N.A.E. Library

C.P. No. 42
(13 112)
A.R.C. Technical Report

NATIONAL AERONAUTICAL ESTABLISHMENT
LIBRARY

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
CURRENT PAPERS

Wind Tunnel Tests on the Effect of Accretion of Ice on Control Characteristics in Two-Dimensional Flow

By

A. S. Halliday, B.Sc., Ph.D., A. S. Batson, B.Sc.,
and Miss D. K. Cox, B.Sc.,
of the Aerodynamics Division, N.P.L.

Crown Copyright Reserved

LONDON : HIS MAJESTY'S STATIONERY OFFICE

1951

Price 2s 6d net

Wind Tunnel Tests on the Effect of Accretion of Ice on Control Characteristics in Two-dimensional Flow.

- By -
A. S. Halliday, B.Sc., Ph.D., A. S. Batson, B.Sc.,
and Miss D. K. Cox, B.Sc.,
of the Aerodynamics Division, N.P.L.

1st May, 1950⁺

SUMMARY

It was thought that a fine trailing-edge angle would reduce the adverse effect of ice accretion as compared with a blunter trailing-edge, which was a feature of the original tail, of Ref. 1 for which ice accretion was found to have dangerous effects on elevator behaviour. Some tests in two-dimensional flow reported herein were carried out at the N.P.L. to provide data for the estimation of the effect of ice accretion when the trailing-edge angle of the aerofoil section is changed. The effects of aspect ratio on the results are computed and plotted in the report.

The results of these tests are disappointing in that for elevators of 40% chord no advantage can be expected from a finer trailing-edge angle so far as the effects of large accretions of ice on the leading edge are concerned; but for a 20% flap the finer trailing-edge appears to be superior. Larger trailing-edge angles, however, give rise to much larger changes in control characteristics due to normal shifts of transition point on the tailplane and to changes in Reynolds number. Where possible b_1 for a rudder should be negative in view of the risks of icing.

1. INTRODUCTION

In Ref. 1 some tests at the R.A.E. on a model of a tailplane and elevator were reported, in which it was shown that ice accretion on the leading edge of the tailplane, such as was observed in flight, would lead to considerable changes in elevator hinge-moment characteristics. These changes took the form of positive additions to b_1 and b_2 which would increase the danger of uncontrollable free-elevator oscillations of the aircraft in pitch. Since it had been found that a trailing-edge angle of the order 10° or less led to a very small influence on b_1 and b_2 due to transition movements and Reynolds number[2], it was considered advisable to test the effect of trailing-edge angle on the adverse results of ice accretion. This was done on N.P.L.1541 section models by two-dimensional tests.

2. DESCRIPTION OF THE MODEL

Figs. 1a and 1b give the leading dimensions of the model. The span of the portion of the model on which the forces were measured was 4 feet, and, as the flow was to be two-dimensional, dummy end pieces of

1' 6"/

⁺This is a revise of 12,403, 9th June, 1949.

Published by permission of the Director, National Physical Laboratory.

1' 6" span, with adjustable flaps, were fixed to the tunnel walls so as to form a continuation of the working portion except for clearance gaps of about 1/16". The tunnel in which the tests were conducted was the 7ft. No. 3.

Eight controls were used for the experiments, four of approximately 12" chord and four of 6" chord with the trailing-edge angles of 4.5°, 9.1°, 15° and 19.2°. The "ice" on the leading edge of the aerofoil was reproduced in plasticine mounted on a thin wood former suitable for attachment to the wing (see Fig. 1c). The photograph in Fig.2 shows the nature of the ice representation, which is "Ice A" of Ref. 1.

3. RANGE OF EXPERIMENT

Hinge moments throughout the experiments were measured for control angles of $\eta = 10^\circ$, 5°, 4°, 3° and 2°, both positive and negative as well as for controls at zero setting. The conditions governing the flow over the wing were as follows:

(1) Smooth wing with no ice and no transition wire;

(2) Simulation of ice on the nose of the wing as shown in Fig. 1c and in the pictorial representation of Fig. 2;

(3) Transition wire of 0.022" diameter at 0.1c from the leading edge of the aerofoil.

For condition (1) lift, pitching moments, and hinge moments were measured for the full range of control angles at angles of incidence of -5°, $\pm 2^\circ$, and 0°.

For conditions (2) and (3) similar measurements were made at angles of incidence of $\pm 2^\circ$ and 0°.

For conditions (1), (2) and (3) with zero control angle, measurements were made at angles of incidence of 5°, 4°, 3° and 1° both positive and negative.

4. PRESENTATION OF RESULTS

Figs. 3 to 10 give values of hinge moment, C_H, plotted against control angle η with $\alpha = 0$, and also against angle of incidence α, with $\eta = 0$ for the four different trailing-edge angles. It will be noted that the hinge moment becomes less negative as trailing-edge angle is increased and that when $E = 0.4$ the effect of adding the transition wire is usually to lighten the control to an extent increasing with increase of trailing-edge angle, except when this angle is very fine: when $E = 0.2$, the effect of adding the transition wire is to lighten the control approximately to an equal extent for all trailing-edge angles. Ice deposit on leading edge always reduces the negative hinge moment. The change of C_H due to ice is more clearly shown in Figs. 11 and 12 where it is plotted against change of α and η respectively. As trailing-edge angle of the 40% flap is reduced change of C_H due to ice deposit is increased for a given control movement but is decreased for a given incidence change. The effect of ice is somewhat similar for the 20% flap but ΔC_H is markedly smaller.

Figs. 13 to 18 give values of a_1, a_2, b_1, b_2 plotted against trailing-edge angle, τ; a_1 and b_1 are the slopes of the curves of lift and hinge moment against α, whilst a_2 and b_2 are

slopes/

slopes of similar curves plotted against η for constant α. The slopes a_2 and b_2 are calculated, using least squares theory, from all observed values between $\eta = \pm 5^\circ$, and also from all observed values between $\eta = \pm 3^\circ$. Straight lines have been drawn for trailing-edge angles up to 15°, this procedure being justified when the accuracy of the experiments is taken into consideration. The results for the largest trailing-edge angle (19.2°), which may be more sensitive to the character of the boundary layer at the trailing edge, do not, however, always fall into line.

The values of a_1, a_2, b_1, b_2 plotted in Figs. 13 to 18 have been corrected for tunnel interference. After allowing for tunnel blockage the corrections+ given in Ref. 2 have been applied. They are as follows:-

$$a_1 = \frac{(a_1)'}{1 + 0.00570\,(a_1)' + 0.01670\,(m_1)'}$$

$$b_1 = \frac{(b_1)'}{1 + D\,(a_1)' + 0.01670\,(m_1)'}$$

$$a_2 = (a_2)' - a_1\left[0.00570\,(a_2)' + 0.01670\,(m_2)'\right]$$

$$b_2 = (b_2)' - b_1\left[0.D\,(a_2)' + 0.01670\,(m_2)'\right]$$

where $D = 0.01721, 0.01571$ for flap chord ratio $E = 0.2, 0.4$ respectively, and $(a_1)'$, $(b_1)'$, $(m_1)'$, $(b_2)'$, $(m_2)'$ are experimental values of $\frac{\partial C_L}{\partial \alpha}$, $\frac{\partial C_H}{\partial \alpha}$, $\frac{\partial C_m}{\partial \alpha}$, $\frac{\partial C_L}{\partial \eta}$, $\frac{\partial C_H}{\partial \eta}$, $\frac{\partial C_m}{\partial \eta}$ respectively after correcting for tunnel blockage, C_m being given about the quarter-chord position.

5./

+The corrections given above differ from those of Ref. 2 in that ℓ_1 and ℓ_2 are replaced by

$$\left\{\frac{1}{4} - \frac{(m_1)'}{(a_1)'}\right\} \quad \text{and} \quad \left\{\frac{1}{4} - \frac{(m_2)'}{(a_2)'}\right\}$$

respectively. Since these corrections were applied, it has been decided and is now accepted that the interference at the centre of the tunnel due to the tunnel-wall boundary layer is negligible. This means that, in the corrections given in Ref. 2, δ^* should be zero. The values of a_1, a_2, b_1, and b_2 given in this report are therefore numerically too large, the approximate error being 1.25% in a_1 and a_2, 1.6% in b_1 and negligible in b_2.

5. CORRECTION FOR ASPECT RATIO

In order to apply the two-dimensional results to wings of finite aspect ratio of rectangular plan-form with full-span controls of constant flap-chord ratio, E , Garner gives the following relations:

$$(1) \qquad \frac{A}{(a_1)_{eff.}} = \frac{A}{a_1} + \frac{1 + \tau'}{\pi} + 0.032 \sqrt{\frac{a_1}{A}}$$

$$(2) \qquad (a_2)_{eff.} = \frac{a_2}{a_1} (a_1)_{eff.}$$

$$(3) \qquad \frac{b_1}{(b_1)_{eff.}} = 1 + \frac{a_1}{A} \left[\frac{1 + \tau'}{\pi} + 0.032\, F \sqrt{\frac{a_1}{A}} \right] ,$$

where $F = 4.09, 3.69$, for $E = 0.2, 0.4$ respectively.

$$(4) \qquad (b_2)_{eff.} = \frac{a_2}{a_1} (b_1)_{eff.} + (a_1)_{eff.} \left(b_2 - \frac{a_2 b_1}{a_1} \right) \left(\frac{1}{a_1} + \frac{1 + \tau'}{\pi A} \right)$$

where $(a_1)_{eff.}$, $(a_2)_{eff.}$, $(b_1)_{eff.}$, $(b_2)_{eff.}$ are the values of the coefficients for finite aspect ratio, A . τ' as defined by Glauert may be taken to be $0.105 \left(\frac{2A}{a_1}\right) - 0.01 \left(\frac{2A}{a_1}\right)^2$.

Using these corrections, curves in Figs. 19 and 20 have been prepared for $E = 0.4$ and 0.2 respectively in which b_1 and b_2 are plotted against the reciprocal of aspect ratio, 1/A . The left-hand figures show the effect of ice as compared with the values of the coefficients with "normal" transition at 0.1c.; whilst the right-hand figures show corresponding effects of normal movements of transition. In the latter case the movement of transition is of the order 0.5c. It is clear that the effects of ice are on the whole of the same order for finite as for infinite aspect ratio, although somewhat reduced as aspect ratio decreases. Fig. 19, representative of an elevator flap (40%) indicates no advantage in reducing trailing edge angle from the point of view of the effects of ice; but the effects of normal movements of transition increase rapidly as trailing-edge angle increases. On the other hand Fig. 20, for a 20% flap, representative of an aileron, suggests some advantage in keeping the trailing edge fine.

6. CONCLUSIONS

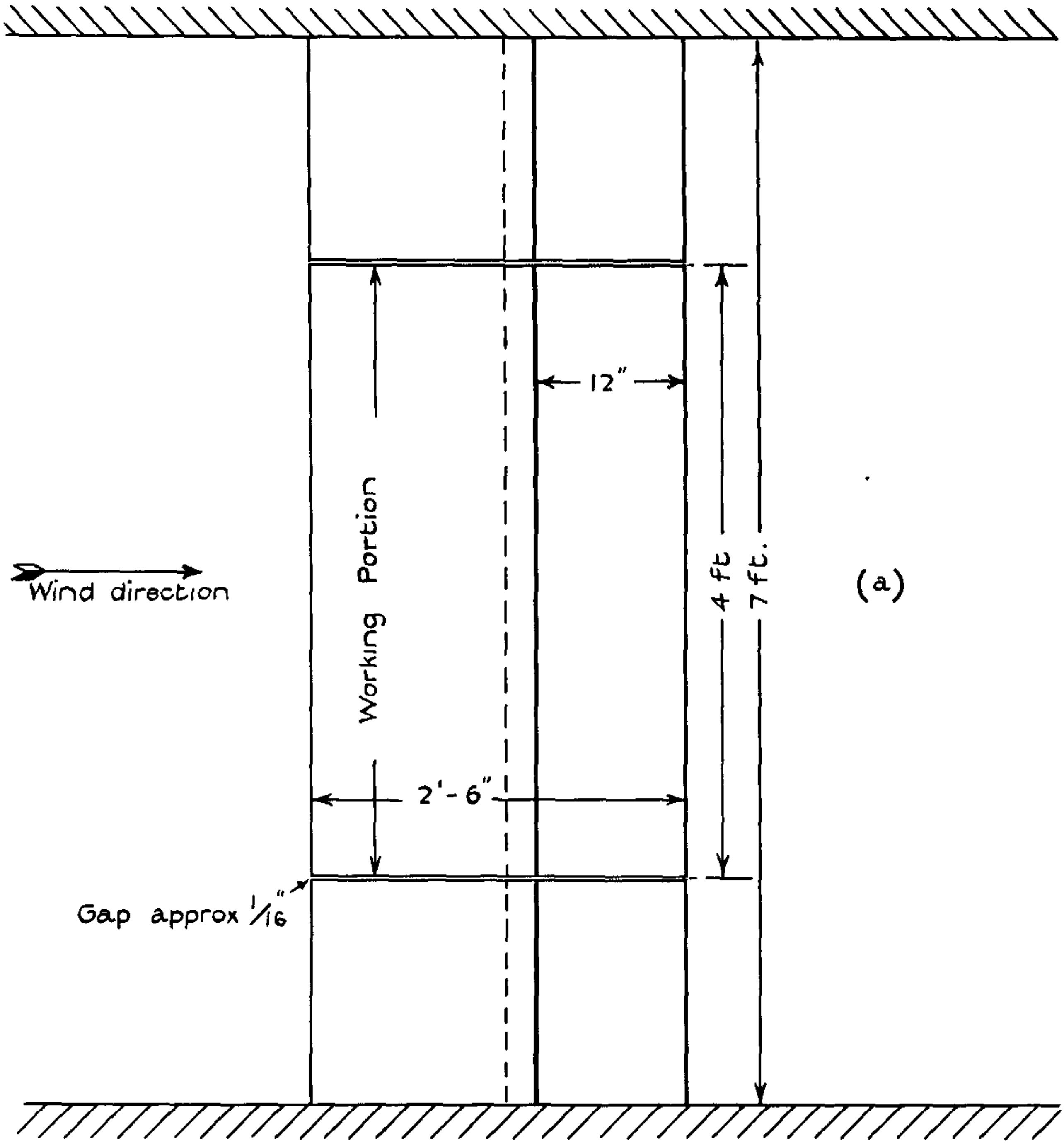
It is pointed out in Ref. 3 that the most serious consequence of the changes in hinge-moment characteristics of elevator or rudder resulting from ice accretion is the increasing risk of undamped oscillations with control free which may prove uncontrollable and even dangerous. It is therefore necessary to design with a sufficient margin in b_1 and b_2 to eliminate such a risk. In Fig. 21 a diagram is shown with co-ordinates b_1 and b_2 with typical stability boundaries for control-free oscillations, boundary R for lateral and boundary E for longitudinal oscillations. The change in the characteristic point of the elevator due to icing of the tailplane of Ref. 1 is shown in the figure. Starting from a representative "safe design" point P the icing effects deduced from the present series of experiments are also shown. It is apparent that if the design b_1 is the maximum permissible positive value, the small trailing-edge angle presents a rather worse case than the large angle with regard to the adverse effects of icing. There is a strong argument for avoiding a positive value of b_1 for the rudder in view of the fact that the boundary R is invariably on the negative side of the b_1 axis. Figure 21a shows the effect of icing given by the R.A.E. tests on the same sections but with a partial span flap on a finite span wing (aspect ratio 2.7).

REFERENCES

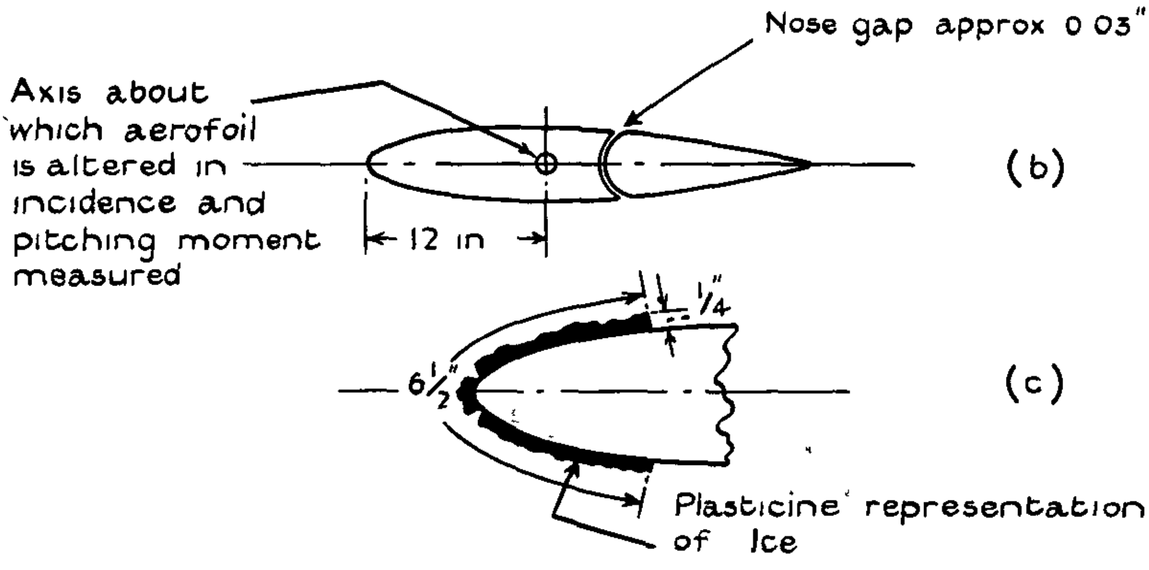
No.	Author(s)	Title, etc.
1	A. S. Worrall and J. R. Cole	Wind Tunnel Measurements of the Effect of Ice Formation on the Hinge-moment Characteristics of an Elevator. R.A.E. Technical Note No. Aero.1875. (March, 1947). A.R.C.10,691
2	L. W. Bryant and A. S. Batson	Two-dimensional Control Characteristics. Hinge Moments on Plain Flaps. (9th December, 1947). A.R.C.11,092 Embodied in a revised form in R. & M.2730
3	D. E. Morris	Designing to avoid Dangerous Behaviour of an Aircraft due to the Effects on Control Hinge Moments of Ice on the Leading Edge of the Fixed Surface. R.A.E. Technical Note Aero.1878. (March, 1947). A.R.C.10,670

KM.

FIG 1.



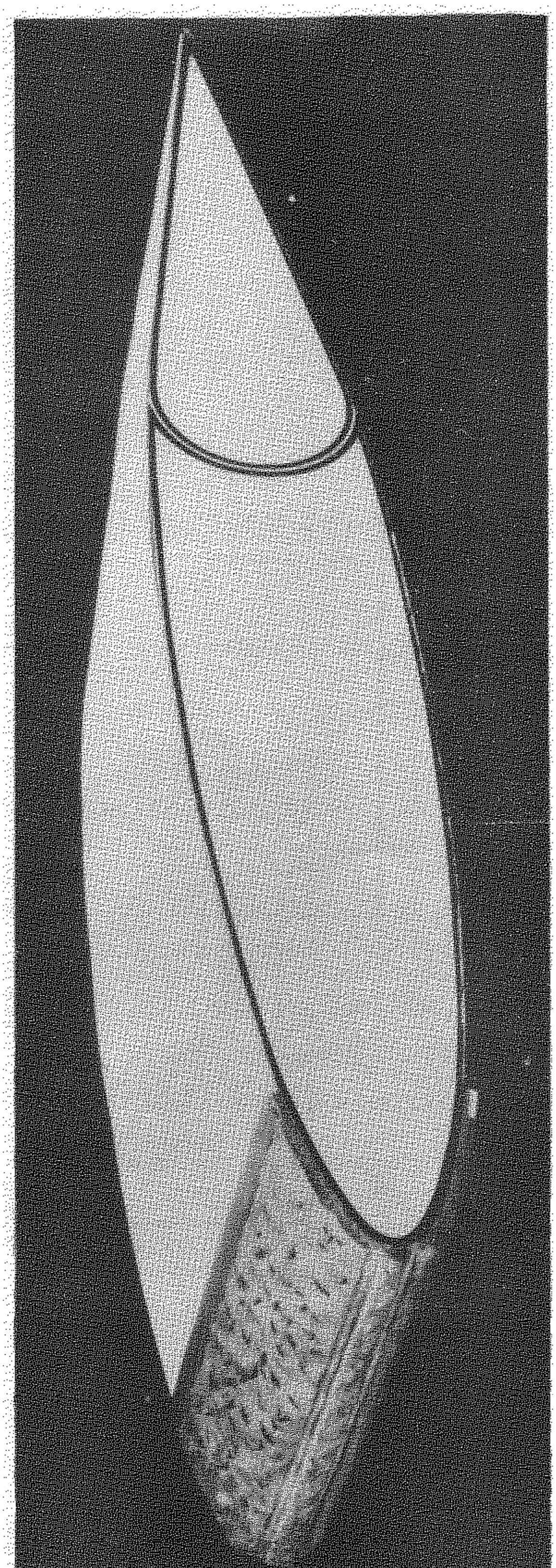
Wind direction
Working Portion
12"
2'-6"
4 ft
7 ft.
Gap approx 1/16"
(a)



Nose gap approx 0 03"
Axis about which aerofoil is altered in incidence and pitching moment measured
12 in
(b)
1/4"
6 1/2"
(c)
Plasticine representation of Ice

OT

Fig. 2.



Photographic Representation of Ice Formation.

FIGS 3, & 4

FIG 3

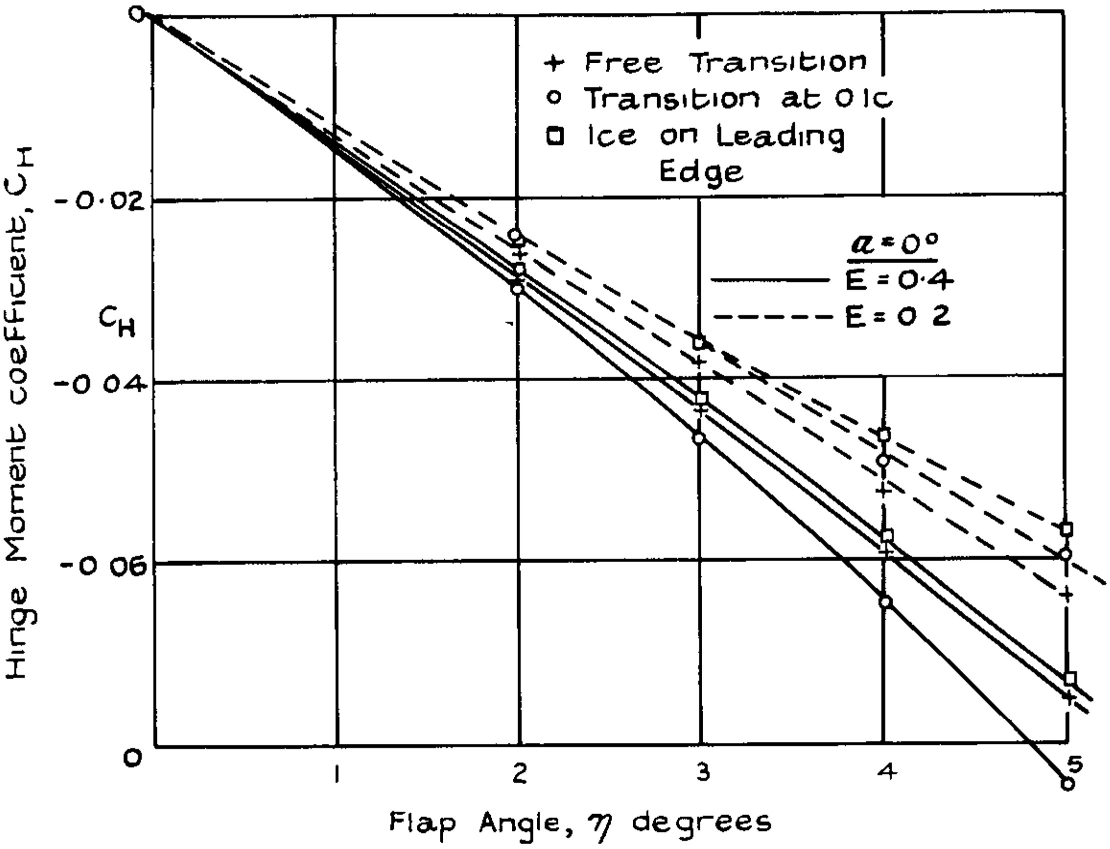
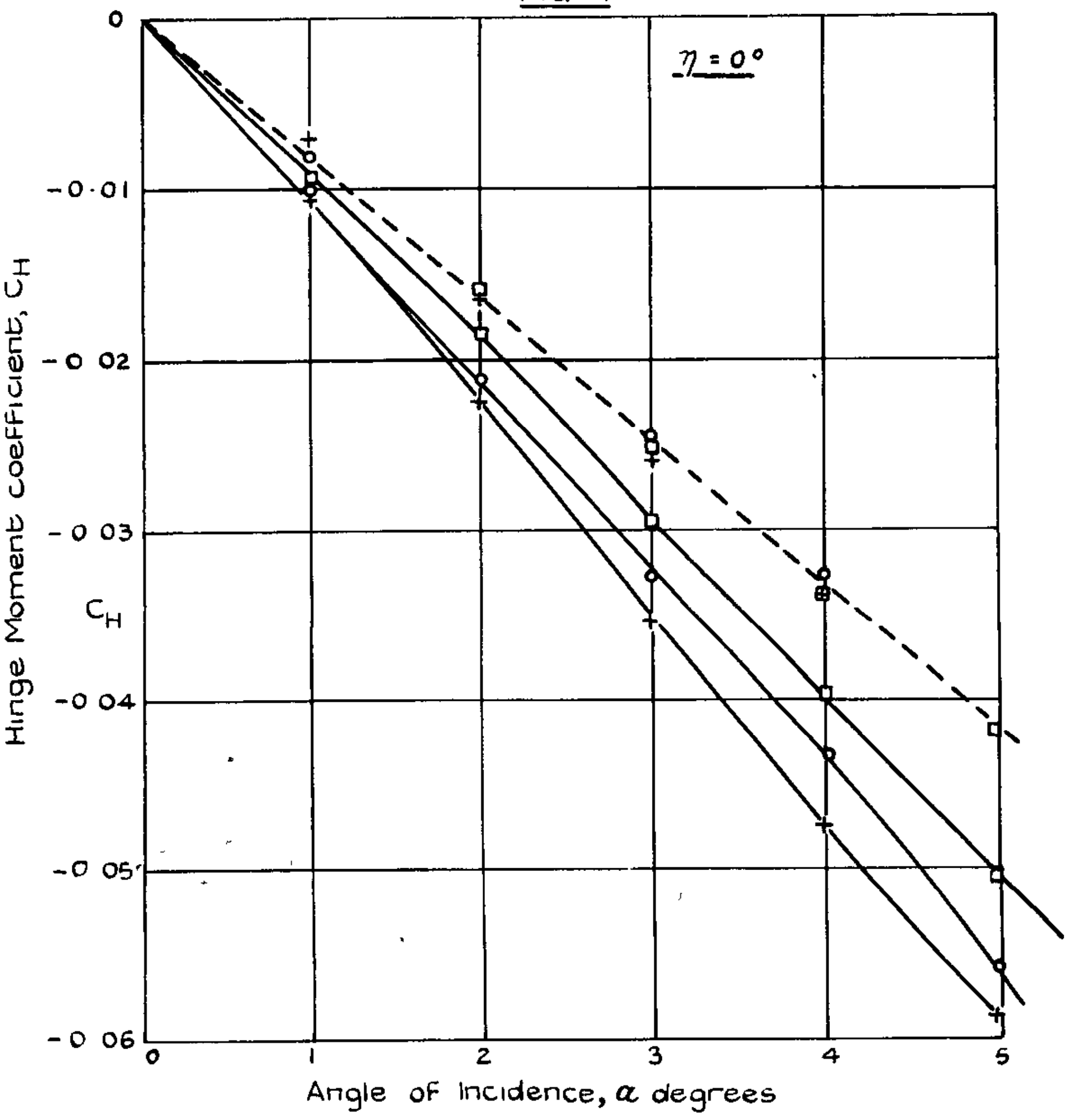


FIG 4



Trailing Edge Angle, τ = 4.5°

FIG 5

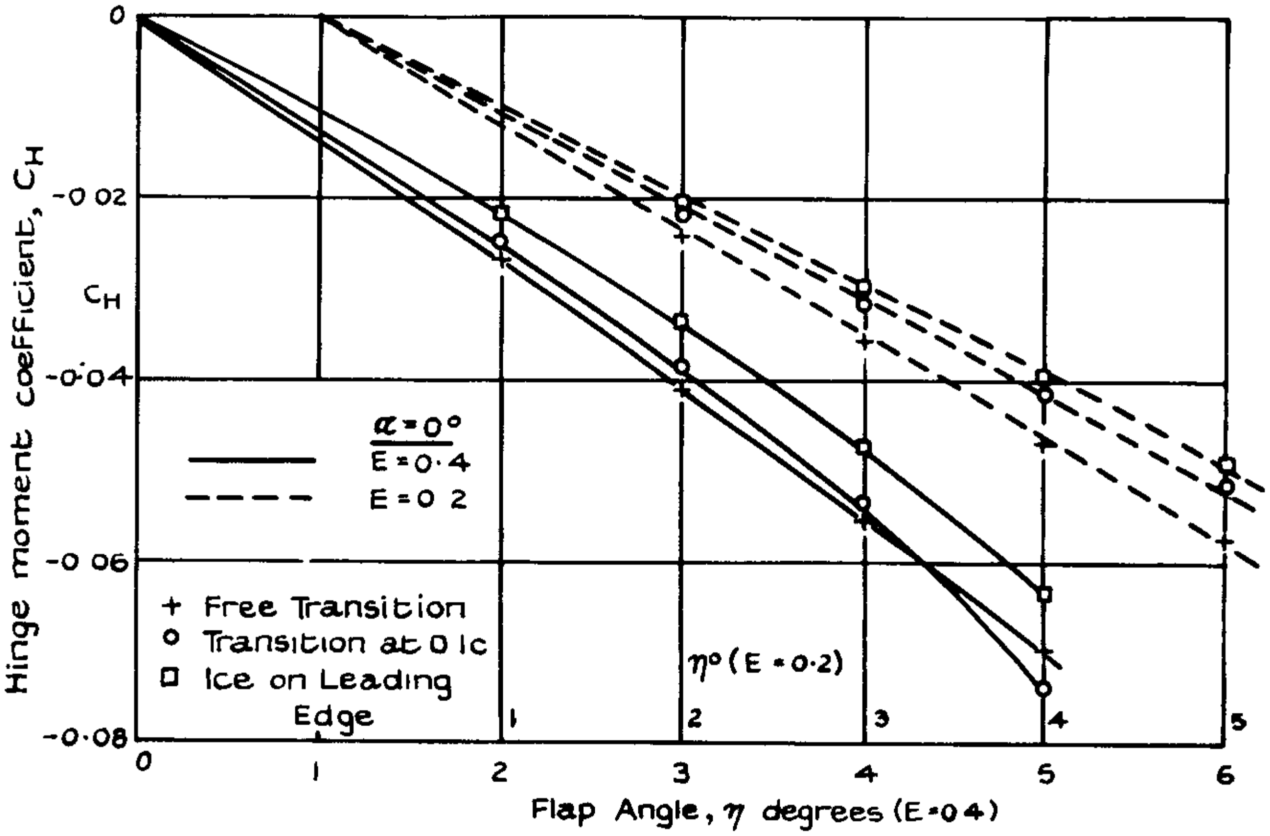
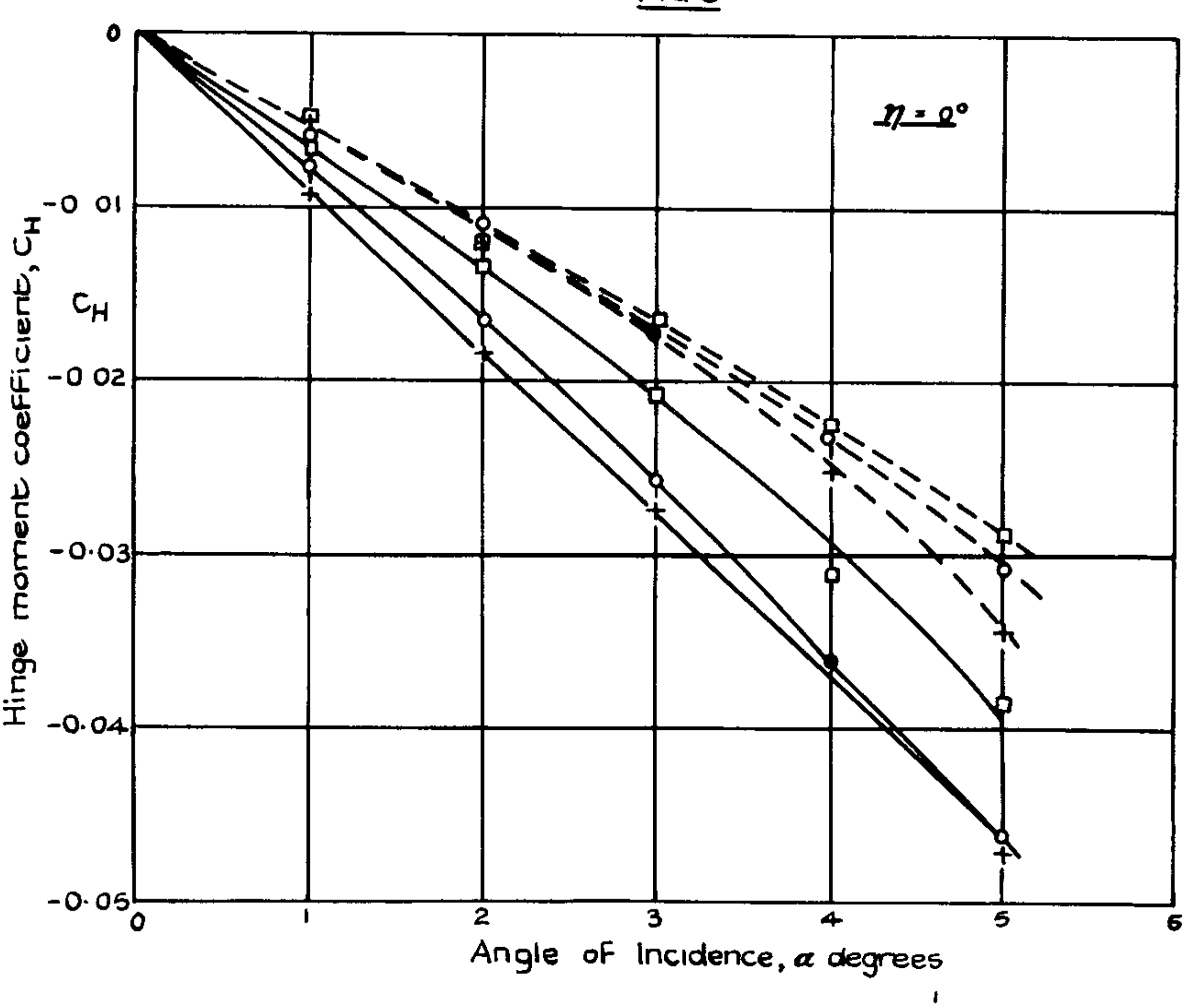


FIG 6



Trailing Edge Angle, $\tau = 9.1°$

FIG 7

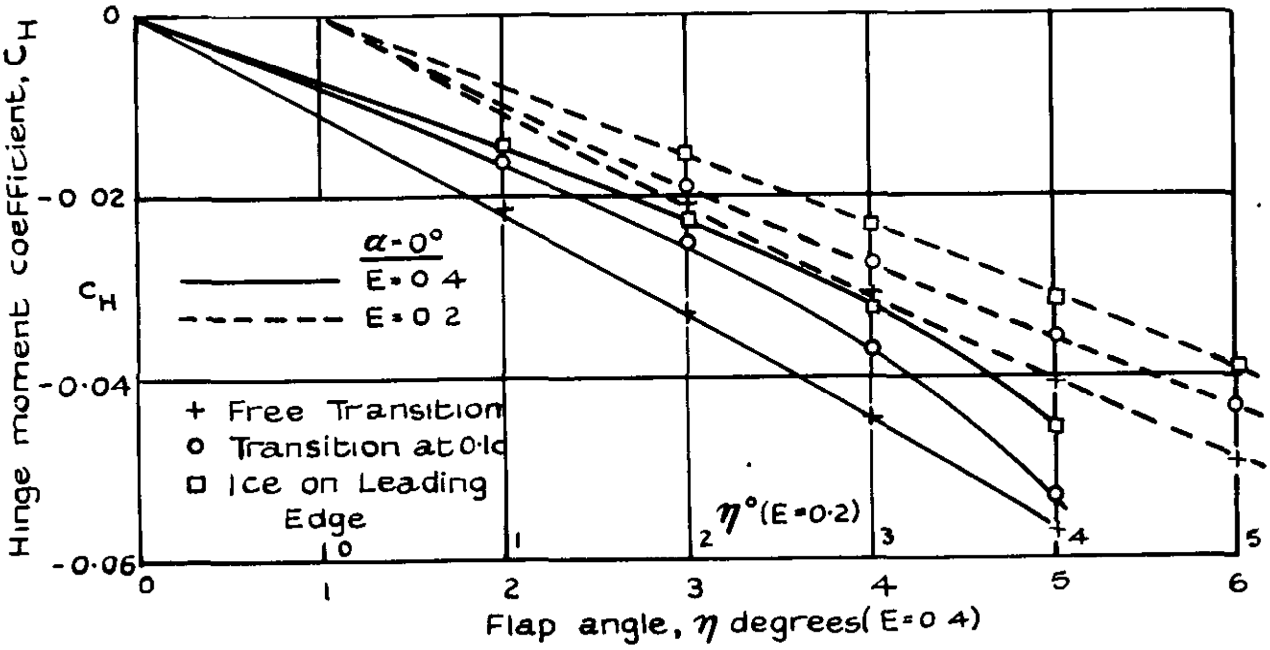
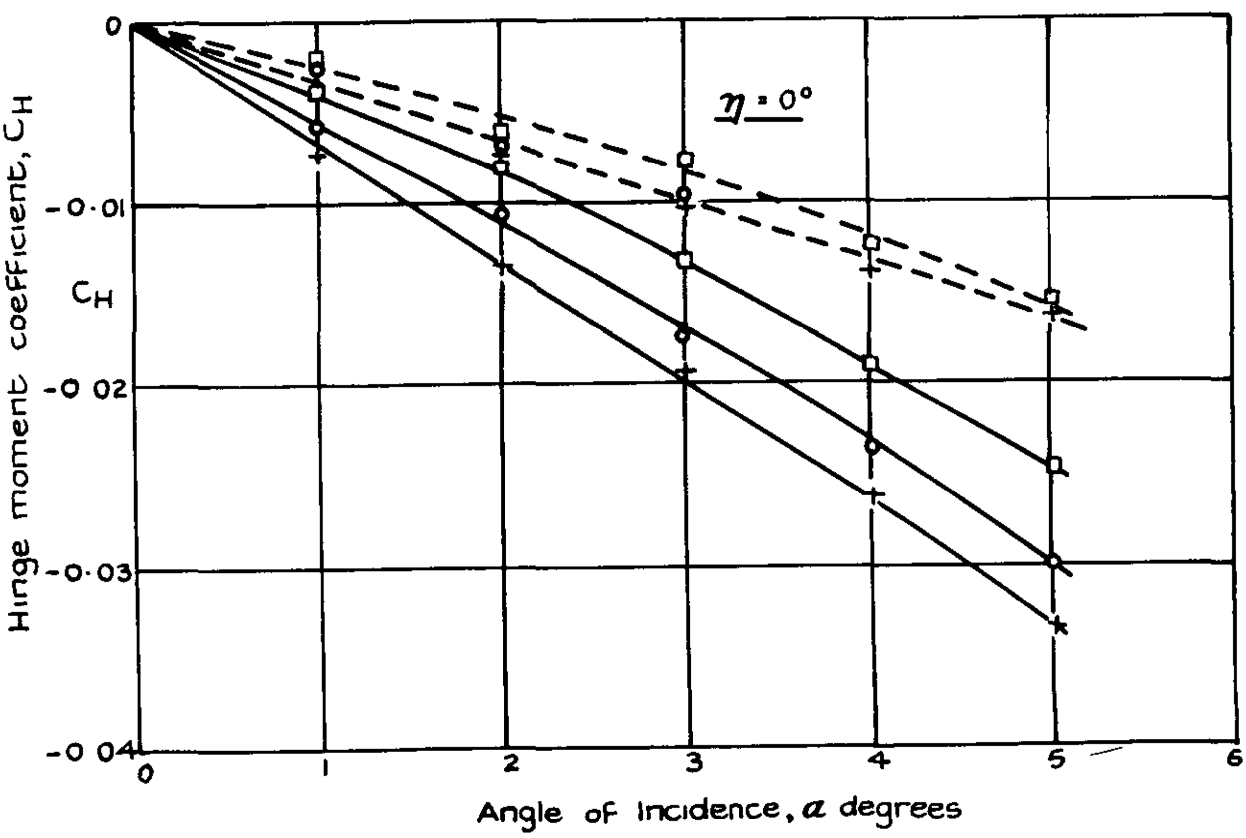


FIG 8



Trailing Edge Angle, $\tau = 15°$

FIG. 9

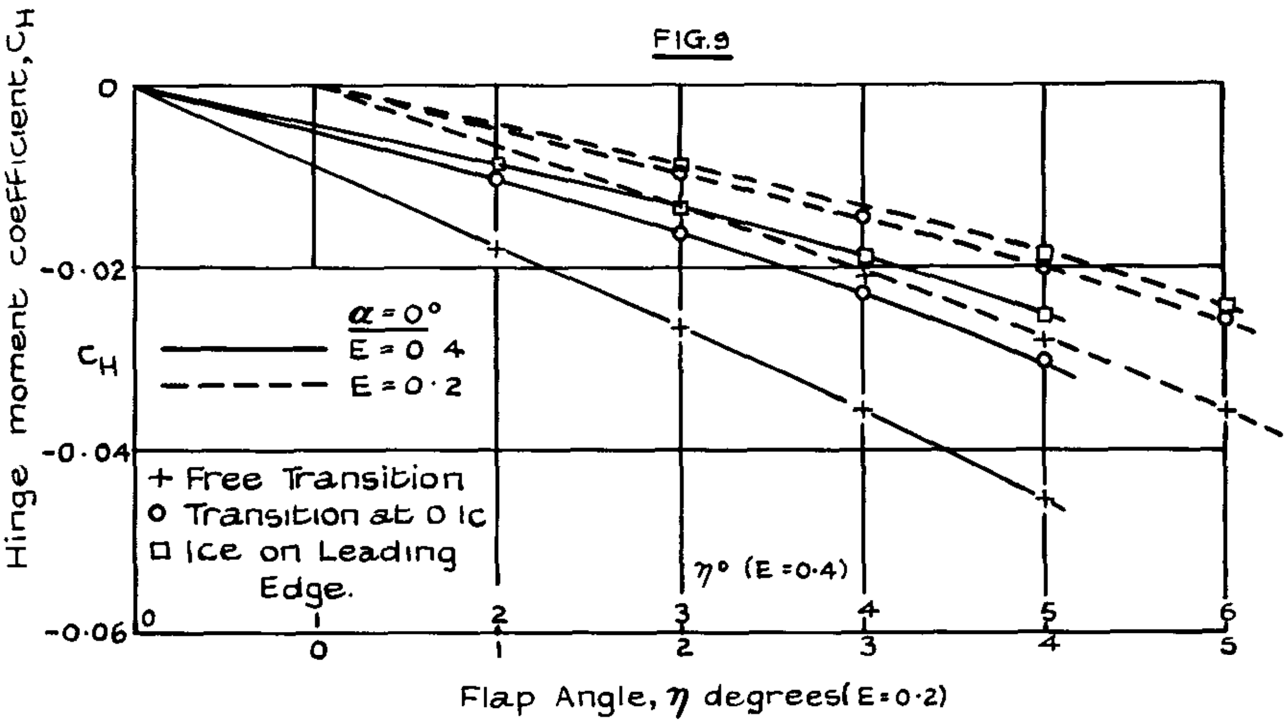
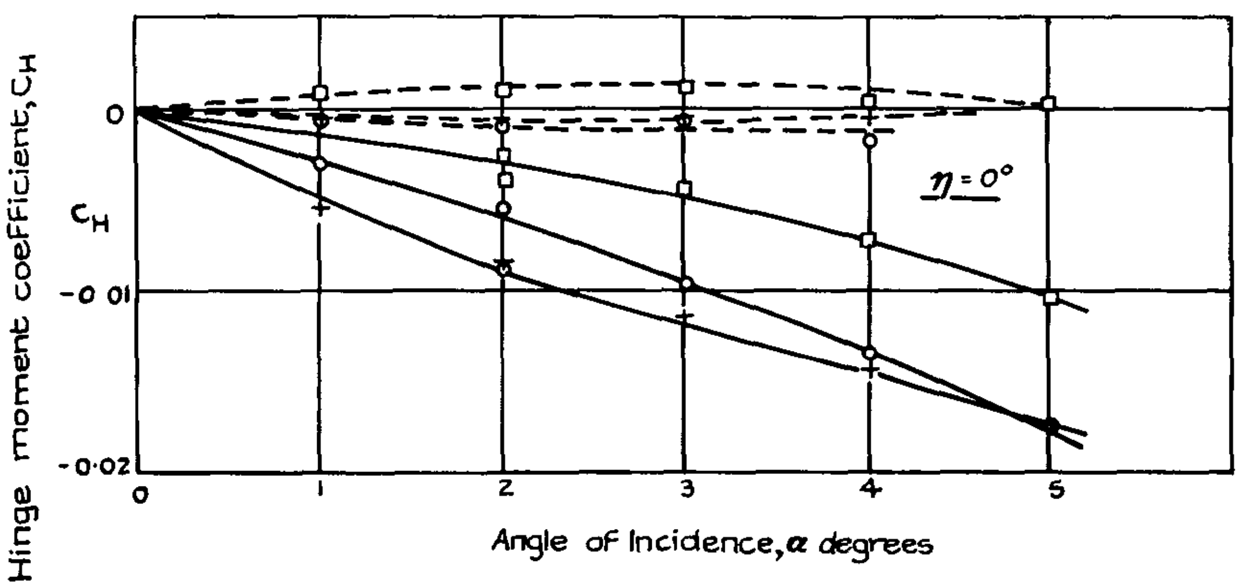


FIG 10



Trailing Edge Angle, $\tau = 19·2°$

FIG 11(a)

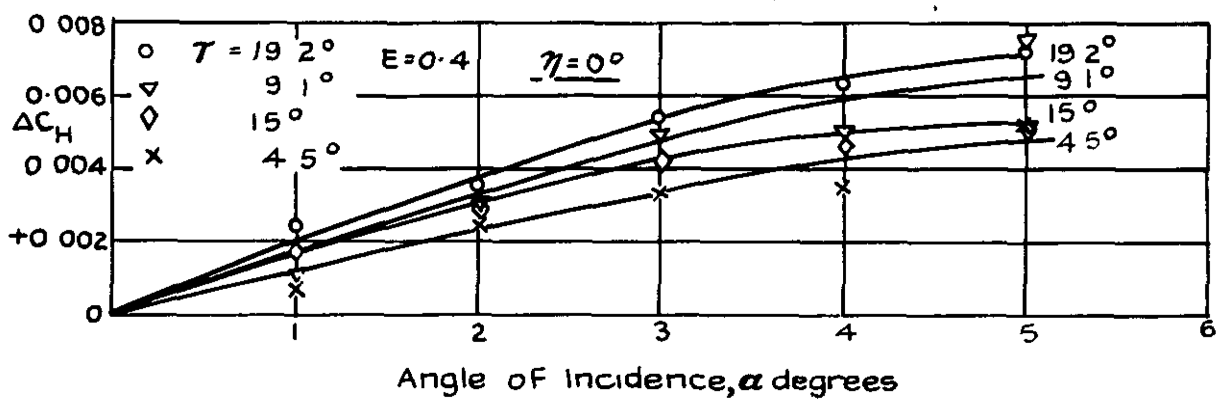


FIG 11(b)

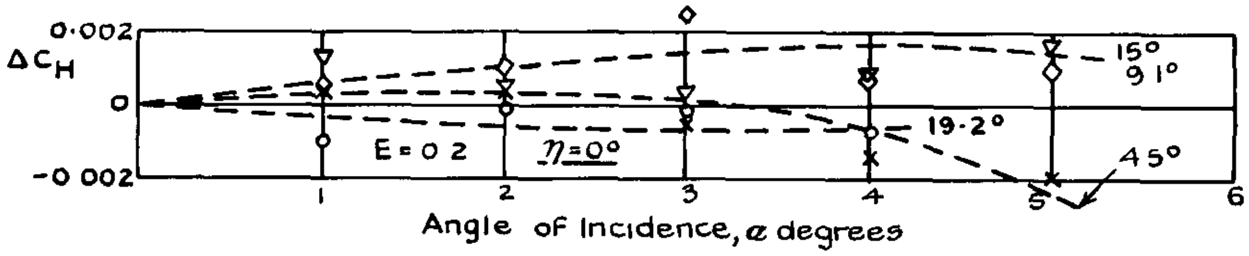


FIG 12 (a)

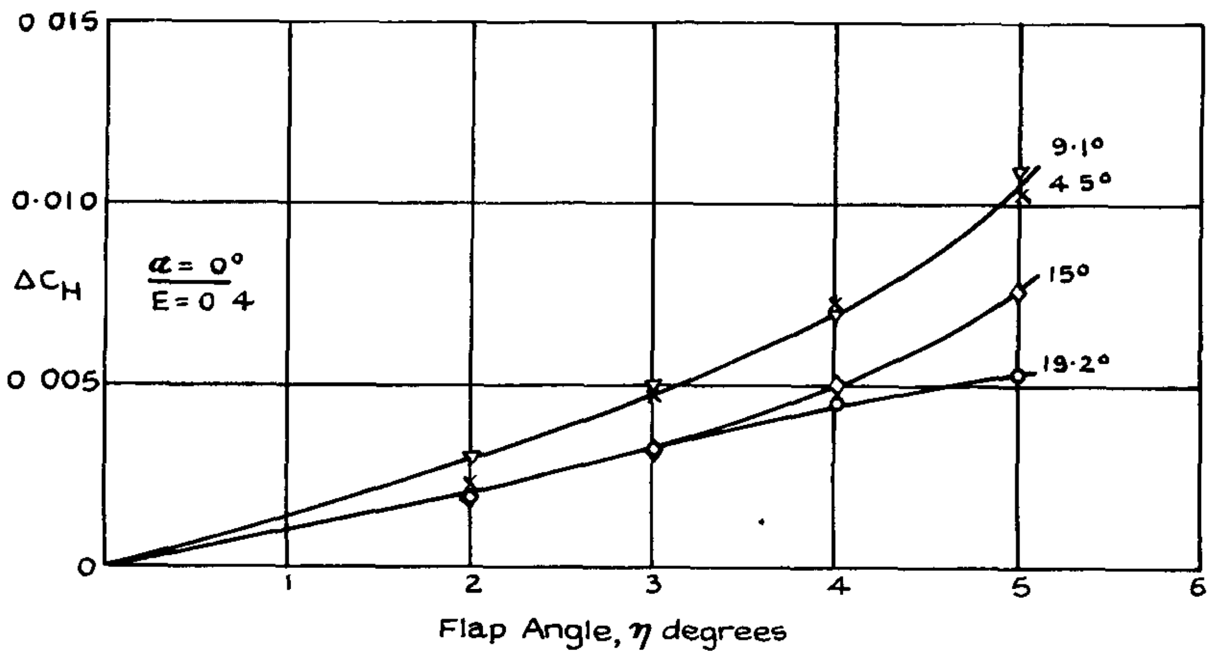
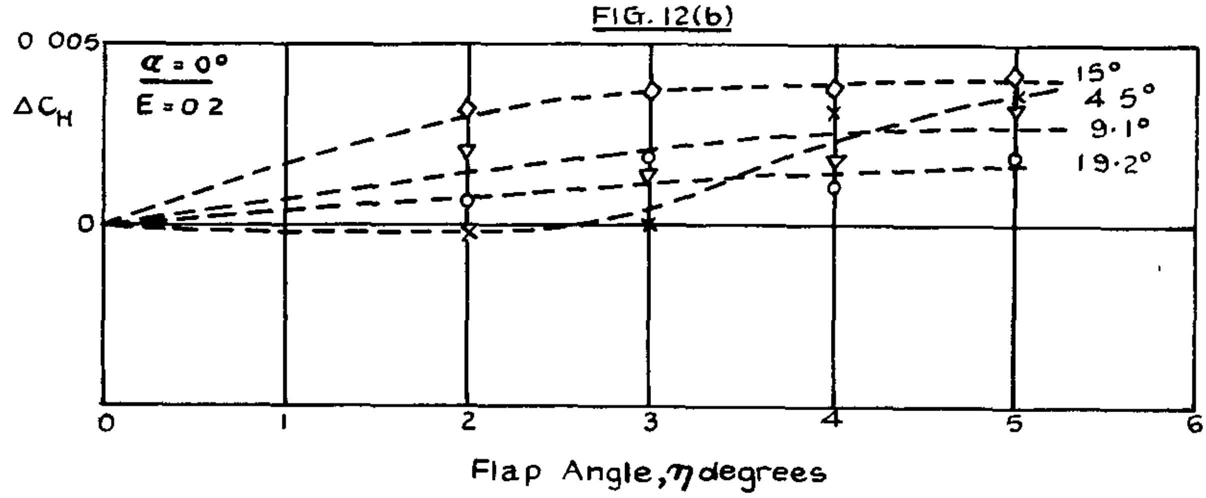


FIG. 12(b)



ΔC_H Due to Ice Compared with Transition at 0·1c

FIG 13

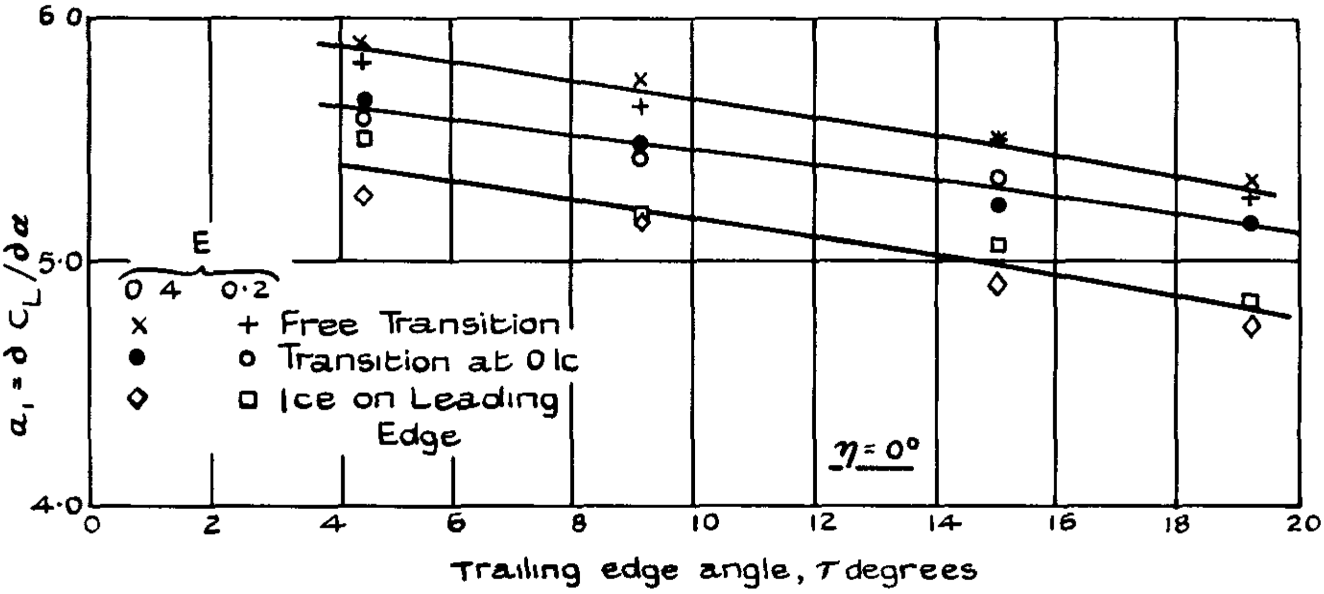

6 0
5.0
4.0
0
2
4
6
8
10
12
14
16
18
20
$a_1 = \partial C_L/\partial\alpha$
E
0 4 0.2
× + Free Transition
● o Transition at 0 lc
◇ □ Ice on Leading Edge
$\eta = 0°$
Trailing edge angle, τ degrees

FIG 14.

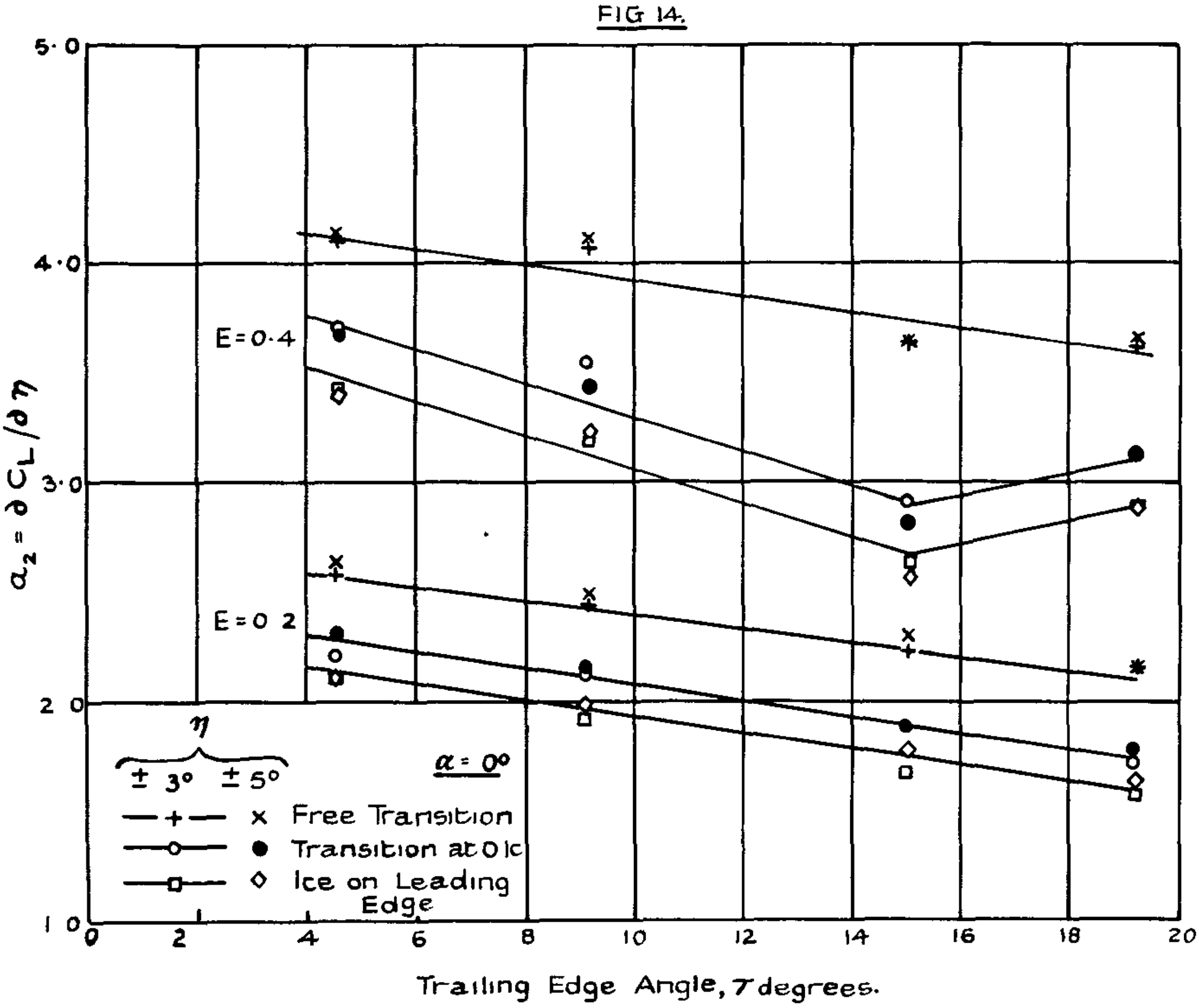
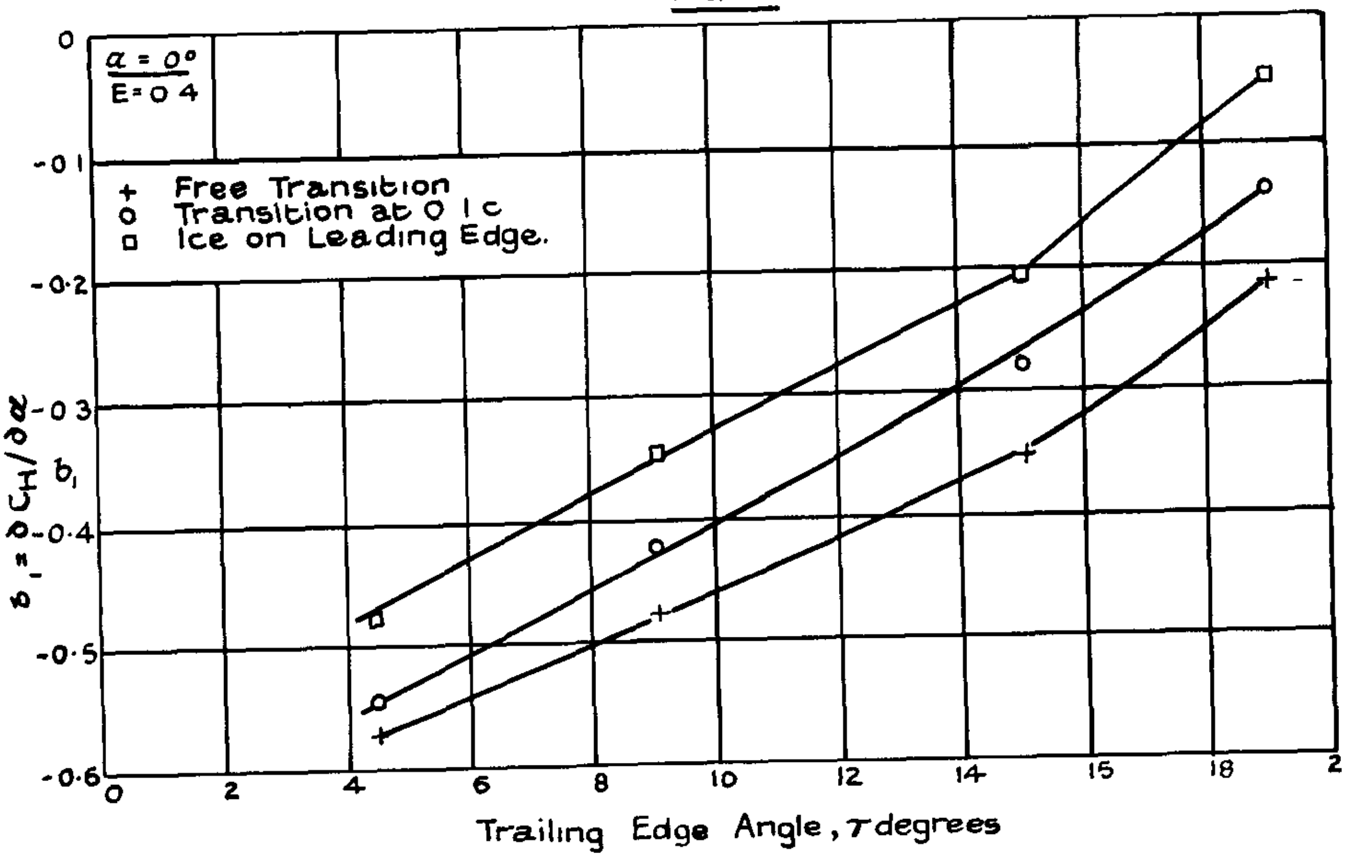
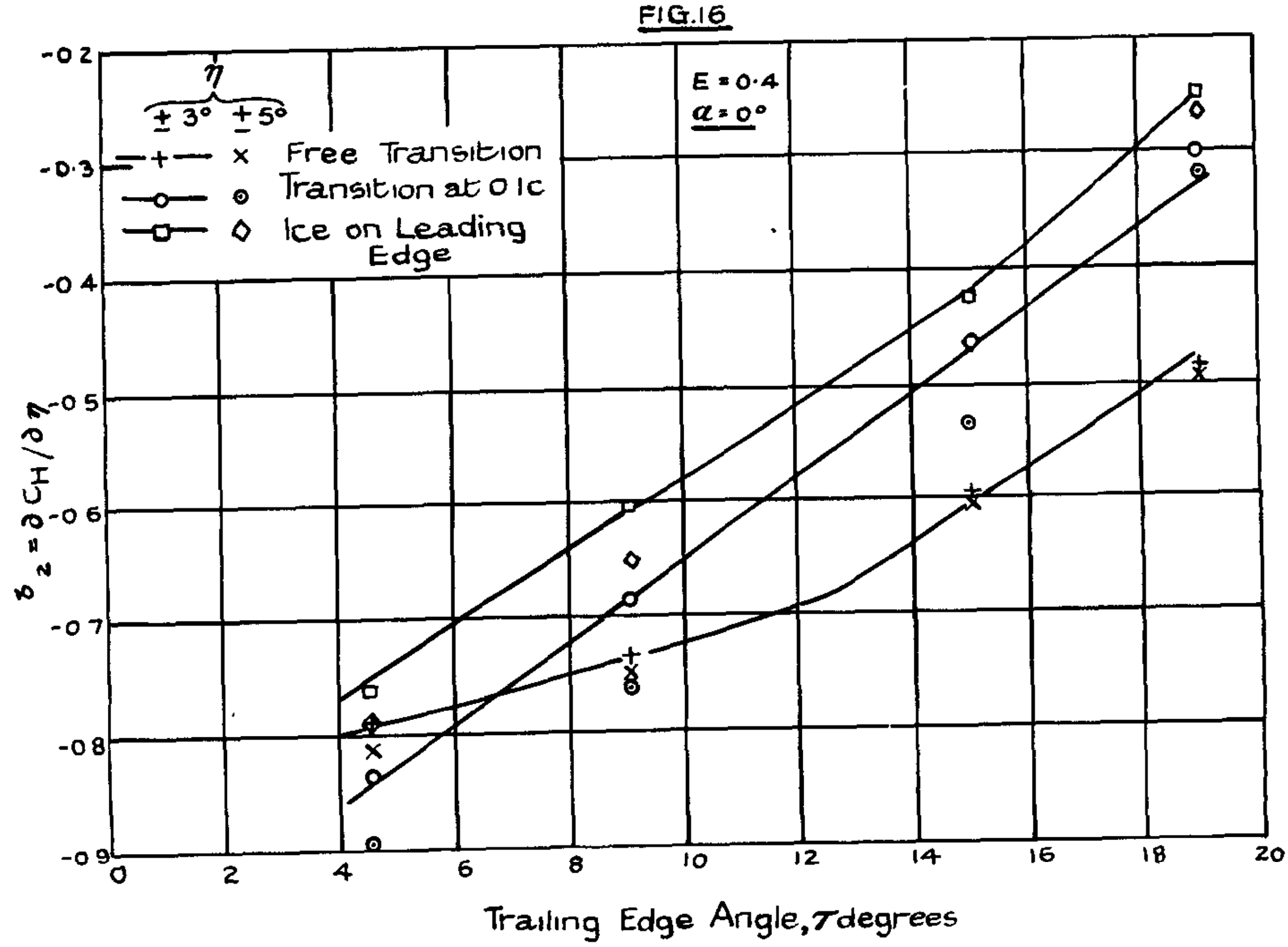

5.0
4.0
3.0
2 0
1 0
0
2
4
6
8
10
12
14
16
18
20
$a_2 = \partial C_L/\partial\eta$
E=0.4
E=0 2
η
± 3° ± 5°
$\alpha = 0°$
—+— × Free Transition
—o— ● Transition at 0 lc
—□— ◇ Ice on Leading Edge
Trailing Edge Angle, τ degrees.

FIG. 15



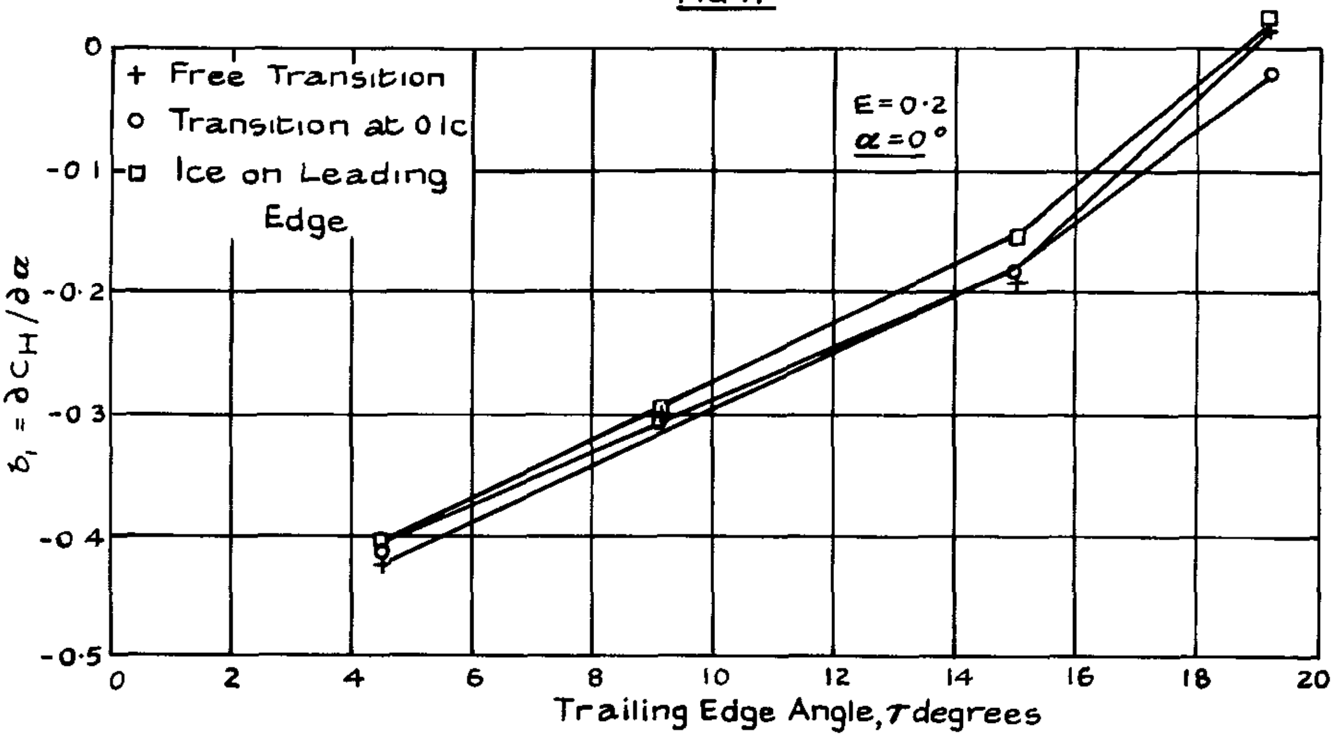
$\alpha = 0°$
E = 0.4
+ Free Transition
o Transition at 0.1c
□ Ice on Leading Edge.
$b_1 = \partial C_H / \partial \alpha$
b_1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
2
4
6
8
10
12
14
15
18
20
Trailing Edge Angle, τ degrees

FIG. 16



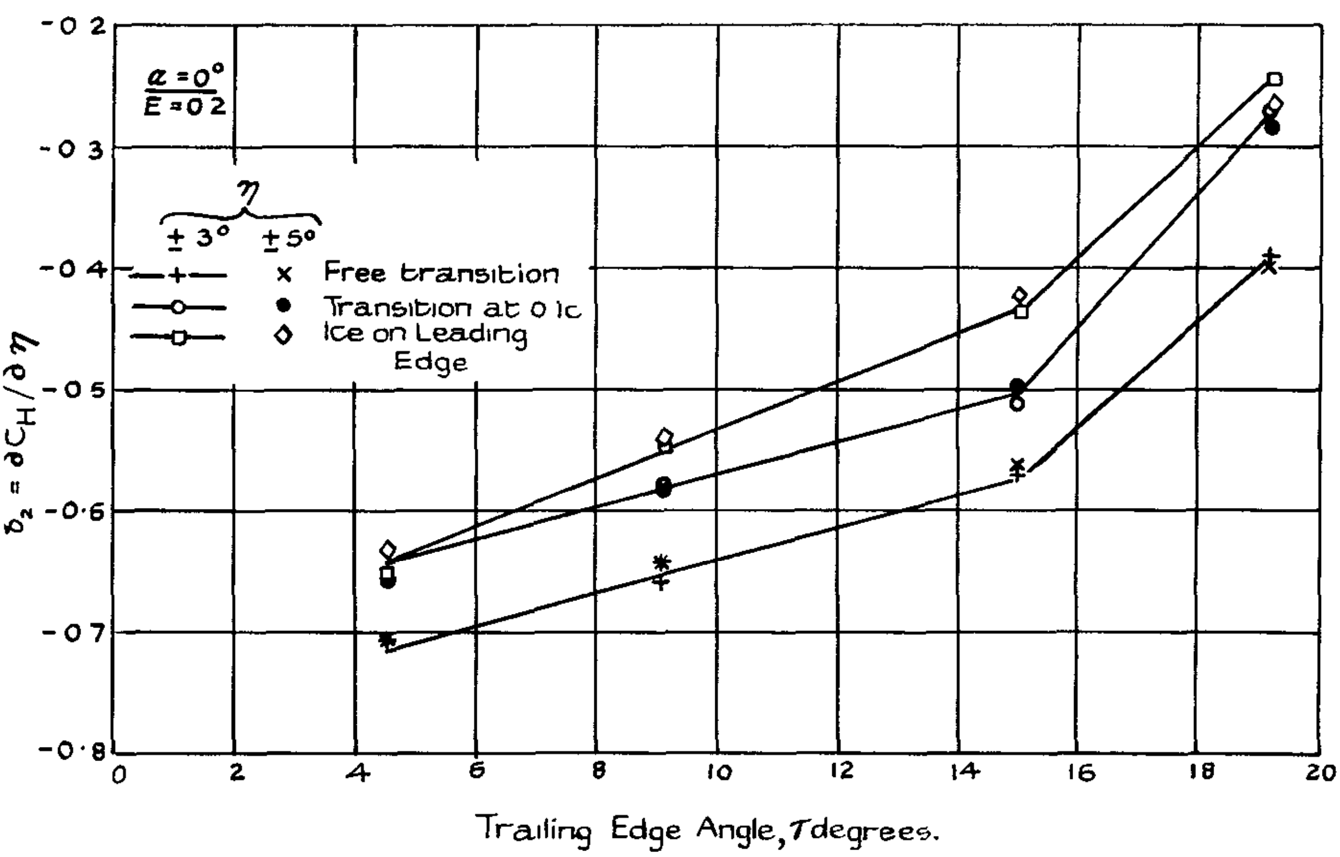
η
±3° ±5°
+ x Free Transition
o ⊙ Transition at 0.1c
□ ◇ Ice on Leading Edge
E = 0.4
$\alpha = 0°$
$b_2 = \partial C_H / \partial \eta$
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
0
2
4
6
8
10
12
14
16
18
20
Trailing Edge Angle, τ degrees

FIG 17



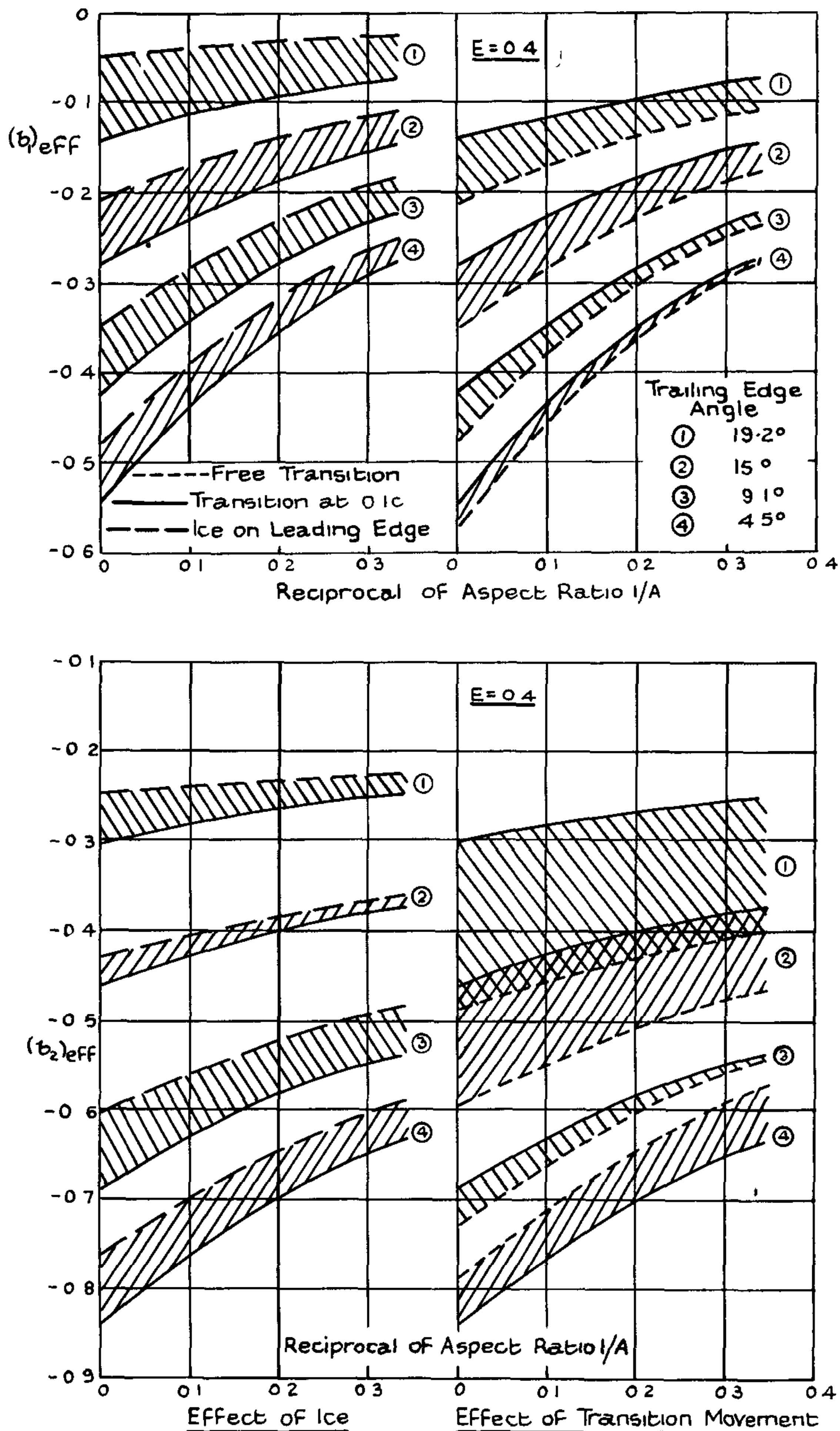
+ Free Transition
o Transition at 0·1c
□ Ice on Leading Edge
E = 0·2
α = 0°
0
-0·1
-0·2
-0·3
-0·4
-0·5
$b_1 = \partial C_H / \partial \alpha$
0
2
4
6
8
10
12
14
16
18
20
Trailing Edge Angle, τ degrees

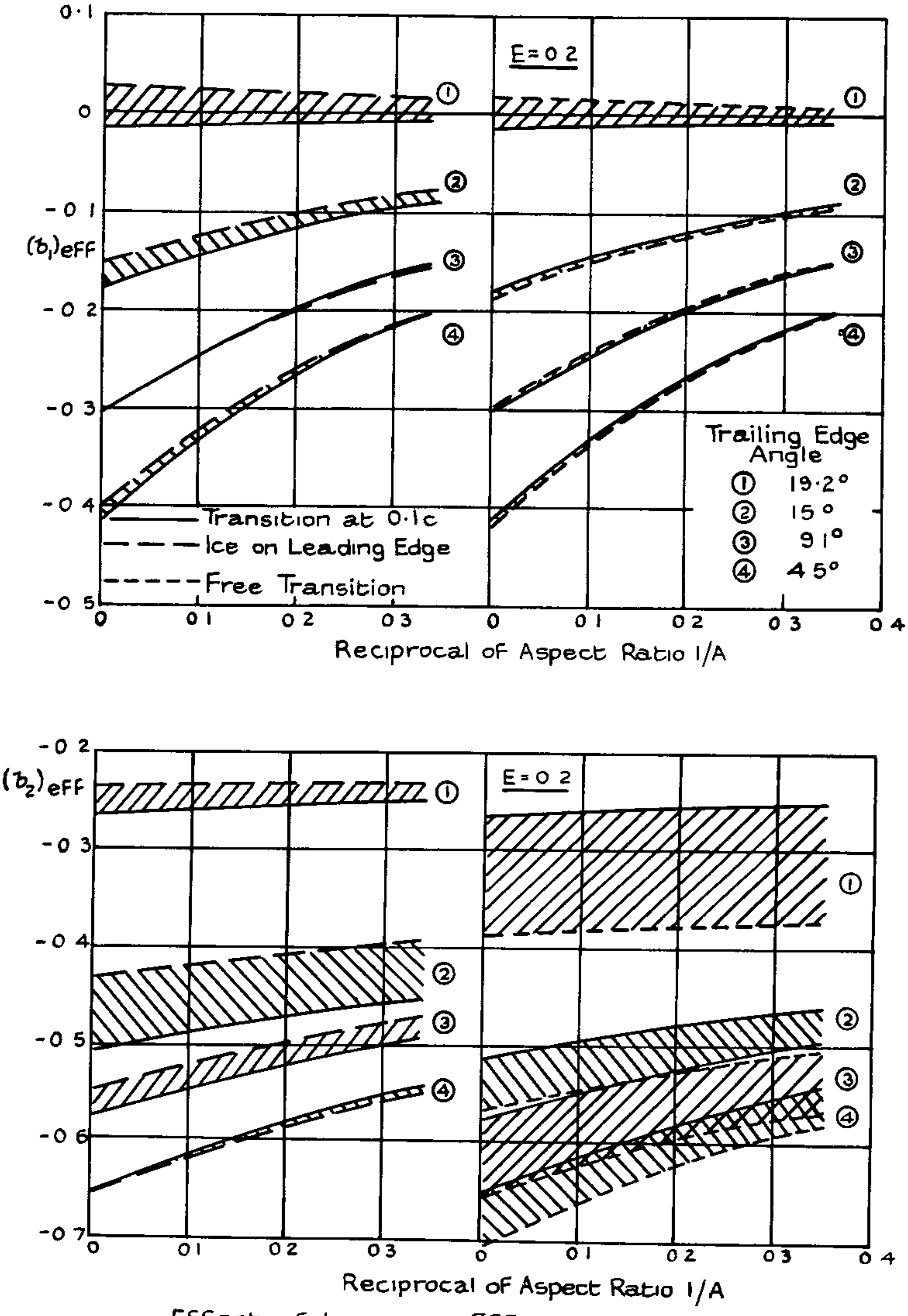
FIG. 18



α = 0°
E = 0·2
η
± 3°
± 5°
Free transition
Transition at 0·1c
Ice on Leading Edge
-0·2
-0·3
-0·4
-0·5
-0·6
-0·7
-0·8
$b_2 = \partial C_H / \partial \eta$
0
2
4
6
8
10
12
14
16
18
20
Trailing Edge Angle, τ degrees.

FIG 19

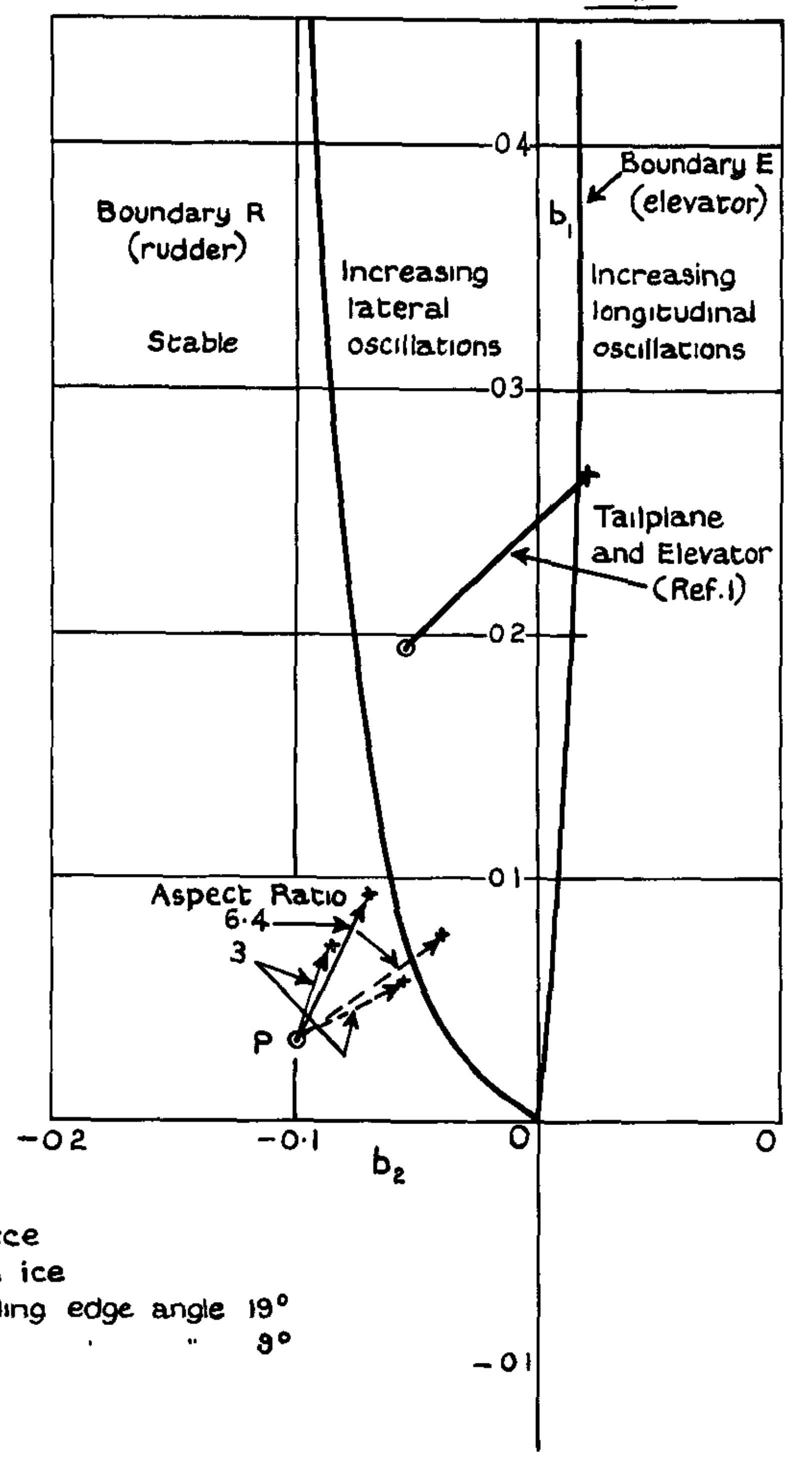

E = 0 4
$(t_1)_{eff}$
0
-0 1
-0 2
-0 3
-0 4
-0 5
-0 6
Free Transition
Transition at 0 1c
Ice on Leading Edge
Trailing Edge Angle
① 19·2°
② 15°
③ 9 1°
④ 4 5°
0
0 1
0 2
0 3
0 4
Reciprocal of Aspect Ratio 1/A
E = 0 4
$(t_2)_{eff}$
-0 1
-0 2
-0 3
-0 4
-0 5
-0 6
-0 7
-0 8
-0 9
Reciprocal of Aspect Ratio 1/A
Effect of Ice
Effect of Transition Movement



Effect of Ice

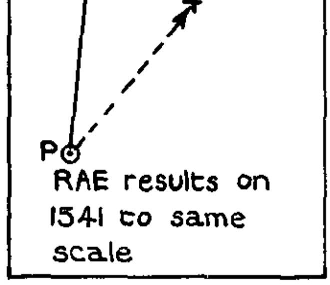
Effect of Transition Movement

FIG.21



⊙ No ice
× With ice
——— Trailing edge angle 19°
- - - - " " " 9°

FIG. 21a



Effect of ice on the characteristic (b_1, b_2) point

C P. No. 42
(13,112)
A.R.C. Technical Report

PRINTED AND PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
To be purchased from
York House, Kingsway, LONDON, W C 2   429 Oxford Street, LONDON, W 1
P O Box 569, LONDON, S E 1
13a Castle Street, EDINBURGH, 2   1 St Andrew's Crescent, CARDIFF
39 King Street, MANCHESTER, 2   Tower Lane, BRISTOL, 1
2 Edmund Street, BIRMINGHAM, 3   80 Chichester Street, BELFAST
or from any Bookseller

1951

Price 2s 6d net

PRINTED IN GREAT BRITAIN

S O. Code No 23-9006-42