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THE LIFT OF SHARP-LEADING-EDGED DELTA WINGS WITH BLOWING

BY

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ABSTRACT

An analysis of the lift augmentation due to a thin jet of air issuing from a slot along the leading edge of a delta wing is presented. The problem is treated with an extension of the method of Brown and Michael, representing the separated flow on the lee side of the wing by a pair of concentrated vortices and corresponding feeding sheets. It is assumed that the jet is not affected by Coanda forces. The analysis produces qualitative agreement with experiments.

NOMENCLATURE

a	wing semi-span
C_μ	jet momentum coefficient
e_j	$= \cos\beta - i\sin\beta$; complex unit vector in direction of ejection
f, g	universal functions in lift coefficient expressions
F	resultant force on singularity system
F_s	force on connecting vortex sheet
F_v	force on vortex
i	$i^2 = 1$
k	constant in lift augmentation expression
m_j	jet momentum flux per unit length
p	exponent in lift augmentation expression
V_∞	free stream velocity
v_d	velocity at center of vortex
W	complex potential in cross-flow plane
α	angle of attack
β	angle of ejection with respect to the span, positive downward
ϵ	half apex angle
Γ	vortex intensity
ρ_j	jet fluid density
ρ	free stream fluid density
σ	complex representation of physical cross-flow coordinates
θ	complex representation of transformed coordinates
σ_o, θ_o	vortex equilibrium location
$(\bar{\ })$	indicates complex conjugate

CONTENTS

INTRODUCTION

A thin jet of air ejecting from a slot along the leading edge of a delta wing alters the equilibrium position of the vorticity system on the wing upper surface, causing a change in the pressure distribution, which results in lift augmentation.

The jet may leave the wing surface in two different ways, as shown in Fig. 1a and 1b. In one mode, the jet may leave the wing surface with a direction determined by the orientation of the slot alone, the jet never attaching to the wing surface. This mode will be called detached blowing. In another mode, the jet may leave the surface in a direction determined through its contact with the wing surface. This mode will be called tangential blowing, with the reorientation of the jet after it leaves the slot being caused by Coanda forces.

In this work only the first form of blowing will be considered, a case for which an inviscid formulation can be postulated. The problem in conical symmetry with blowing in the direction tangent to the wing the span, was solved by Barsby[1,2], who based his analysis on Smith's[3] description of the separated flow about a conical, flat delta wing. Although Barsby analyzed both flat and cambered wings, his procedure didn't reveal the analytical relationships between the different parameters, nor was the angle of ejection an independent variable. His results are in qualitative agreement with experiments reported by Trebble[4].

The objective of this report is to conduct a first investigation of the effect of the angle of ejection as an additional parameter, in a much simpler mathematical framework than that used by Barsby, and to infer plausible scaling laws between the wing and jet parameters. Parallel to this study, two additional efforts are under way at Stanford; a more extensive, fully non-linear analysis of this problem is being conducted, and an experimental phase is planned to enlarge the presently quite poor data base. To achieve the objectives of this study, the theory first proposed by Brown and Michael[5] is extended to account for blowing at an arbitrary angle with the span. In this approach the separated flow on the wing is represented by a pair of vortices connected to the leading edges by straight vortex sheets, as shown in Fig. 2. Brown and Michael solve the problem in the cross-flow plane by requiring that the forces, but not the moments, acting on the singularity system should be in equilibrium. This method leads to a complex-valued, implicit equation for the equilibrium position of the singularity system. Once the equilibrium position is established, the vortex and sheet intensities are determined from the tangency condition at the leading edge, and with this the lift is readily obtained.

The procedure developed here follows the same steps, except that the force-balance condition is altered to account for the momentum ejected from the wing, at a given angle with the span. The implicit relationship for the equilibrium position of the singularity system in this case differs from that of Brown and Michael's in that it contains a source term, proportional to the momentum intensity of the jet.

MATHEMATICAL MODEL

In order to determine the condition for equilibrium of the singularity system, consider the cross-flow plane with the control volume shown in Fig. 3. The resultant force acting on the singularity system must balance the momentum transfer through the volume walls.

$$F = \int \rho_j \mathbf{v}\mathbf{v}\cdot\mathbf{n}\,dA \qquad (1)$$

Assuming that the momentum associated with the jet aligns itself with the direction of the core within the control volume, and interpreting F as a complex quantity, Eq. (1) becomes

$$F = -m_j e_j \qquad (2)$$

Here F must be the sum of all the aerodynamic forces acting on the singularity system. Expressions for these forces are derived in the complex plane, with the force vectors represented as complex numbers. In the complex representation of the cross-flow plane the wing span is defined on the real axis, as shown in fig. 4. Eq. 2 is now rewritten

$$F_s + F_v = -m_j e_j \qquad (3)$$

The force acting on the feeding sheet is, to first order

$$F_s = i\rho V_\infty \frac{d\Gamma}{dx}(\sigma_0 - a) \qquad (4)$$

The force acting on the main vortex is

$$F_v = -i\rho\left(v_d - V_\infty \epsilon \frac{\sigma_0}{a}\right)\Gamma \qquad (5)$$

where v_d is the velocity induced at the main vortex position by the disturbance potential produced by the wing and the rest of the singularity system. Substituting Eqs. (4) and (5) into Eq. (3) we find

$$v_d = V_\infty \epsilon \left(\frac{2\sigma_o}{a} - 1\right) - i\frac{m_j}{\rho\Gamma}e_j \tag{6}$$

To compute v_d we make use of the transformation

$$\theta = \sqrt{\sigma^2 - a^2} \tag{7}$$

which maps the cross-flow plane into a plane where the wing is represented by a slot along the imaginary axis, as illustrated in fig. 4. In the transformed plane the resultant complex potential is

$$W(\theta) = -\frac{i\Gamma}{2\pi}\log\frac{\theta - \theta_o}{\theta + \bar{\theta}_o} - iV_\infty \alpha\theta \tag{8}$$

The conjugate of the velocity induced at the location of the right-hand vortex is determined from the limit

$$\bar{v}_d = \lim_{\sigma \to \sigma_o}\left[\frac{dW}{d\theta}\frac{d\theta}{d\sigma} + \frac{i\Gamma}{2\pi(\sigma - \sigma_o)}\right] \tag{9}$$

where the second term in the right-hand side represents the velocity induced by the vortex under consideration.
Carrying out this limit and introducing v_d in Eq. (6) we find the following implicit expression for the vortex equilibrium position

$$\frac{i\Gamma}{2\pi}\left[\frac{1}{\theta_o^2 + \theta_o\bar{\theta}_o} - \frac{1}{\theta_o\bar{\theta}_o} - \frac{1}{\theta_o^2} + \frac{a^2}{2\sigma_o^2\theta_o^2}\right]\sigma_o - V_\infty \epsilon\left(\frac{2\bar{\sigma}_o}{a} - 1\right) = i\frac{m_j}{\pi\Gamma}\bar{e}_j \tag{10}$$

The requirement that the velocity at the leading edge be finite yields

$$\frac{2\pi V_\infty \alpha}{\Gamma} = \frac{1}{\theta_o} + \frac{1}{\bar{\theta}_o} \qquad (11)$$

Introducing now the following definition of the jet momentum coefficient:

$$C_\mu = \frac{2m_j}{\rho V_\infty^2 a} \qquad (12)$$

With Eqs. (11) and (12) the equilibrium condition becomes

$$\left[\frac{1}{\theta_o^2 + \theta_o\bar{\theta}_o} - \frac{1}{\theta_o\bar{\theta}_o} - \frac{a^2 - 2\sigma_o^2}{2\sigma_o^2\theta_o^2}\right]\sigma_o + i\frac{\epsilon}{\alpha}\left[\frac{1}{\theta_o} + \frac{1}{\bar{\theta}_o}\right]\left[\frac{2\bar{\sigma}_o}{a} - 1\right] = \frac{a}{4\pi}\frac{C_\mu}{\alpha^2}\left[\frac{1}{\theta_o} + \frac{1}{\bar{\theta}_o}\right]^2 \bar{e}_j \qquad (13)$$

The term in the right-hand side contains the blowing information.
Let's consider the expression for the lift coefficient derived by Brown and Michael

$$C_L = \frac{4\pi}{a^2}\epsilon\alpha\theta_o\bar{\theta}_o + 2\pi\alpha\epsilon \qquad (14)$$

The first term on the right-hand side represents the vortex lift, a non linear function of α, and the second term represents the linear part of the lift, that which would be produced by the wing in the attached flow case. To assess what form Eq. (14) will take in our case, we notice that the apex angle, angle of attack, momentum coefficient appear in two groups in Eq. (13), while the direction of blowing, β, appears through the definition of e_j. Since the product $\theta_o\bar{\theta}_o$ is obtained by solving Eq. (13), the lift coefficient will take the following form

$$C_L = \frac{4\pi}{a^2}\epsilon\alpha f\left(\frac{\epsilon}{\alpha}, \frac{C_\mu}{\alpha^2}, \beta\right) + 2\pi\alpha\epsilon \qquad (15)$$

In this expression f represents a universal function of its arguments, and is not given analytically since no exact analytic solution of Eq. (13) is possible. For some limiting values of the arguments, however, analytical approximations to Eq. (15) are possible. Notice that the blowing information appears in the group C_μ/α^2. This dependence could be helpful in arranging the problem parameters when conducting experiments.

To obtain such limiting forms consider first the approximation to the lift coefficient in the absence of blowing, as obtained by Brown and Michael through linearization of Eq. (13)[5]

$$\frac{C_L}{\epsilon^2} = \frac{2\pi\alpha}{\epsilon} + k(\alpha/\epsilon)^{5/3} \qquad (16)$$

Hence, the condition that the no-blowing case should revert to Eq. (16) gives

$$\frac{C_L}{\epsilon^2} = \frac{2\pi\alpha}{\epsilon} + k_1(\alpha/\epsilon)^{5/3}\left[g(C_\mu/\alpha^2, \beta) + 1\right] \qquad (17)$$

Here g is another universal function of its arguments. To analyze the form of g for small values of its argument, we will consider the case of $\beta = 0$. It can be shown numerically that g is regular for $C_\mu/\alpha^2 \rightarrow 0$. Expanding g in C_μ/α^2, we ge the following liminting form, valid for small C_μ/α^2 and $\beta = 0$:

$$\Delta C_L = k(\epsilon/\alpha)^{1/3} C_\mu \qquad (18)$$

where k has been redefined as a constant to be determined from experiments. The constraint imposed on blowing intensity in order for Eq. (18) to be applicable guarantees that no singularity at zero angle of attack will occur. Verification of Eq. (18) would require extremelly small blowing intensities. For moderate values of C_μ/α^2, and within a range of such values, a convenient representation is obtained by expressing the function in Eq. (17) as a power of its argument, this leads to

$$\Delta C_L = k\epsilon^{1/3}\alpha^{(5/3-2p)} C_\mu{}^p \qquad (19)$$

Experiments[4] have shown that the lift grows slowly for increasing α at moderate blowing intensity; this fact imposes the constraint $p < 5/6$.
It can also be shown, by numerical evaluation of the function g, that the dependence on angle of ejection is rather weak for $\beta < 30°$, so that Eqs. (18) and (19) can also be considered a good approximation for small ejection angles.

RESULTS AND DISCUSSION

Fig. 5 shows the comparison between theory and the experimental results of Trebble[4], currently the only available source of experimental information. In this case the angle of ejection is equal to zero. The calculations reproduce the correct trend, but they produce values significantly lower that the measurements. In contrast, Barsby's theoretical results were significantly higher than the measurements. The discrepancies between the present method and the experiments are most likely due to the oversimplifying assumptions of the model, which make it intrinsically weak.

Figs. 6, 7, 8 and 9 illustrate the increment of lift coefficient in carpet form, for different angles of ejection and the same apex angle. The angle of ejection is considered positive downward. It can be seen that the influence of ejection angle on the aerodynamic component of the lift is quite small for angles less than 30°. For the same inclination with respect to the span, the jet pointing upward causes more deterioration of lift gain.

The measurements presented in Ref. 4 didn't lend themselves to an accurate evaluation of the exponent p in Eq. (19). However, using the healthiest part of such data, a preliminary assessment was made; it was found that for C_μ in the range .1 to .175 the estimated value of p from the exponent of α in Eq. (19) was about .77, while the value of p from the exponent of C_μ was in the range .7 to .75.

CONCLUSIONS

The problem of blowing from the leading edges of a slender delta wing has been analyzed using a generalization of the vortex-connecting-sheet model for the separated flow on the lee side of the wing. The results lead to the following observations:

Blowing from the leading edges of a slender delta wing causes an increment of lift, beyond the vertical component of ejected momentum. Both theory and experiments suggest that with blowing coefficients of about 0.05, gains in lift of the order of 30% are possible. This lift improvement is rather insensitive to small values of the angle of ejection. For ejection angles of up to 30° there is little effect on lift augmentation. The aerodynamic component of lift augmentation deteriorates more quickly as function of angle of ejection in the case of downward ejection. It appears that the optimum angle of ejection is about 0°.

The theory reproduces the same trends as the ones shown by the only available source of experimental information. However, it underpredicts the lift gain by about 30%.

The theory suggests a way of grouping the different non-dimensional quantities of the problem, in such a manner that the non-linear part of the lift becomes a function of $\epsilon\alpha$, ϵ/α, and C_μ/α^2. Since the angle of attack appears in more than one non-dimensional group, checking this conclusion would require conducting experiments with wings of different apex angles.

It is expected that this particular way of grouping the wing and jet parameters will reduce considerably the size of the matrix of an experimental program.

Results indicate that for small values of C_μ/α^2 the lift gain is a linear function of blowing intensity.

For small values of α/ϵ and ejection angles of less than 30°, the lift gain due to blowing is expected to scale in the following form:

$$\frac{\Delta C_L}{\epsilon^2} = k(\alpha/\epsilon)^{5/3} g(C_\mu/\alpha^2)$$

When both α/ϵ and C_μ/α^2 are small, the scaling takes the form:

$$\Delta C_L = k(\epsilon/\alpha)^{1/3} C_\mu$$

For moderate C_μ/α^2 the following arrangement could be used for fitting experiemtnal data:

$$\Delta C_L = k\epsilon^{1/3} \alpha^{(5/3-2p)} C_\mu{}^p$$
$$p < 5/6$$

Although the exponent p is not independent of blowing setting, such an arrangement could still be helpful in conducting a best fit withing a range of blowing intensity.

REFERENCES

1. J.E. Barsby: Calculations of the effect of blowing from the leading edges of a slender delta wing. ARC R&M 3692, 1971.

2. J.E. Barsby: Calculations of the effects of blowing from the leading edges of a cambered delta wing. ARC R&M 3800, 1978.

3. J.H.B. Smith: Improved calculations of leading edge separation from slender delta wings. RAE TR 66070, 1966.

4. W.J.G. Trebble: Exploratory investigation of the effects of blowing from the leading edge of a delta wing. ARC R&M 3518, 1966.

5. C.E. Brown and W.H. Michael: On slender delta wings with leading edge separation. NACA TN 3430, 1955; Journal of the Aerospace Sciences, Vol 21, 1954.

FIGURES

(a) (b)

Fig. 1 Detached and tangential blowing schemes.

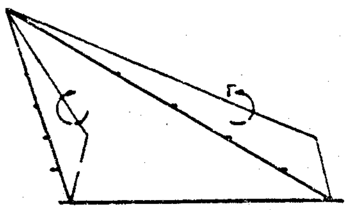

Fig. 2 Brown and Michael model.

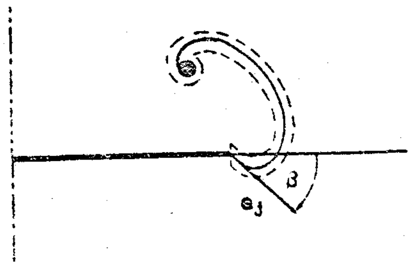

Fig. 3 Jet sheet control volume.

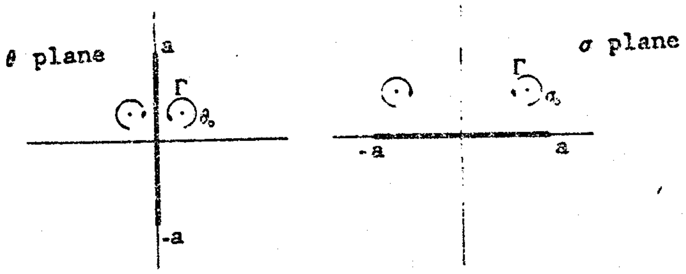

Fig. 4 Comformal transformation of cross-flow plane.

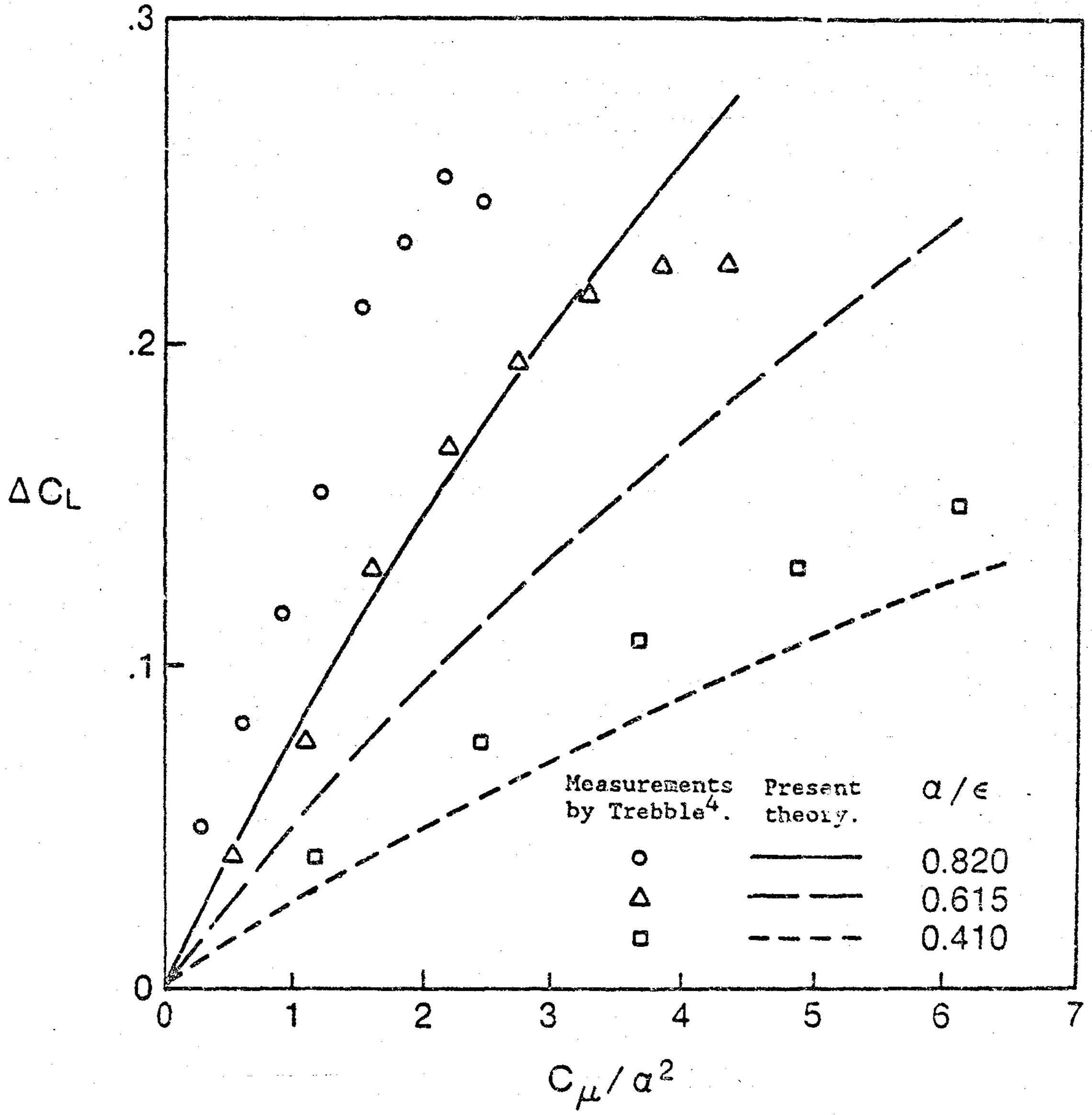

Fig. 5 Comparison of theory and experiment, $\epsilon = 20°$.

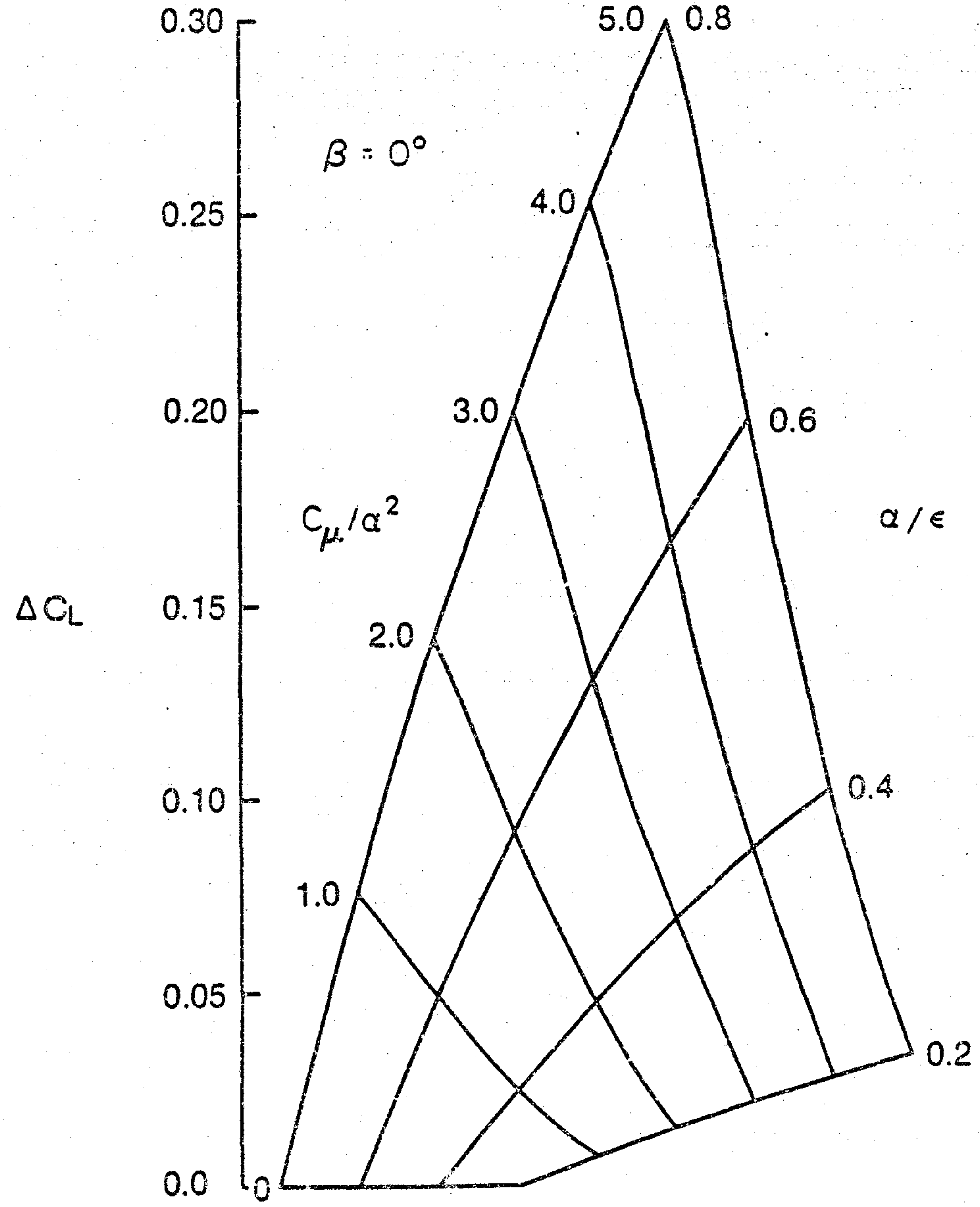

Fig. 6 Performance plot.
$\epsilon = 20°$

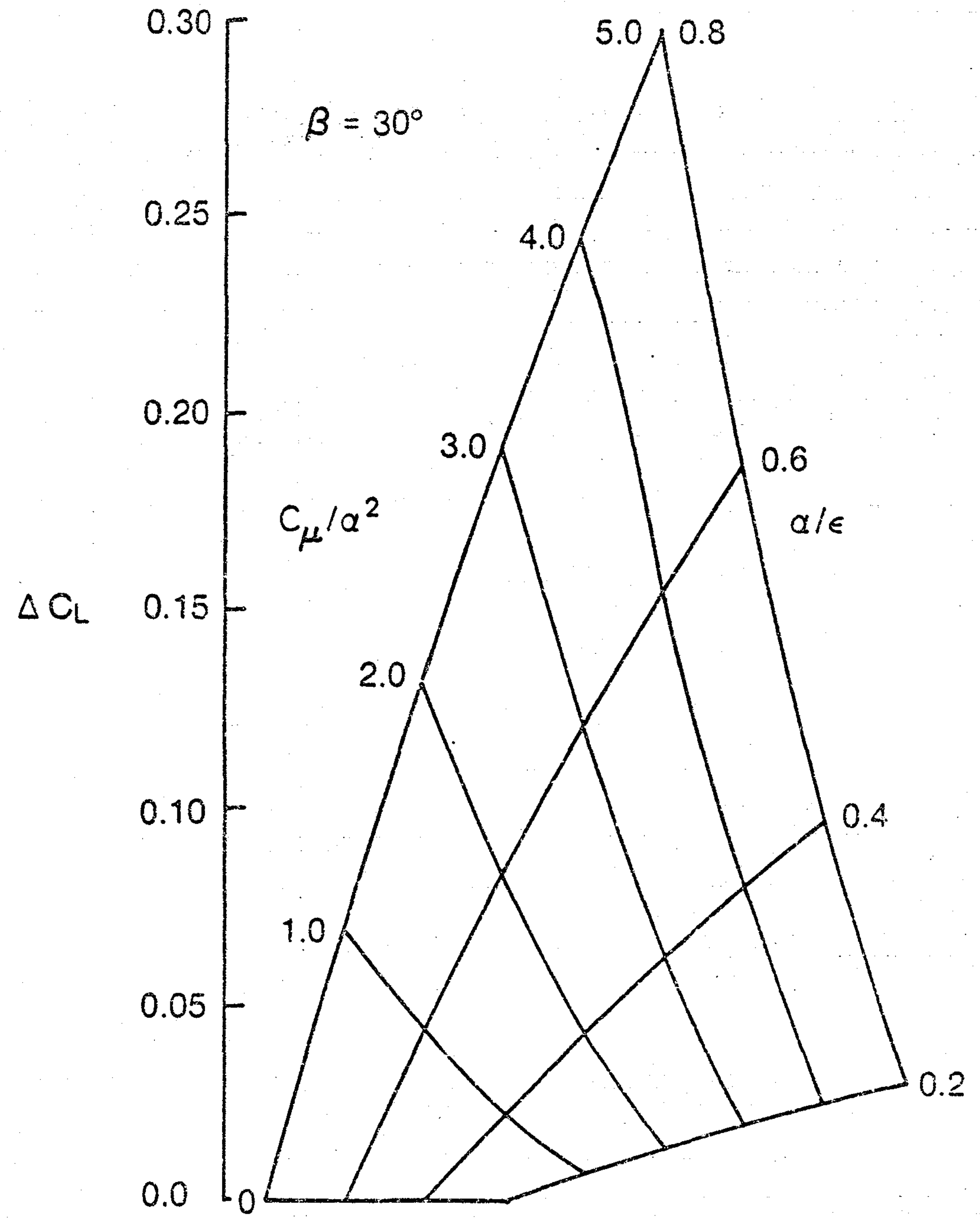

Fig. 7 Performance plot.

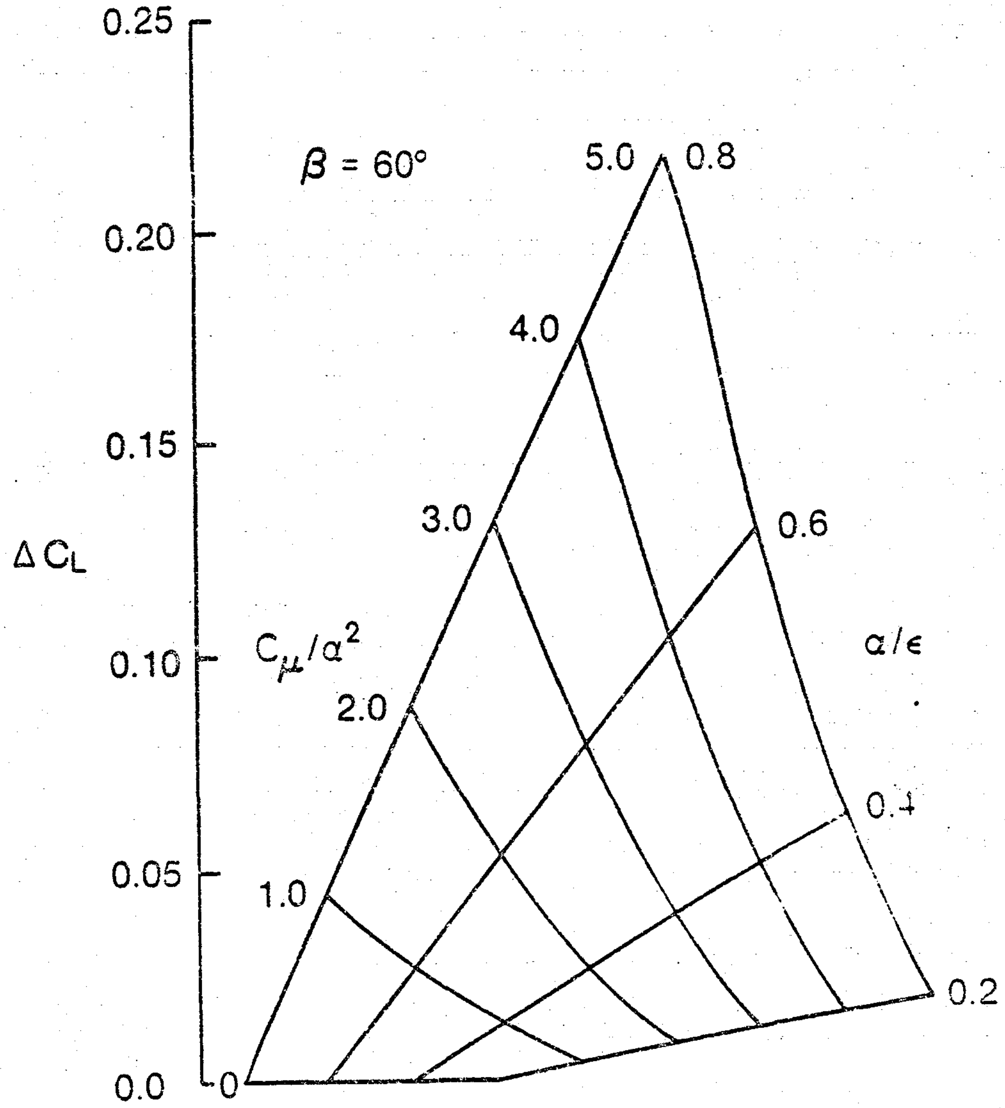

Fig. 8 Performance plot.

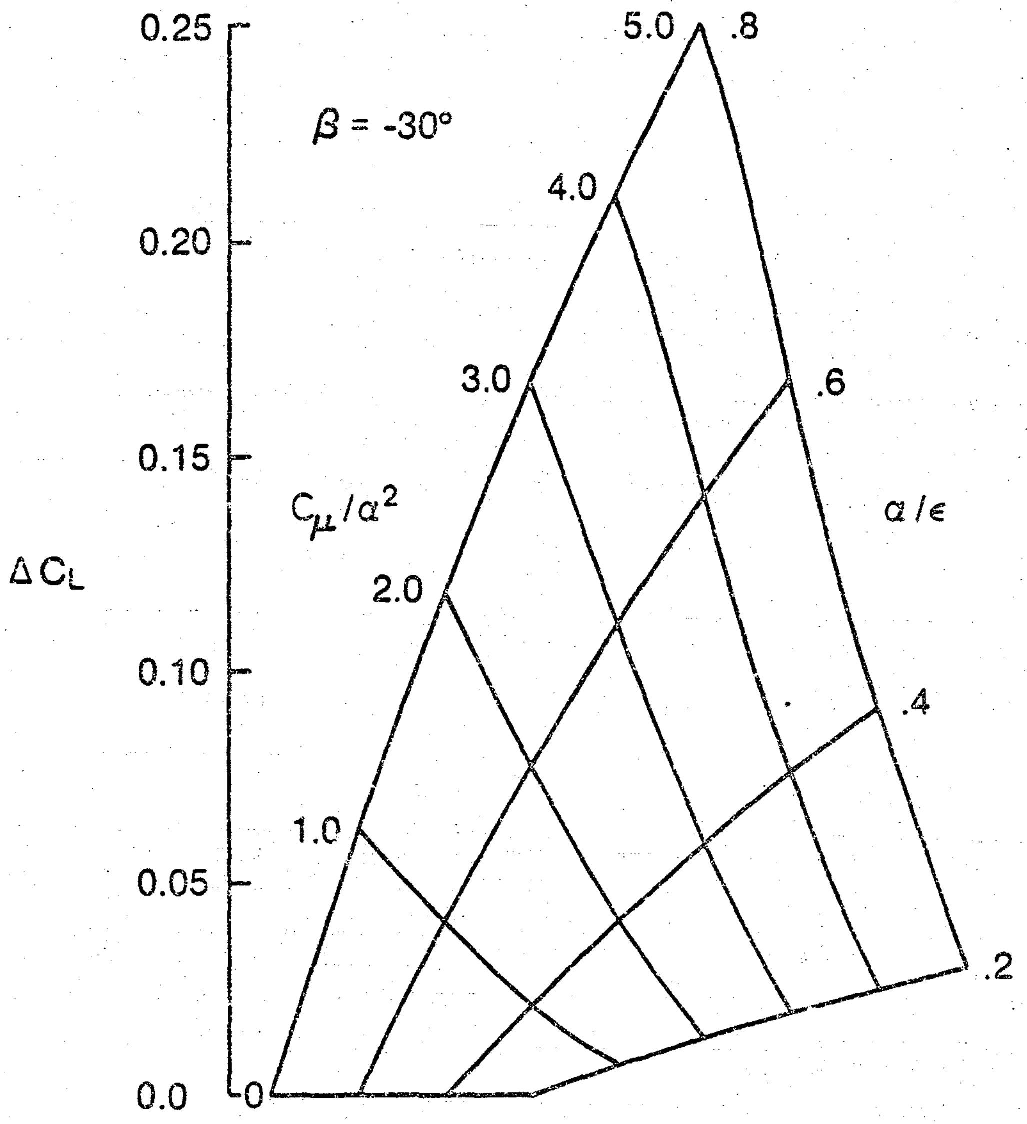

Fig. 9 Performance plot.

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