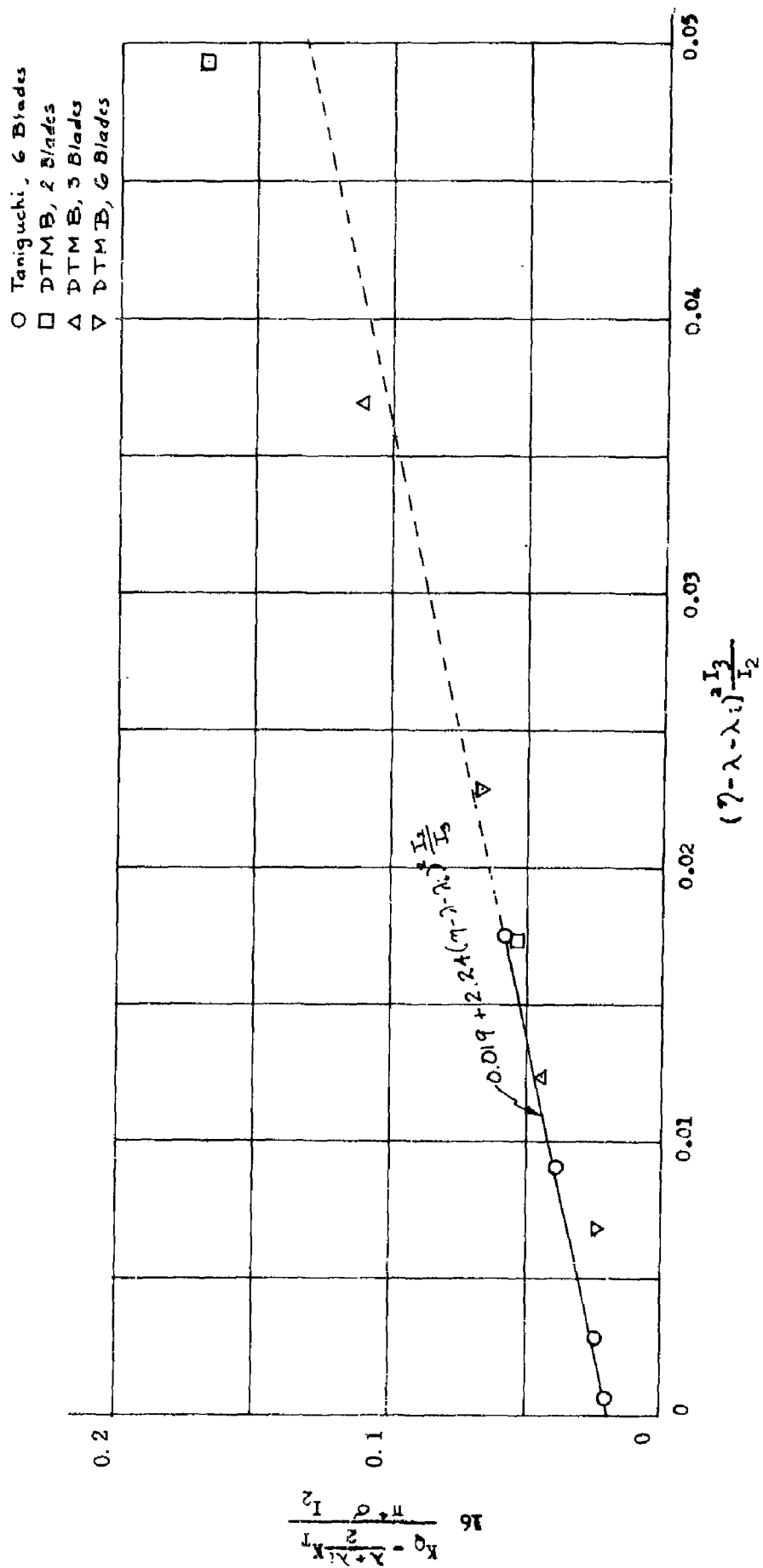


Figure 12 - Plot for Evaluating the Section Drag Coefficient

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