SANDIA REPORT SAND85-7003 - Unlimited Release - UC60
Printed November 1985

A FIRST ORDER ANALYSIS OF THE EFFECT OF PITCHING ON THE DRAG COEFFICIENT

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

A First Order Analysis of the Effect of Pitching on the Drag Coefficient

by

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October, 1984

SUMMARY

A first order analysis was made for the drag coefficient of a pitching NACA 0015 airfoil below stall. The inviscid velocity distribution for a translating NACA 0015 airfoil was superimposed with the additional circulation velocity for a pitching ellipse. The resulting velocity distribution was used to numerically integrate a momentum/boundary layer formulation to obtain the drag coefficient.

For both laminar and turbulent boundary layers it was found that the effect of pitching on the drag coefficient can be approximated by a shift in angle of attack. The shift angle was found to be a linear function of the pitching velocity and to be less than the induced angle of attack caused by the pitching.

INTRODUCTION

The blade of a Darrieus wind turbine experiences a wide variety of angles of attack and unsteady flow conditions during each revolution of the rotor. Despite the complex flow field created by the Darrieus turbine, a quasi-steady inviscid analysis has been shown to do an adequate job of predicting loads below stall [1]. The inviscid quasi-steady analysis [1] has contributions from three sources; first, a Kutta-Joukowsky force which includes the circulation due to the pitching motion; second, a chordwise harmonic force due to pitching; and third, a normal harmonic force due to the normal acceleration. The Kutta-Joukowsky force is dominant for the current designs of Darrieus Rotors. State-of-the-art methods used for performance analysis of the Darrieus Rotor employ a quasi-steady approach for performance analysis below stall [2,3,4,5] using only the Kutta-Joukowsky term for lift. Drag is also used.

In these quasi-steady analyses, the lift and drag coefficients are obtained by entering tables of static airfoil data with an equivalent angle of attack adjusted for the pitching circulation. This approach is certainly reasonable for evaluating the lift coefficient, however this approach is questioned for prediction of drag coefficient. The reason for questioning this approach for determination of the drag coefficient lies in the alteration of the airfoil pressure distribution caused by the pitching motion. The present study investigated the effect of steady pitching motion on the drag coefficient of an unstalled NACA 0015 airfoil by a numerical momentum/boundary layer analysis.

Below is a summary of the features of the model:

1) The velocity distribution was a superposition of two flows,
    a) the streaming motion past a NACA 0015 airfoil as a function of geometric angle of attack, and
    b) the relative velocity on the surface of an ellipse pitching at a constant rate in still fluid. Ghodoosian [6] has shown that the pressure distribution about a pitching NACA 0015 airfoil is adequately predicted by the superposition of the potentials for the streaming motion of an NACA 0015 airfoil and for an ellipse with the same leading edge shape as the NACA 0015 airfoil.
2) The drag coefficient was calculated by a boundary layer quadrature of the combined velocity distribution to obtain the momentum thickness at the trailing edge.
3) A lift calculation was performed by integration of pressure coefficient around the airfoil in order to check the accuracy of the method.

The velocity and the pressure distribution were not corrected for boundary layer displacement thickness. The method is therefore a first order approximation for drag.

Both laminar and turbulent boundary layer cases were run. Two methods were tried for predicting the point of transition to turbulence, the first due to Michel [7] and the second used by Eppler [8]. The test cases were selected to approximate the range of operating Reynolds numbers and pitch rates encountered in normal operation of Sandia National Laboratories' 17m research vertical axis wind turbine.

The following paragraphs describe the development of the model along with the results of the investigation.

VELOCITY DISTRIBUTION - NACA 0015 AIRFOIL

The data of Abbott and von Doenhoff [9] were used for the potential flow velocity distribution on the airfoil. For symmetric airfoils the velocity consists of two components, a basic thickness velocity plus an additional velocity due to the circulation. That is

$$\left.\frac{u}{V}\right|_{\text{Translation}} = \left.\frac{u}{V}\right|_{\text{Thickness}} \pm \frac{\Delta u_a}{V} C_L(\alpha)$$

The values for the velocity were available at 19 points along the chord. The spacing of these points gave a fairly smooth distribution except near the leading edge. At the leading edge, the velocity gradient is the largest and the need for accuracy the greatest. For the present study the data was smoothed for $0.0 < x/c < 0.005$. The basic thickness velocity was modeled by the distribution on the leading edge of an ellipse, following the form of the analytical solution. The circulation velocity data was smoothed by three-point Lagrangian interpolation. Together these effects produced a model for total velocity that was similar to the flow near the leading edge of an ellipse. Linear interpolation was used between total velocity values on the remainder of the airfoil. Next an expression for the pitching component of the velocity was needed.

PITCHING ELLIPSE

The additional bound circulation created by the pitching motion of the Darrieus blade affects the pressure distribution on the blade and therefore the growth of the boundary layer. Within the accuracy of the present analysis the pitching airfoil can be modeled by a pitching ellipse, for which a closed form solution exists. A 20% thick ellipse was found to be a good approximation to the basic thickness velocity of a NACA 0015 airfoil near the leading edge [6]. The analysis for the inviscid flow relative to a pitching ellipse in a static fluid was carried out following the general method given by Milne-Thomson [10].

This method involves the mapping of a translating and rotating ellipse with chord c and thickness t, as shown in Figure 1, into a circle of radius R by the Joukowski transformation

$$z = \zeta + \frac{r^2}{\zeta}$$

where: $r^2 = (c^2 + t^2)/16$

$R = (c + t)/4$

The complex potential is obtained from the boundary function, a vortex is added to the center of the circle and the Kutta condition is applied at the trailing edge to obtain the strength of the pitching circulation, Γ_p. With the complex potential established, the velocity relative to the ellipse, q', can be found from

$$q' = \frac{dW}{dz} - \left(U_x - iU_y\right) + i\Omega\tilde{z}$$

where: W = complex potential in ellipse plane

Ω = angular velocity of ellipse

$U_x - iU_y$ = complex velocity of the origin

For the present model the translational velocity terms were removed from the complex velocity of the ellipse leaving only the effects due to pitching

$$U_x = -V\cos\alpha$$

$$iU_y = V\sin\alpha + \Omega c\left(\frac{1}{2} - \frac{x_o}{c}\right)$$

Non-dimensionalizing the local relative complex velocity due to pitching yields

$$\frac{q'}{V} = \frac{1}{V}\frac{dW}{d\zeta}\frac{1}{dz/d\zeta} + i\,\varepsilon\,\frac{\tilde{z}}{c} + i\,\varepsilon\,\left(\frac{1}{2} - \frac{x_o}{c}\right)$$

where $\varepsilon = \frac{\Omega c}{V}$ and V is a reference velocity. The reference velocity used in this study is the free stream velocity relative to the airfoil.

The local relative velocity from this analysis was combined with the velocity for a translating NACA 0015 airfoil to obtain the total velocity distribution. With the total velocity distribution established as a function of angle of attack and pitching velocity, calculation of the drag and the lift coefficients followed.

CALCULATION OF DRAG COEFFICIENT

In a steady uniform flow, the drag on an object can be determined by calculating the momentum deficit in the wake far downstream of the object [12]. In terms of the momentum thickness far downstream, Θ_∞,

$$C_D = \frac{2\Theta_\infty}{c}$$

To obtain an expression in terms of the velocity on the airfoil, a form of the momentum-integral equation,

$$\frac{d\ln\Theta}{dx} + (H+2)\,\frac{d\ln u}{dx} = 0$$

can be integrated downstream from the trailing edge to infinity. With the approximation for the average shape factor, $H \doteq 1/2\ (H_{te} + H_\infty)$ the integral yields,

$$\Theta_\infty = \Theta_{te} \left(\frac{u_{te}}{V}\right)^{1/2(H_{te} + H_\infty + 4)}$$

Further assuming that $H_\infty \doteq 1$ and $H_{te} \doteq 2$, the expression for drag coefficient becomes,

$$C_D = 2 \frac{\Theta_{te}}{c} \left(\frac{u_{te}}{V}\right)^{7/2}$$

Here u_{te} is the trailing edge velocity.

Substituting the expression for momentum thickness due to Thwaites [7],

$$\Theta^2 = \frac{0.45}{(u/V)^6} \frac{\nu c}{V} \int_0^{s/c} \left(\frac{u}{V}\right)^5 d\left(\frac{s}{c}\right),$$

the equation for the drag coefficient with a laminar boundary layer becomes

$$C_D = \sum_{\substack{\text{Upper} \\ \text{\& lower} \\ \text{surfaces}}} \left[\frac{1.422}{Re_c^{\ 3/5}} \left\{\frac{u_t}{V} \int_0^{\frac{s_t}{c}} \left(\frac{u}{V}\right)^5 d\left(\frac{s}{c}\right)\right\}^{3/5} + \frac{0.02429}{Re_c^{\ 1/5}} \int_{s_t/c}^{1} \left(\frac{u}{V}\right)^4 d\left(\frac{s}{c}\right)\right]^{5/6}$$

The subscript 't' denotes the point of transition to turbulent boundary layer and the s-coordinate follows the surface of the airfoil.

The numerical integration was carried out using the trapezoidal rule with approximately 400 integration points on the airfoil. A varying step size gave good refinement near the leading edge.

LIFT COEFFICIENT

The pressure coefficient was calculated from the total velocity by the steady Bernoulli equation. Force coefficients in the x- and y-coordinate directions were calculated by integrating the pressure coefficient around the airfoil

$$F_x = \int_{\text{airfoil}} C_p \, d\left(\frac{y}{c}\right)$$

$$F_y = \int_{\text{airfoil}} C_p \, d\left(\frac{x}{c}\right)$$

The lift coefficient was resolved from F_x and F_y as a function of angle of attack by

$$C_L = \left(F_y \cos \alpha - F_x \sin \alpha\right)$$

The final question to resolve was how to determine the point of transition to turbulent boundary layer.

TRANSITION TESTS

Two methods of calculating transition points were investigated.

The first method, given by Michel [7], predicts transition based on local momentum thickness. Transition is said to occur when

$$Re_\theta \geqslant 2.9 \, Re_s^{0.4}$$

where the s-coordinate follows the surface. This method was convenient since the momentum thickness was already calculated.

The second method, used by Eppler [8], required the calculation of the energy thickness, $H_{32} = \delta_3/\Theta$.

The criterion for transition was

$$\ln Re_\theta \geqslant 18.4 H_{32} - 21.74$$

The calculation of H_{32} by Pohlhausen momentum integral methods outlined in Schlichting [12] involved an expression for the second shape factor, $K = \frac{\Theta^2}{\nu} (\frac{du}{ds})$, which contains the surface velocity derivative. In comparing results of the two methods it was found that Michel's test, which involves integration of the velocity, was more stable and consistent than the velocity derivative dependent test used by Eppler for the numerical calculations of the present model. All of the following results involving turbulent boundary layer calculations were obtained using Michel's transition test.

RESULTS

The accuracy of the code was checked by comparing static airfoil drag coefficient results with Eppler predictions for the NACA 0015 airfoil [13]. Figure 2 shows drag coefficient vs. angle of attack for $Re = 2 \cdot 10^6$. The agreement is good at low and moderate angles of attack.

The primary purpose of the investigation was comparison of pitching with non-pitching results. For the pitching cases the parameters were chosen to approximate the geometry and operating conditions of the Sandia 17m vertical axis wind turbine. The airfoil was NACA 0015 and the center of rotation of the airfoil was $x_o/c = 0.38$. Two Reynolds numbers were run with five values of angular velocity parameter as outlined in Table 1.

TABLE 1

Case	Reynolds Number	Angular Velocity Parameter $\varepsilon = \frac{c\Omega}{V}$
Laminar	10^6	0., ± 0.07, ± 0.105
Turbulent	$1.5 \cdot 10^6$	0., ± 0.07, ± 0.105

For the first case the boundary layer was assumed to be fully laminar. For the second case transition was allowed to occur.

Note that for a symmetrical airfoil the $\pm\varepsilon$ runs for positive angle of attack cover all conditions of pitching encountered by a Darrieus rotor. That is:

$(+\alpha, +\varepsilon)$ is equivalent to $(-\alpha, -\varepsilon)$

$(+\alpha, -\varepsilon)$ is equivalent to $(-\alpha, +\varepsilon)$

The majority of the results hereafter are presented only for the turbulent case with $\varepsilon = \pm 0.105$ for clarity of presentation.

Figure 3 illustrates the effect of positive pitching on the drag coefficient. There is a drag reduction at negative angles of attack, corresponding to the downwind half of a Darrieus rotor, and a drag rise at positive angles of attack on the upwind portion of the rotor. The change in drag coefficient with pitching can be approximated by a shift in angle of attack such that

$$C_D(\alpha)\Big|_{\text{pitching}} = C_D(\alpha + \alpha_{ds})\Big|_{\text{static}}$$

where: α = geometric angle of attack

α_{ds} = drag shift angle

The drag shift angle was found to be a linear funciton of the pitching velocity parameter, ε. For the laminar case the drag shift angle was

$$\alpha_{ds} = 0.18\ \varepsilon$$

For the turbulent case the drag shift angle was

$$\alpha_{ds} = 0.23\ \varepsilon$$

An insignificant reduction in the calculated value of C_{D_o} occurred, from 0.00724 to 0.00718.

The lift coefficient is dependent only upon the angle of attack and pitching circulation and was therefore the same for laminar and turbulent cases. Figure 4 shows the calculated lift coefficient versus angle of attack for the various pitching rates.

The change in lift coefficient due to pitching circulation is well approximated by a pitching angle of attack, α_p, such that

$$C_L(\alpha)\Big|_{\text{pitching}} = C_L\left(\alpha + \alpha_p\right)\Big|_{\text{static}}$$

The pitching angle is a linear function of the pitch velocity. For the present model of a NACA 0015 airfoil, the induced pitching angle was

$$\alpha_p = 0.39\ \varepsilon$$

This value compares favorably with theoretical values of the induced pitching angle. With the same center of rotation as the airfoil, the theoretical values of α_p for a pitching flat plate and a pitching 15% thick ellipse are $\alpha_p = 0.37\ \varepsilon$ and $\alpha_p = 0.42\ \varepsilon$, respectively. Ghodoosian [6] obtained $\alpha_p = 0.385\ \varepsilon$ for the NACA 0015 airfoil.

In previous quasi-steady analyses the pitching angle α_p has been used as a best estimate for the drag shift angle α_{ds}. The error in this approach can be seen by expressing calculated α_{ds} as a fraction of α_p:

Laminar Case $\alpha_{ds} = 0.46\ \alpha_p$

Turbulent Case $\alpha_{ds} = 0.59\ \alpha_p$

The addition of pitching circulation is seen to affect drag coefficient less than lift coefficient.

The investigation was next refined to analyze separately the effects of pitching on the suction and pressure surfaces of the airfoil.

Figure 5 shows the transition points on suction and pressure surfaces as a function of angle of attack. For this Reynolds number and pitch velocity, transition was affected much more on the pressure side than on the suction side.

A major portion of the drag on an airfoil at moderate angle of attack comes from the suction surface where adverse pressure gradients cause rapid boundary layer growth. Figure 6 illustrates this behavior for a static airfoil and demonstrates the effect of pitching on the relative contributions from each surface, i.e. $C_D = C_{D_s} + C_{D_p}$. Pitching is seen to increase the drag on the suction surface and decrease the drag on the pressure surface for positive pitching.

Figure 7 is a plot of the contribution from each surface to the increment in C_D due to pitching, ΔC_{D_i}. That is,

$$\Delta C_{D_i} = C_{D_i}(\text{pitching}) - C_{D_i}(\text{static})$$

where: $i = s$, suction surface

$i = p$, pitching surface

It is seen that ΔC_{D_i} is a non-linear function of angle of attack, with the increment in C_D due to pitching increase due to effects on the suction surface of the airfoil.

CONCLUSIONS

The present first order analysis has shown that for the range of Reynolds number and pitch velocity investigated:

1) The effect of pitching on drag coefficient can be approximated by a linear shift in the angle of attack, allowing the use of static airfoil data in quasi-steady aerodynamic analyses.
2) The effect of pitching on the drag coefficient is due to a change in boundary layer development, since:
    a. a larger portion of the change in drag due to pitching occurs on the suction surface of the airfoil, and,
    b. the change in drag is not due to a shift in transition point on the suction surface.

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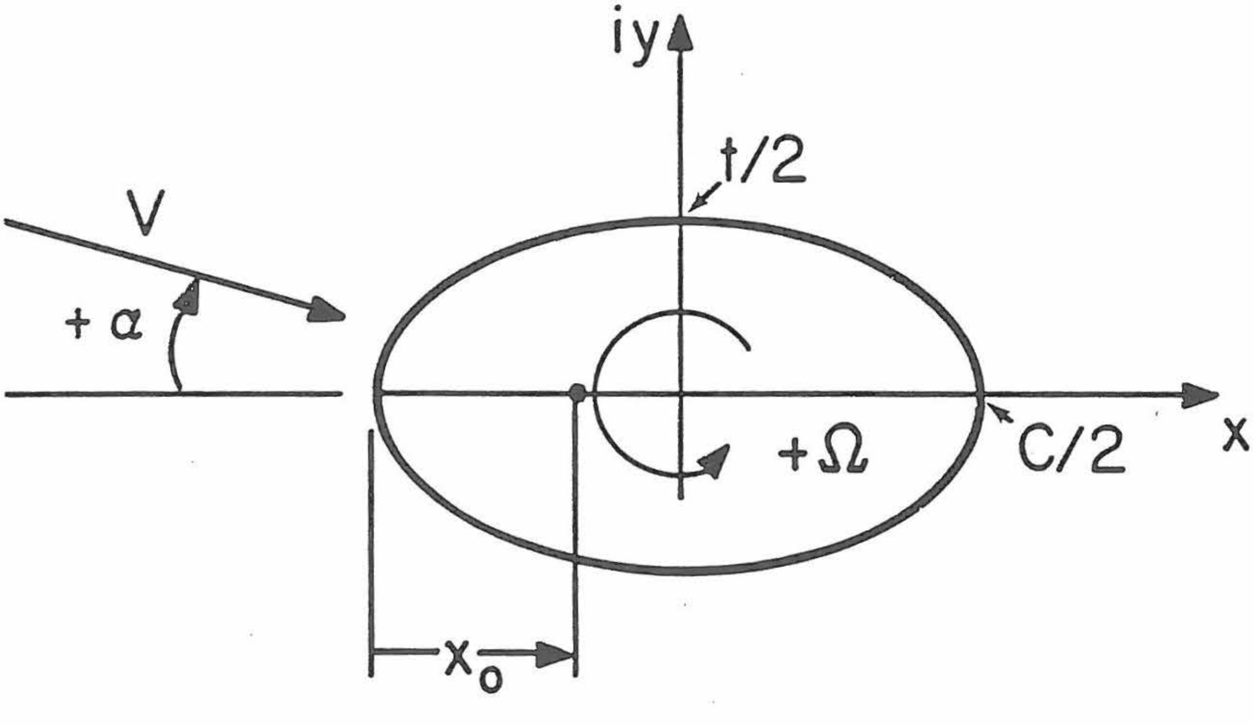

FIGURE 1. Ellipse in z-plane. Sign conventions on α and Ω.

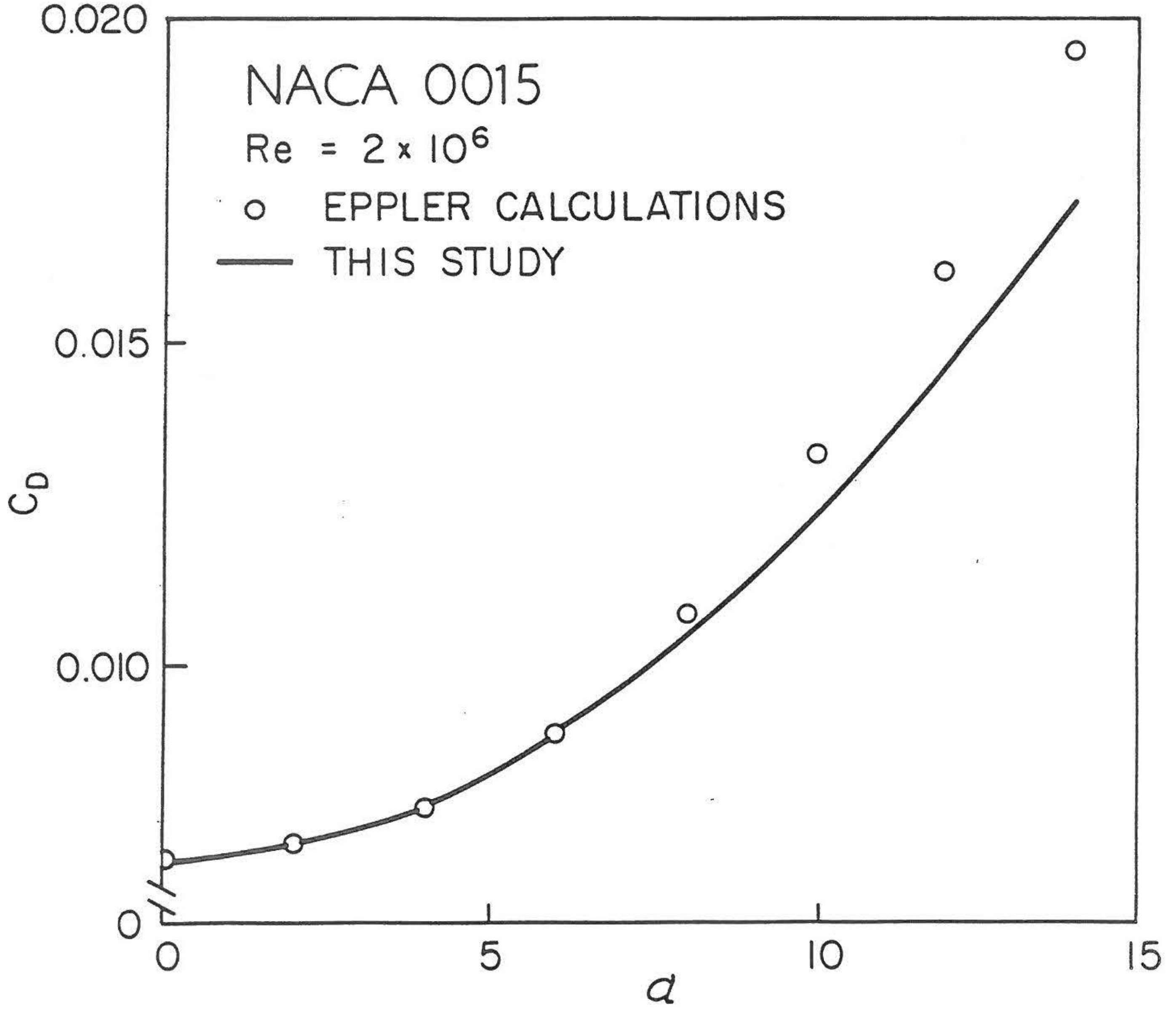

FIGURE 2. Drag coefficient as a function of angle of attack for static airfoil

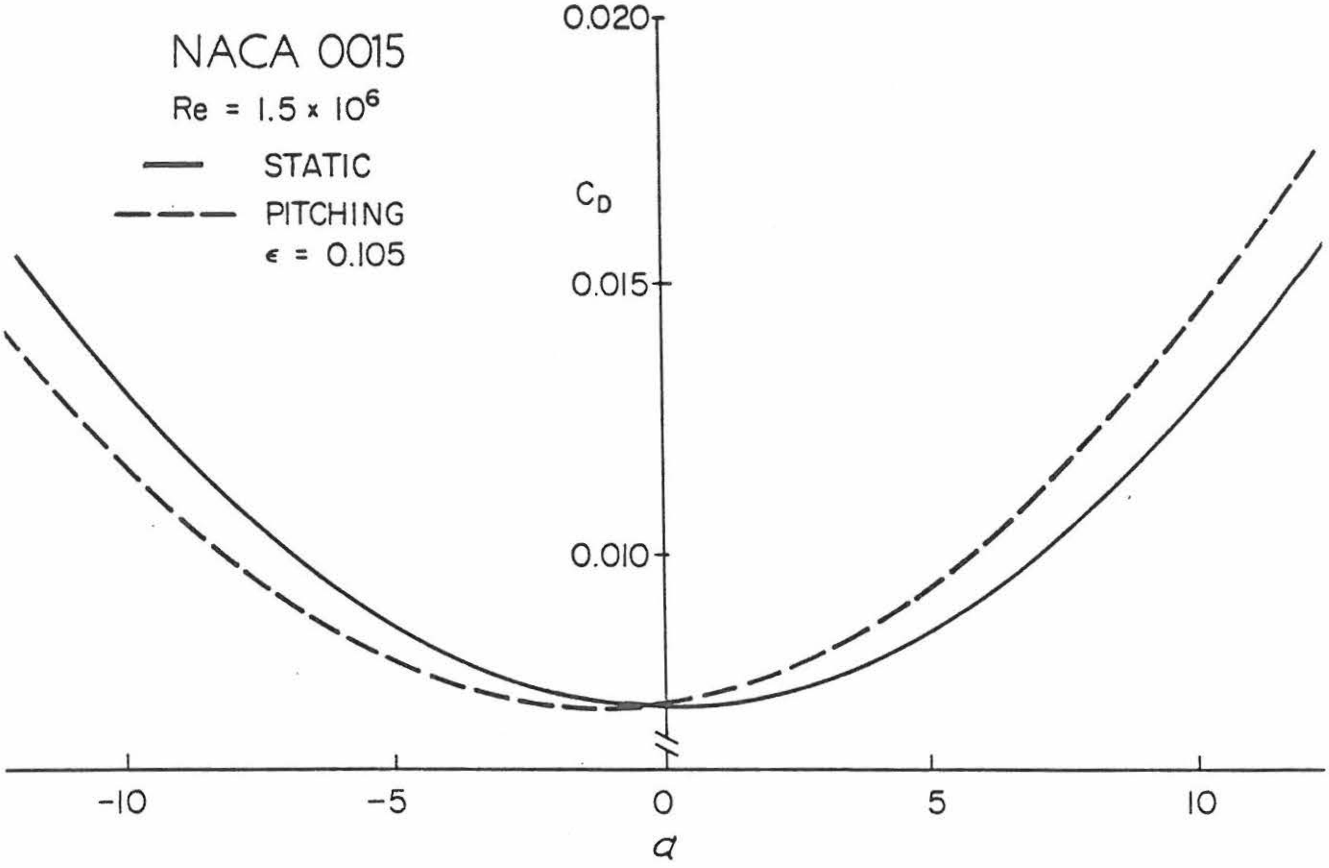

FIGURE 3. Effect of positive pitching on drag coefficient.

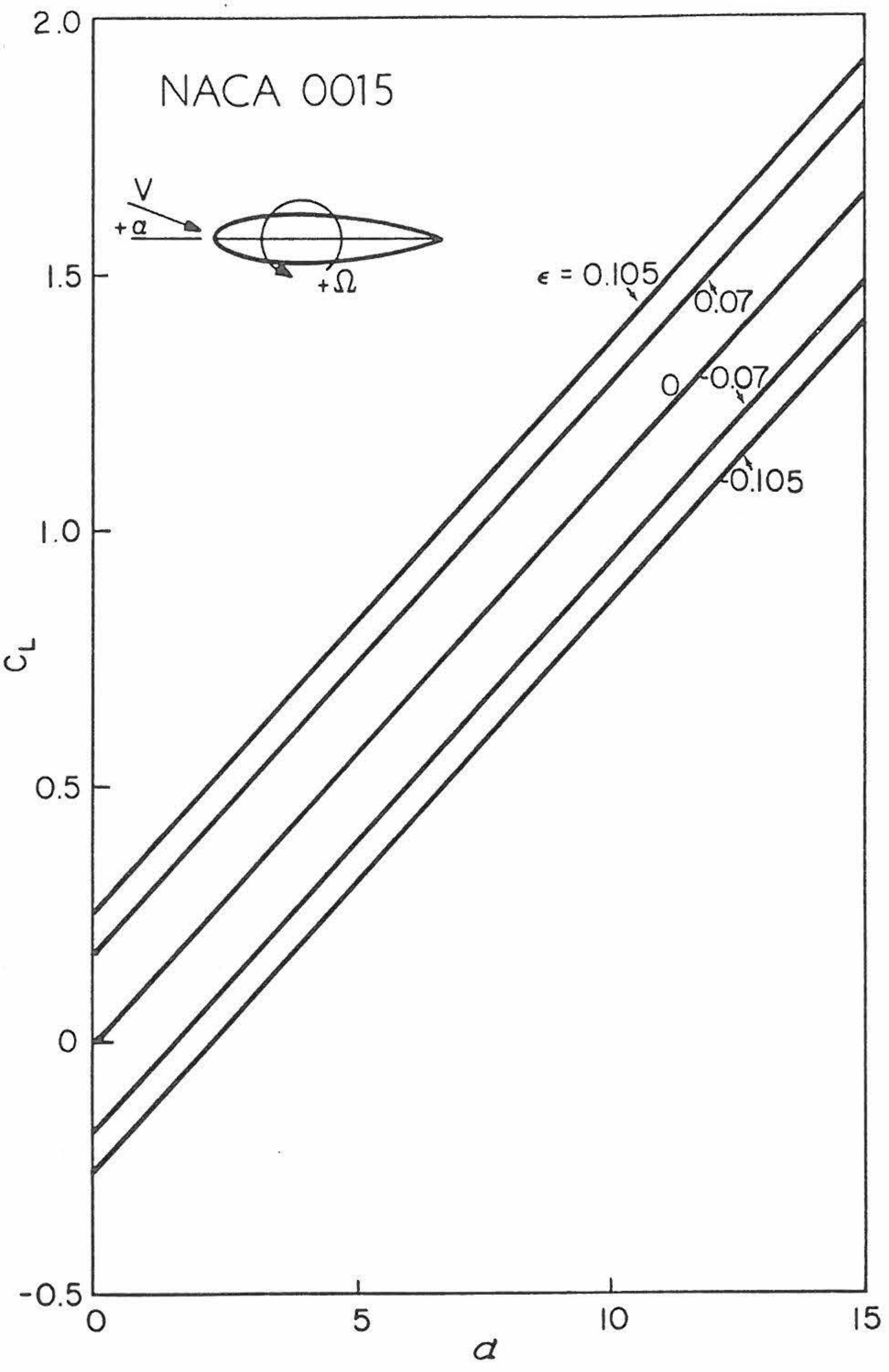

FIGURE 4. Lift coefficient as a function of local aerodynamic angle of attack.

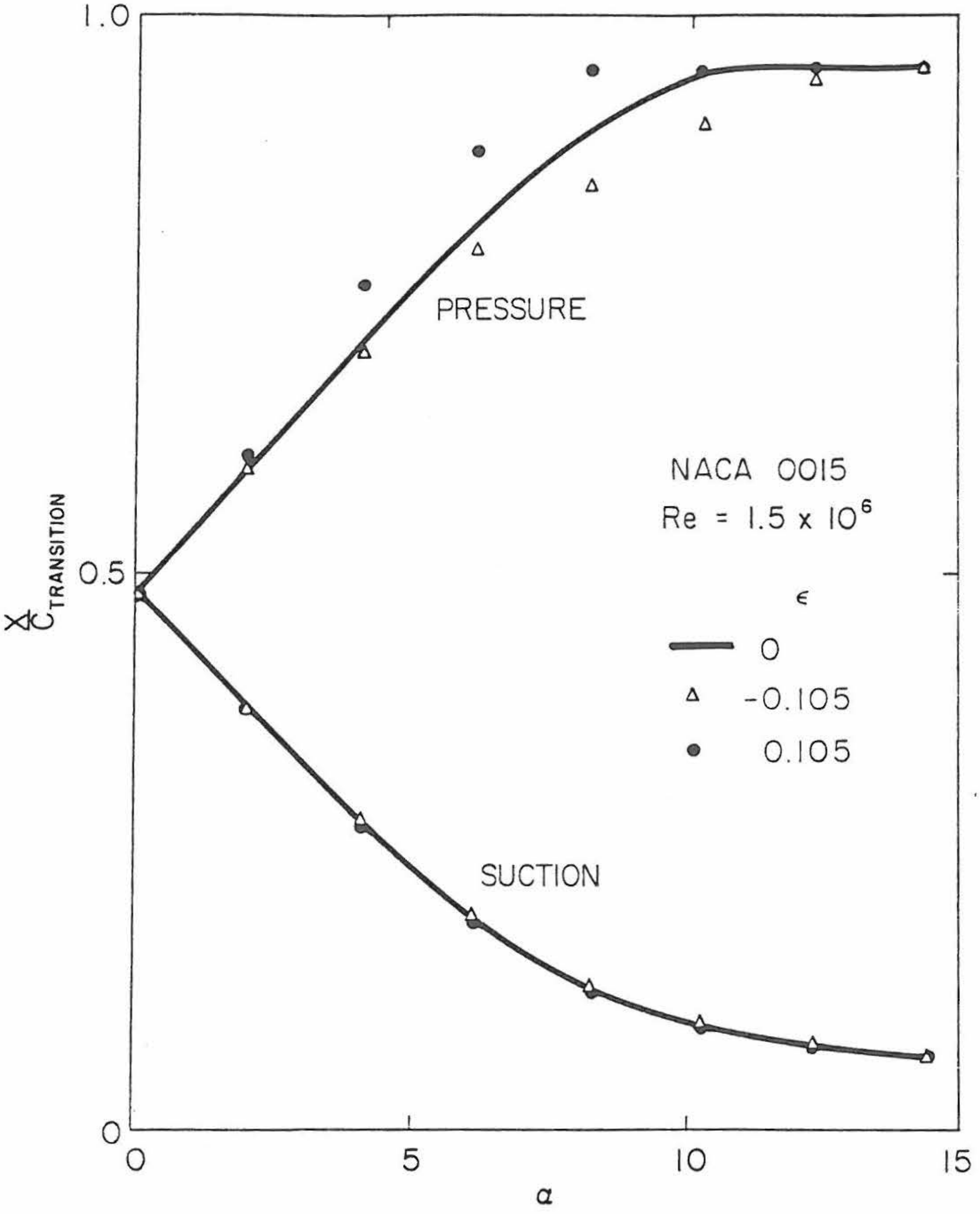

FIGURE 5. Effect of pitching on transition to turbulent boundary layer.

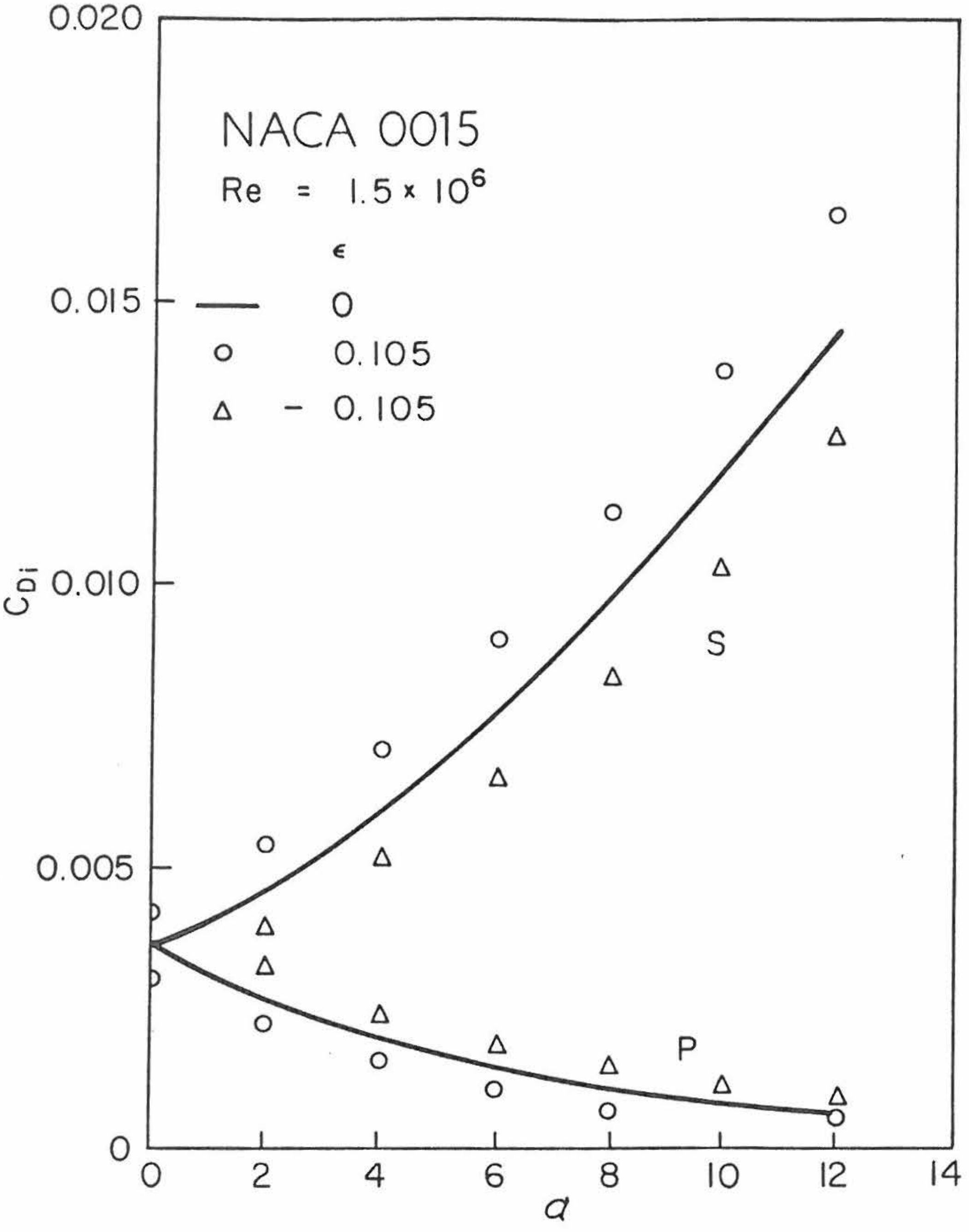

FIGURE 6. Contribution to drag coefficient from suction and pressure surfaces (i = s, suction surface; i = p, pressure surface).

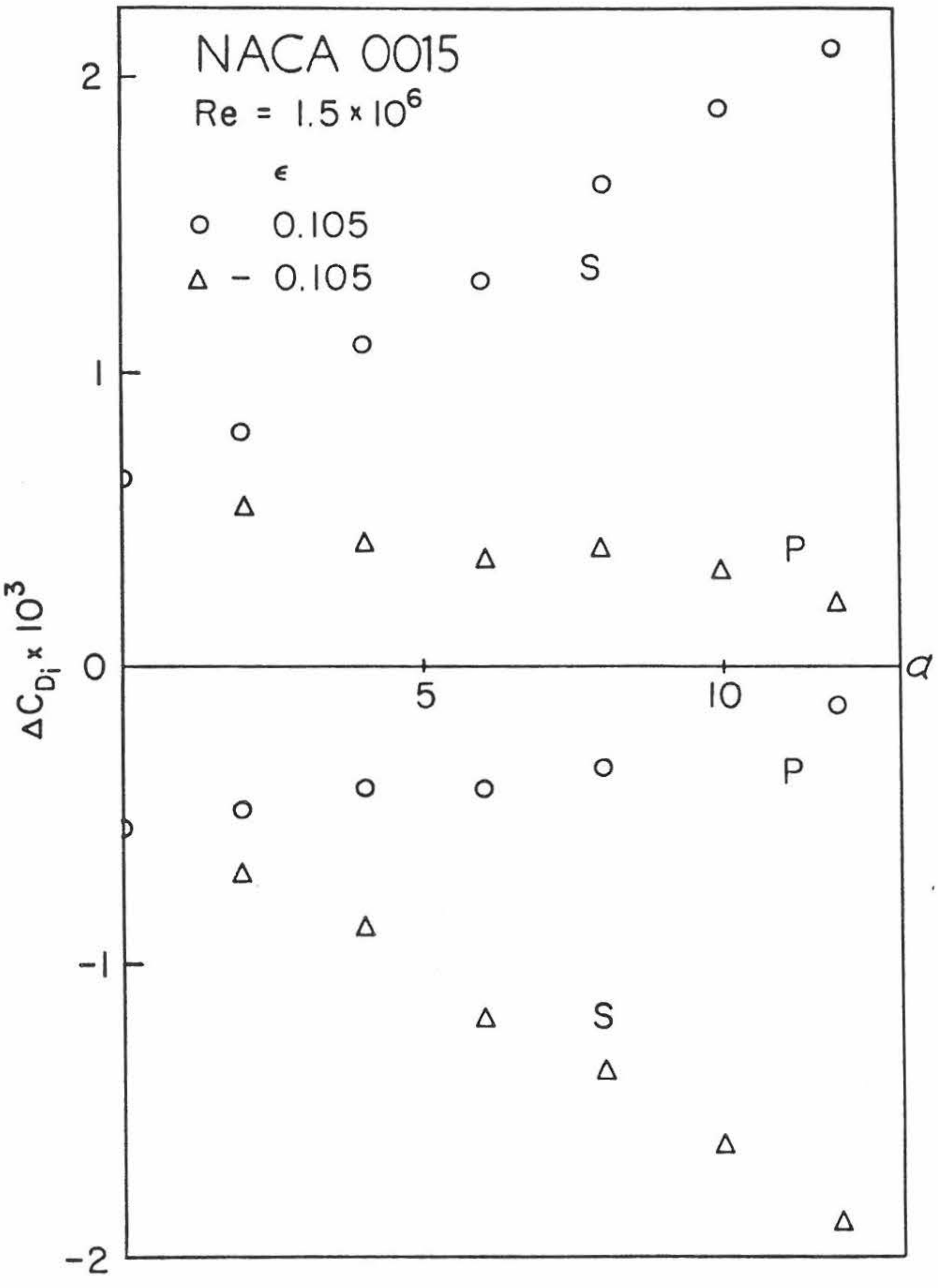

FIGURE 7. Increment in C_d due to pitching (i = s, contribution from suction surface; i = p, contribution from pressure surface).

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