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By

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MEASUREMENT OF LIFT AND PITCHING MOMENT ON FOUR OGEE WINGS AT SUPERSONIC SPEEDS

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SUMMARY

Measurements have been made of the lift and pitching moments of one plane and three cambered slender ogee wings ($p = 0{\cdot}45$, $S_T/c_o = 0{\cdot}208$) at four supersonic Mach numbers up to 2·0. The plane wing and one of the cambered wings are smaller scale versions of models tested previously, and provide a link between tests in the 3 ft × 3 ft and 8 ft × 8 ft wind tunnels at R.A.E. Bedford. The agreement between the two sets of results is very good. The other two models incorporate modifications to the original camber design, and the effects of these are discussed.

Replaces R.A.E. Tech. Note No. Aero. 2841-A.R.C. 24,570

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1 INTRODUCTION

This Note gives the results of tests made in the 3 ft × 3 ft wind tunnel at Bedford on four slender ogee wings. All wings had the same planform (Fig.1) and form a direct continuation of the test series reported by Taylor in Ref.1. In fact two models are simply smaller scale versions of Taylor's wings and are intended to form a link between tests on large models in the 8 ft × 8 ft tunnel and tests on smaller models of the same type in the 3 ft × 3 ft tunnel and in the A.R.A. $2\frac{1}{2}$ ft × $2\frac{1}{4}$ ft supersonic tunnel.

The two link models consisted of an uncambered wing (wing 15 of Ref.1) and a cambered wing designed[2] by slender wing theory for a design C_L of zero and a ΔC_m (i.e. C_{m_0} for this wing) of 0·00853 (wing 16 of Ref.1). For this wing it had been found that ΔC_m dropped off rapidly with Mach number so that at M = 2·0, for example, ΔC_m was only 0·004. Because of this, the second cambered wing of the present series was a redesign of wing 16 having the same values of design parameters ($(C_L)_d$ and $(\Delta C_m)_d$) but with the shape obtained by use of full linear theory for a Mach number of 2·0. The third cambered wing also had the same values of design parameters as wing 16 but incorporated some anhedral and dihedral over the rear of the wing[3]; because this type of modification had been found necessary to improve the lateral characteristics at low speeds. Details of the wings are given in Section 2.1.

In this Note results are given of lift and pitching moment for the four models at four supersonic Mach numbers, 1·42, 1·61, 1·82 and 2·0. Although drag was measured in the tests the results are not presented since the method of fixing transition on these shapes at the low test Reynolds number introduced large drag penalties and at the present time the precise values of these penalties are unknown. It is expected that the general problem of fixing transition on these shapes will be discussed in a later Note.

2 EXPERIMENTAL DETAILS

2.1 Details of models

Four shapes were tested, one plane, the others cambered. All four had the same planform and thickness distribution. The shapes are shown in Figs.1 and 2. Fuller details of the planform and thickness distributions, together with reasons for their choice are given by Taylor in Ref.1.

All four models were of the same size with an overall length of 24 inches and a total span of 9·98 inches. One of the cambered models (the slender wing design) was made of steel; all the others were made of glass-cloth and araldite formed onto a metal core. The models were sting mounted in the tunnel and all had a cylindrical sting shroud of 1·04 inches diameter (Fig.2). The shroud was symmetrically disposed at the trailing edge and was arranged to disappear at the same station on the upper and lower surfaces. However, because of the camber the cross-sectional area distributions of the shroud on the two surfaces were not equal. The measured forces have been corrected for this asymmetry (see Section 2.3).

All three cambered wings were designed for $C_L = 0$ and $C_{m_0} = 0{\cdot}00853$. This value was chosen so that at $C_L = 0{\cdot}075$ the cambered wing would have its centre of lift 7% c_0 forward of that of the plane wing. The variation of design load is shown in Fig.3. Details of the centre-line camber and the cross-sectional shapes of the wings designed by slender wing theory and linear theory are shown in Figs.3 to 6. As can be seen the main effect of using linear theory is to change the longitudinal camber with only small changes across the span, thus the cross-sectional shapes of the two wings are almost identical. The third cambered wing had a cranked trailing edge as shown in Fig.5. This deflection decreased forward of the trailing edge so that ahead of about $0{\cdot}6\ c_o$ the wing shape was the same as that of the original slender-theory design.

For convenience the three cambered wings are referred to as the slender-theory wing, the linear-theory wing and the gull wing, respectively.

2.2 Details of tests

The tests were made in the supersonic test section of the 3 ft × 3 ft wind tunnel at R.A.E. Bedford at Mach numbers of 1·42, 1·61, 1·82 and 2·0. Measurements were made of normal force, pitching moment and axial force for an incidence range from -4° to 12° in one-degree steps with the model the right way up and from -4° to $+4^\circ$ in one-degree steps with the model inverted. Except at M = 2·0 the tests were made at a constant Reynolds number of $1{\cdot}6 \times 10^6$ per foot, at M = 2·0 the Reynolds number was $1{\cdot}35 \times 10^6$ per foot.

In all the force tests bands of distributed roughness were applied to fix transition on both surfaces (when the flow was not separated). They consisted of glass balls (ballotini) fixed to the wing with araldite. For M = 2·0 the balls had a maximum diameter of 0·0138 inches; for lower Mach numbers a maximum diameter of 0·0116 inches. The bands were 0·15 inches wide (normal to the edge) and started approximately 0·1 inches in from the edge. It was found that this distribution gave a penalty on axial force[4] but did not influence lift or pitching moment.

2.3 Accuracy

The balance results have been corrected for interaction effects and sting deflection before being reduced to coefficient form. The coefficients are based on the plan areas of the wings; the reference length for C_m is $\bar{\bar{c}}$ (the aerodynamic mean chord) and the moment reference point is at $0{\cdot}5\bar{\bar{c}}$ ($0{\cdot}692\ c_o$) i.e. at the centre of area. Incidence and pitching moment have been corrected for flow deflection and curvature of the tunnel stream; these corrections were derived from the mean of the results for the models the right way up and inverted. The corrections so obtained were applied throughout the full test range.

As mentioned in Section 2.1 the sting shroud protruded from the upper and lower surfaces by different amounts, in effect distorting the camber surface. The estimated corrections for this (see Appendix of Ref.1) are:-

Slender-theory wing,	ΔC_m	$= 0{\cdot}0003/\beta$
Linear-theory wing,	ΔC_m	$= 0$
Gull wing,	ΔC_m	$= 0{\cdot}0008/\beta$

For all wings there is no correction for lift. The pitching moment correction has been applied to all the plotted results.

The initial test results showed that for the plane wing C_m was not zero at zero C_L, and inspection showed that the model was distorted; in particular the tips were turned up slightly. Calculations based on the measured camber surface gave values of C_{m_0} in general agreement with the measured values. The measured values were then used to correct the pitching moment curves so as to pass through the origin. No other corrections have been applied for distortion of the models under load, but possible effects of this distortion are discussed in Section 3.1.

It is estimated that the accuracies of the measured results are:-

C_L ±0·003

C_m ±0·0003

α ±0·05°

3 DISCUSSION OF RESULTS

Results for all four models are presented in Figs.7 and 8. Those for the two link models are compared with the corresponding results from the 8 ft × 8 ft tunnel in Figs.9 and 10. It should be noted that for the cambered wings, incidence is measured from the design condition (Fig.4).

3.1 Comparison with 8 ft × 8 ft results

The lift results (Fig.9) from the two tunnels are in excellent agreement for both pairs of models. In comparing the pitching moment results it should be noted that while three of the four models were made of steel, the 3 ft × 3 ft plane model was made of glass-cloth and araldite. The plane wing results show that the aerodynamic centre measured in the 3 ft × 3 ft tunnel is approximately 1% further forward than that measured in the 8 ft × 8 ft tunnel. This movement is consistent with aeroelastic distortion of the araldite model, i.e. the tips bending up and off-loading the trailing edge. Furthermore the shift of 1% is close to the value deduced by Taylor on some araldite cambered models of the same planform at approximately the same dynamic pressure. Thus it may be assumed that the differences shown for the plane wings are caused by distortion of the 3 ft × 3 ft model. On the cambered, steel, models the measured aerodynamic centres from the two tunnels are in close agreement (better than ¼%). At M = 1·8 the values of C_{m_0} are the same. However, at M = 1·4 the 3 ft × 3 ft value of C_{m_0} is 0·0007 lower than the 8 ft × 8 ft value.

3.2 Results for linear-theory wings

Fig.7 shows that near zero incidence the linear-theory, slender-theory and plane wings have approximately the same lift curve slope but at higher incidence the increase in slope is slightly greater on the two cambered wings, particularly at the lower Mach numbers. It is interesting to note that on both cambered wings the zero-lift angle becomes more negative with increase in Mach number (Fig.11). This angle should be zero for the linear-theory wing at M = 2·0 and for the slender-wing theory at M = 1·0. As can be seen the zero lift angle of the linear-theory wing is close to zero at M = 2·0 and that of the slender-theory wing appears to approach zero at M = 1·0.

In discussing the pitching moment results (Fig.8) it should again be noted that both the plane wing and the linear-theory wing are subject to aeroelastic distortion. For convenience the 8 ft × 8 ft plane wing results are dotted on Figs.8(a) and 8(c). The results of Fig.8 show that at low C_L the aerodynamic centres of the three wings are in approximately the same position, but that at higher C_L the linear-theory wing has a much more marked forward movement than the slender-theory wing. This difference in forward shift between the two wings appears to be slightly greater than could be accounted for by distortion, i.e. by applying the plane wing correction to the linear-theory wing. However the main forward shift occurs at values of C_L greater than 0·2 and is thus of minor importance (the cruise C_L being about 0·1).

Turning now to the pitching moment at zero lift (Fig.11) we find that on both the cambered wings C_{m_o} decreases with Mach number, the curves for both wings being approximately parallel. Furthermore extrapolation of the slender wing results back to M = 1·0 suggest that at this Mach number the value of C_{m_o} will be close to the design value of 0·0085. On the other hand at its design speed of M = 2·0 the linear-theory wing only achieves 77% of the design C_{m_o}. A possible reason for the deficiency may be sought by considering this wing at its design incidence (α = 0); at this incidence the measured C_L is 0·004 instead of zero, and the measured C_m is 0·0064 instead of 0·0085. Reference to the design load distribution (Fig.3) suggests that the discrepancy arises from the failure to achieve the large negative load near the trailing edge.

No attempt is made in this Note to relate the measured lift curve slopes and aerodynamic centres with theory since this has already been done by Taylor, (Figs.32 and 33 of Ref.1).

3.3 Results for gull wing

In discussing the results for the gull wing model it should be recalled that this wing is simply a redesign of the slender-theory wing incorporating some anhedral and dihedral at the rear of the wing; ahead of 0·6 c_o the two wings are almost identical.

Comparison of the variations of C_L with α for the two wings (Fig.7) shows that the use of anhedral and dihedral at the rear does not greatly effect either the lift development with incidence, or the variation of zero lift angle with Mach number. However, it does have an effect on pitching moment, particularly at the lower Mach numbers (Fig.8), the main effect being an increase in C_{m_o} above that of the slender-theory wing. The increase is approximately 0·0024 at M = 1·42 falling to zero at M = 2·0. There appears to be virtually no change in aerodynamic centre, although since the gull wing model was made of araldite its true (i.e. rigid-model) aerodynamic centre may be further aft that is deduced from the results of Fig.8. However, the additional curvature introduced by the gull shape increases the stiffness relative to that of the plane wing so that the correction for aeroelastic distortion is likely to be less than that shown for the plane wing. Thus the aerodynamic centres of the slender-theory and gull wings are unlikely to differ by more than about ½% $\bar{\bar{c}}$ at the same C_L.

4 CONCLUSIONS

Measurements of lift and pitching moment on four slender ogee wings have given the following results:

(1) Results obtained in the 8 ft × 8 ft and 3 ft × 3 ft tunnels on models of different scale are in close agreement provided the effects of aeroelastic distortion are allowed for.

(2) For the model designed by linear theory the zero-lift pitching moment is only 77% of the design value at the design Mach number. The deficiency may result from the rather rapid variations in design load distribution near the trailing edge. Although this wing fails to achieve its design C_{m_o} the measured C_{m_o} is approximately 60% greater than that measured on the corresponding slender-theory design.

(3) Use of dihedral and anhedral towards the rear of the wing to modify the low speed behaviour does not alter the lift development at supersonic speeds, but does give a greater zero-lift pitching moment than on the corresponding cambered wing with a straight trailing edge.

LIST OF SYMBOLS

c_o	root chord
$\bar{\bar{c}}$	aerodynamic mean chord
C_L	lift coefficient
C_m	pitching moment coefficient (based on $\bar{\bar{c}}$)
$L(x)$	spanwise integral of loading/$\frac{1}{2}\rho U^2$
M	Mach number of free stream
p	planform parameter = wing area/2 $S_T c_o$
$s(x)$	local semi-span
S_T	semi-span
S	plan area
$S(x)$	cross-sectional area distribution
V	wing volume
α	incidence (in degrees). Measured from design attitude for cambered wings
β	$(M^2-1)^{\frac{1}{2}}$
τ	volume parameter = $V/S^{3/2}$

LIST OF REFERENCES

No.	Author(s)	Title, etc.
1	Taylor, C.R.	Measurements, at Mach numbers up to 2.8, of the longitudinal characteristics of one plane and three cambered slender 'ogee' wings. A.R.C. R. & M. 3328. December, 1961.
2	Weber, J.	Design of warped slender wings with the attachment line along the leading edge. A.R.C. 20,051. September, 1957.
3	Weber, J.	Design of warped slender wings with dihedral and anhedral at the rear. A.R.C. 22,736. October, 1960.
4	Mabey, D.G.	Drag penalties due to distributed roughness on slender wings at supersonic speeds. Unpublished M.O.A. Report.

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$$\frac{s(x)}{s_T} = \frac{x}{c_o}\left\{1 \cdot 2 - 2 \cdot 4\frac{x}{c_o} + 2 \cdot 2\frac{x^2}{c_o^2} + 3\frac{x^3}{c_o^3} - 3\frac{x^4}{c_o^4}\right\}$$

$$\frac{s_T}{c_o} = 0 \cdot 208.$$

$$P = \frac{\text{AREA}}{2 s_T c_o} = 0 \cdot 45.$$

$$\bar{\bar{c}} = 0 \cdot 616\, c_o.$$

MOMENT CENTRE AT

$0 \cdot 5\bar{\bar{c}}$ OR $0 \cdot 692\, c_o$.

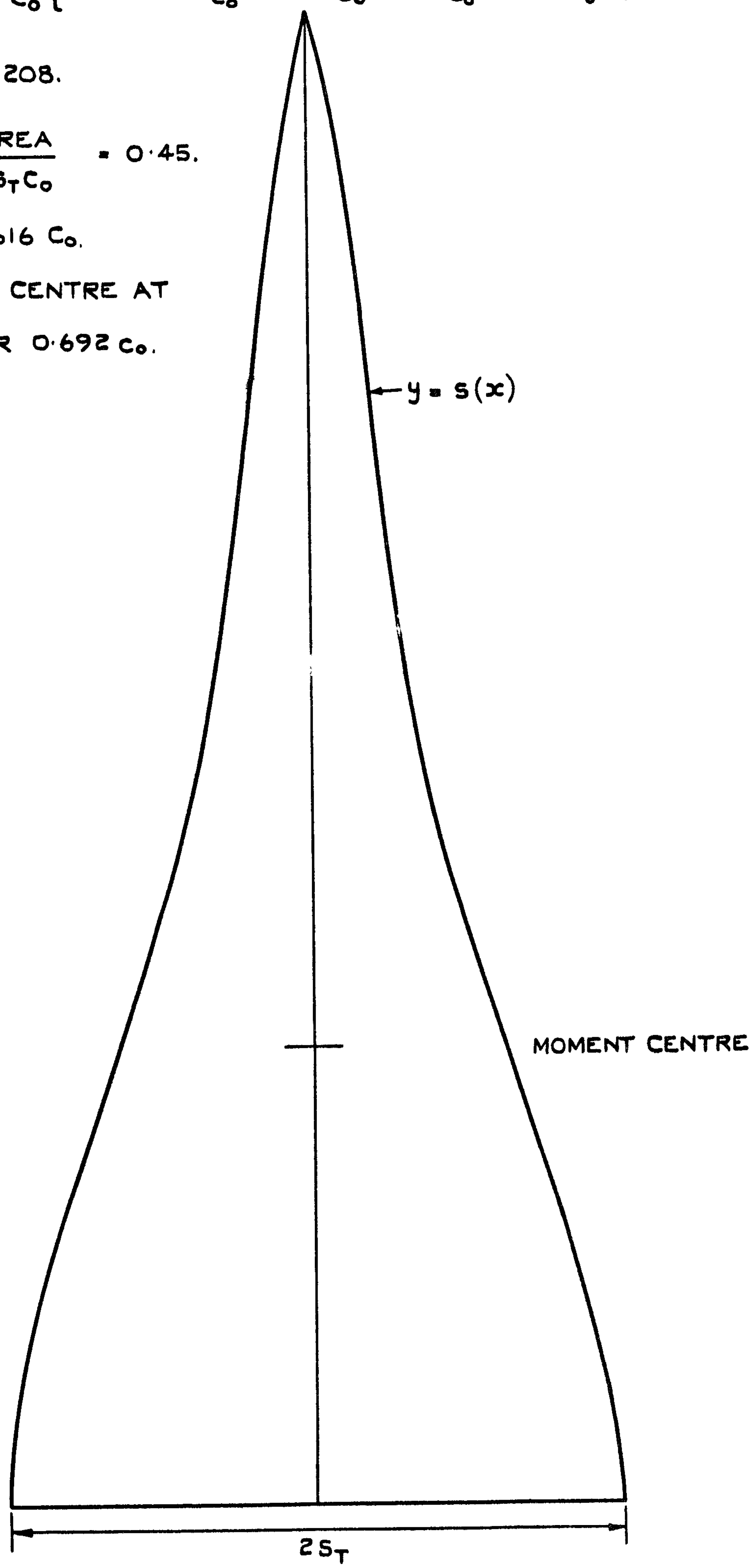


FIG. 1. DETAILS OF PLANFORM.

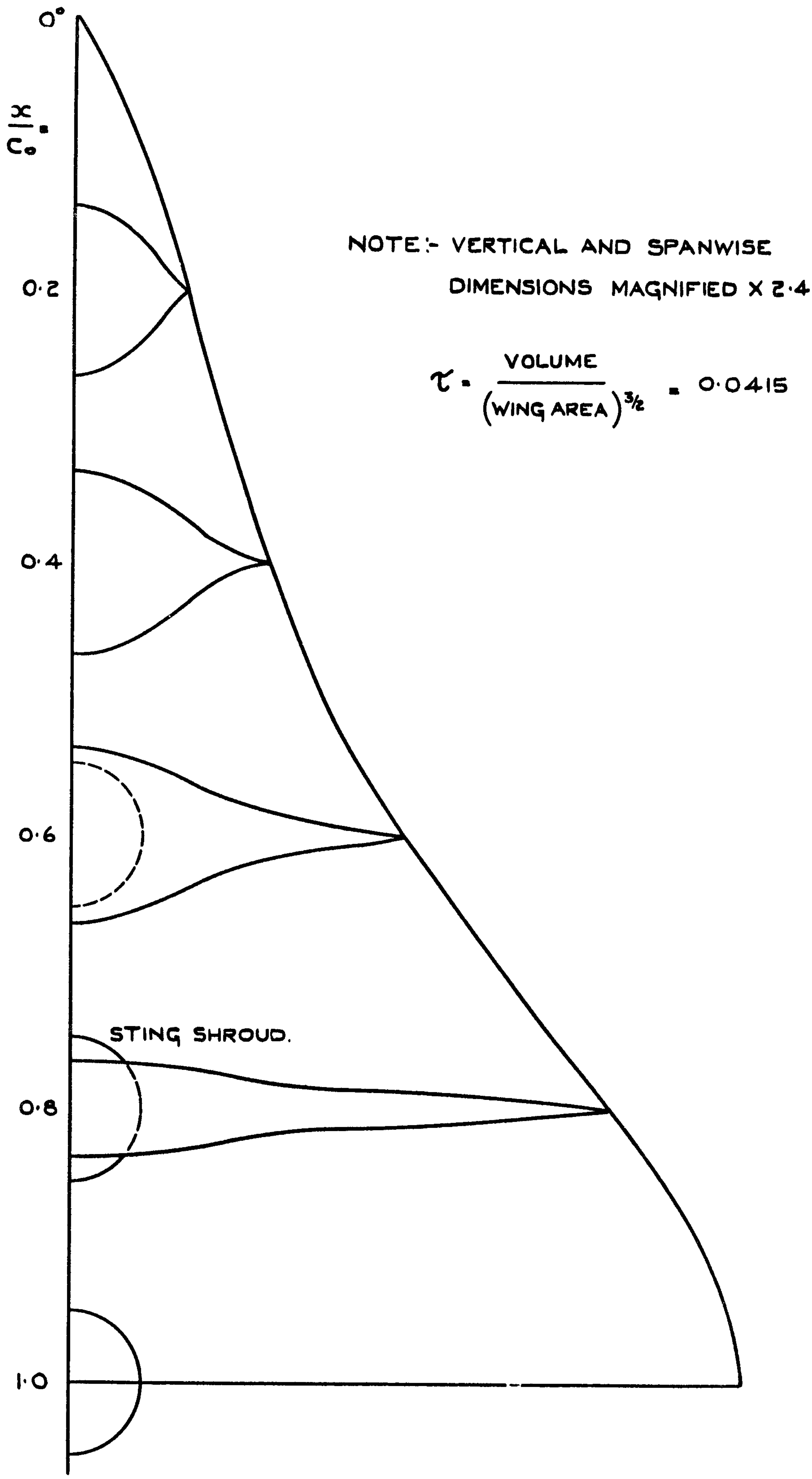


FIG. 2. DETAILS OF THICKNESS DISTRIBUTION
(ALL MODELS.)

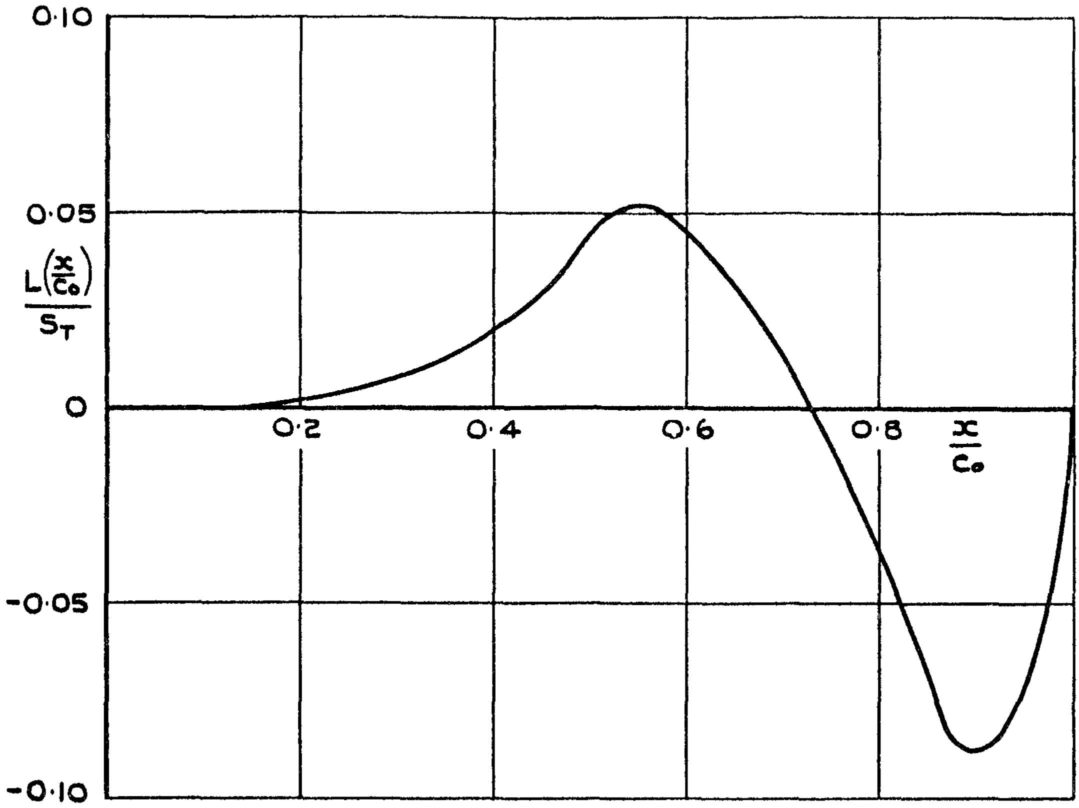


FIG. 3. CHORD WISE VARIATION OF SPAN LOADING FOR CAMBERED MODELS AT DESIGN CONDITION.

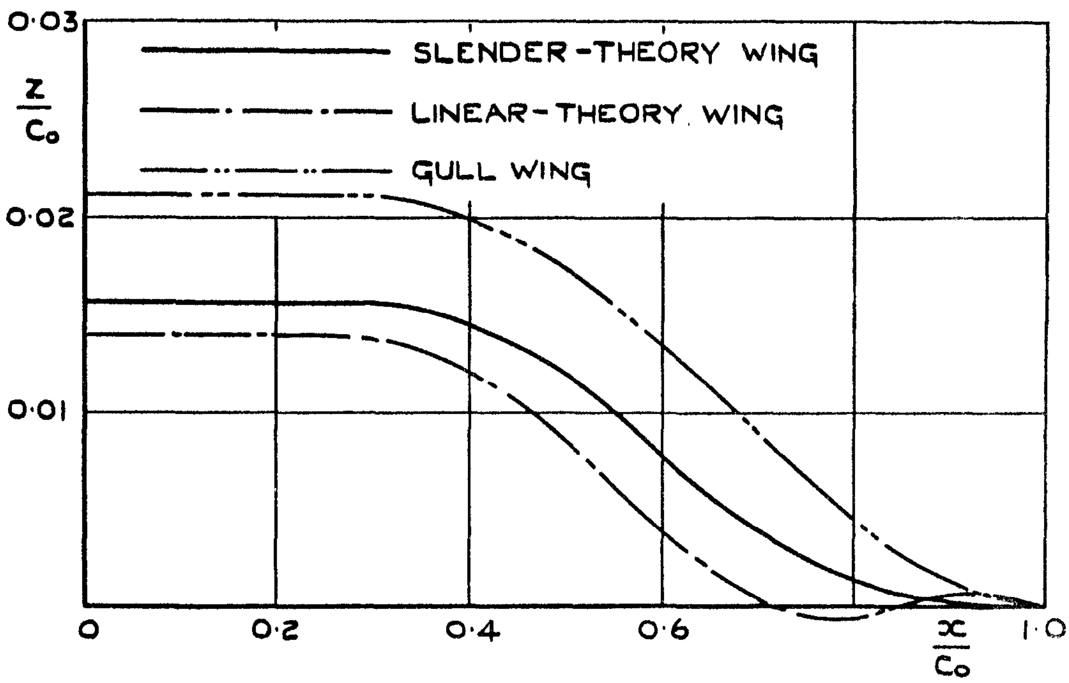


FIG. 4. CENTRE-LINE CAMBER AT DESIGN ATTITUDE.

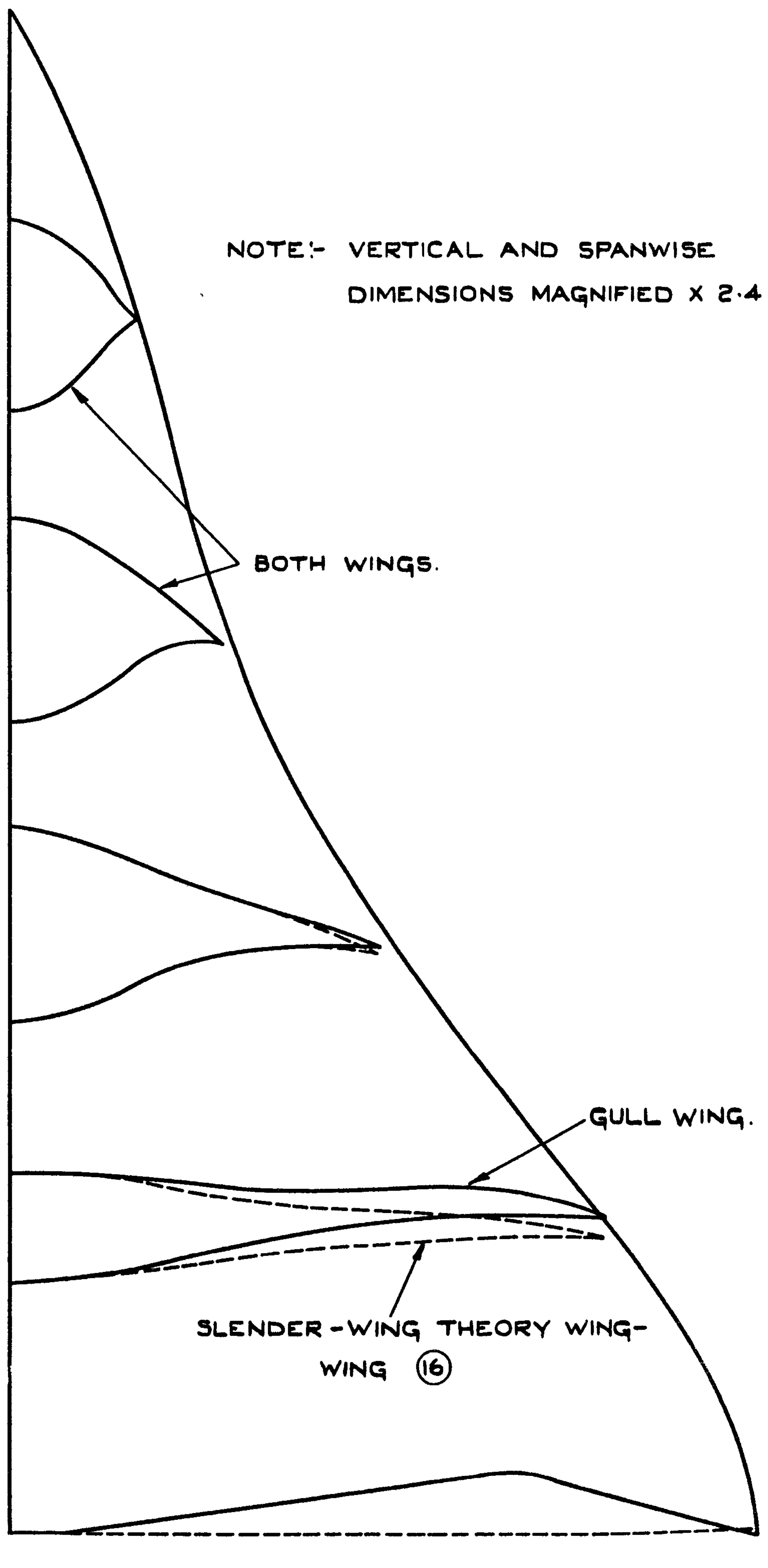
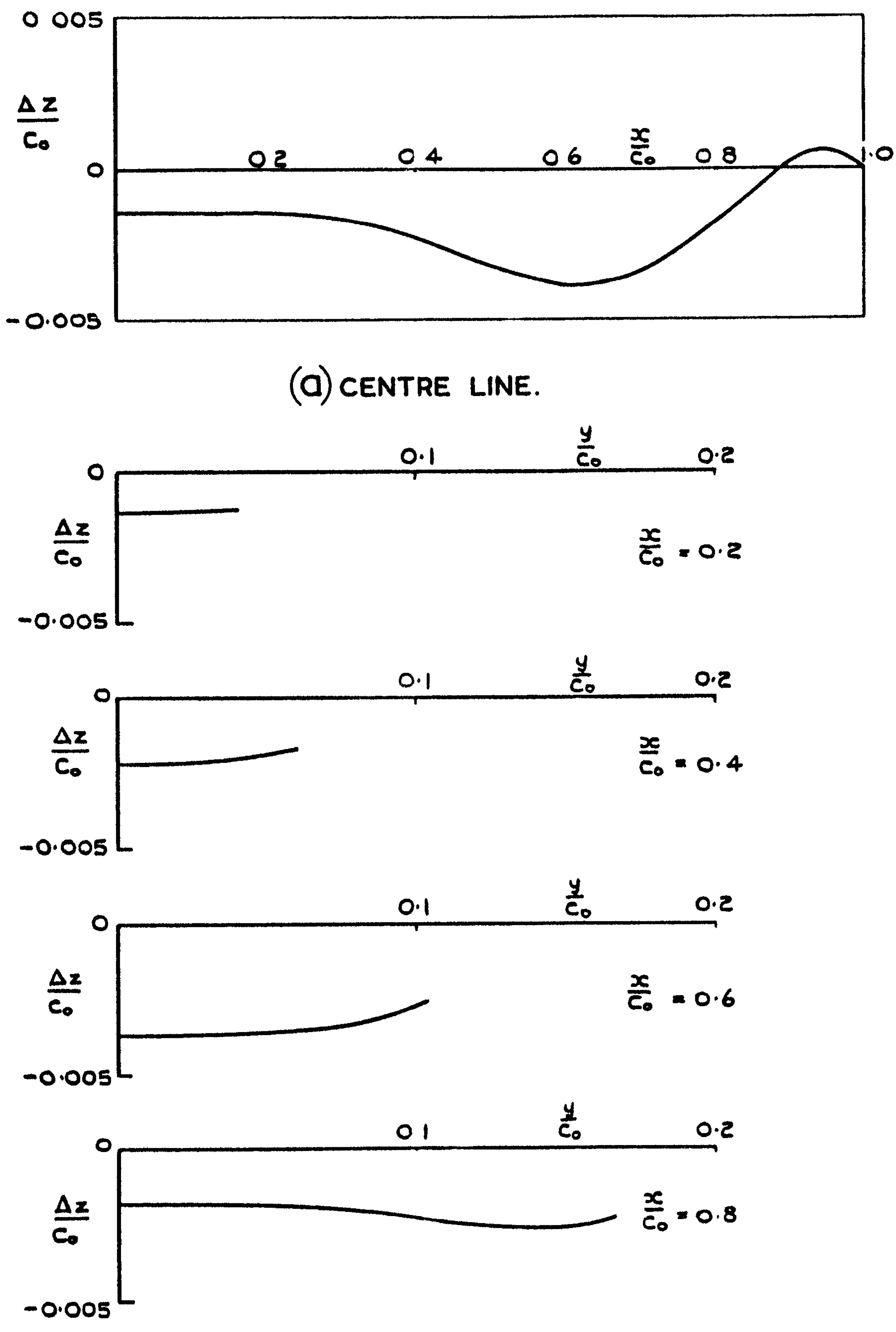


FIG. 5. SECTIONS OF SLENDER-WING THEORY AND GULL WINGS.



(b) SPAN-WISE VARIATION

$$\left(\frac{z}{c_0}\right)_{\text{LINEAR THEORY}} = \left(\frac{z}{c_0}\right)_{\text{SLENDER THEORY}} + \left(\frac{\Delta z}{c_0}\right)$$

FIG. 6. CHANGE IN SURFACE SHAPE BETWEEN LINEAR AND SLENDER THEORY WINGS.

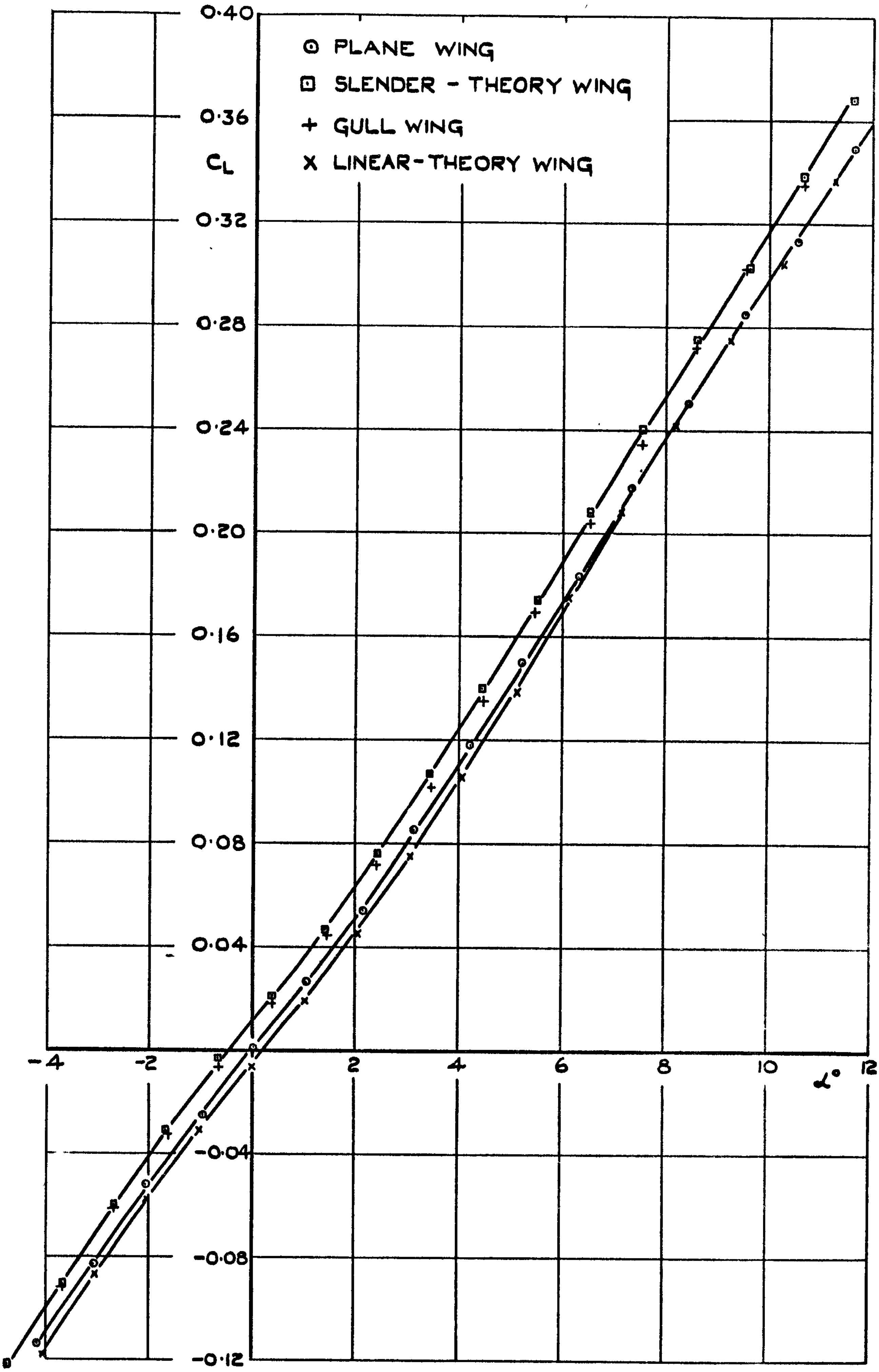


FIG. 7 (a) VARIATION OF C_L WITH α: M = 1·42.

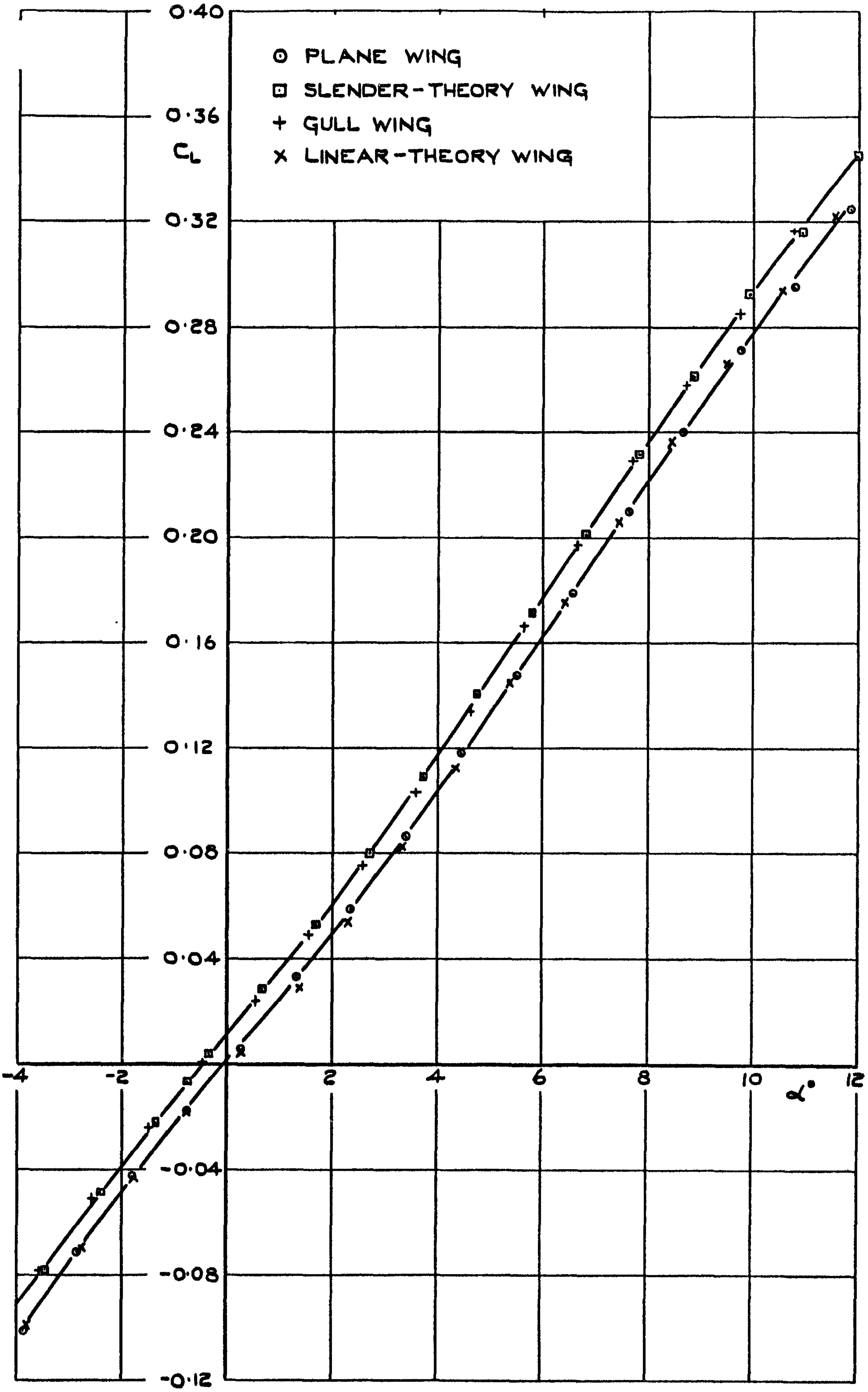


FIG. 7(b) VARIATION OF C_L WITH α: M=1·61.

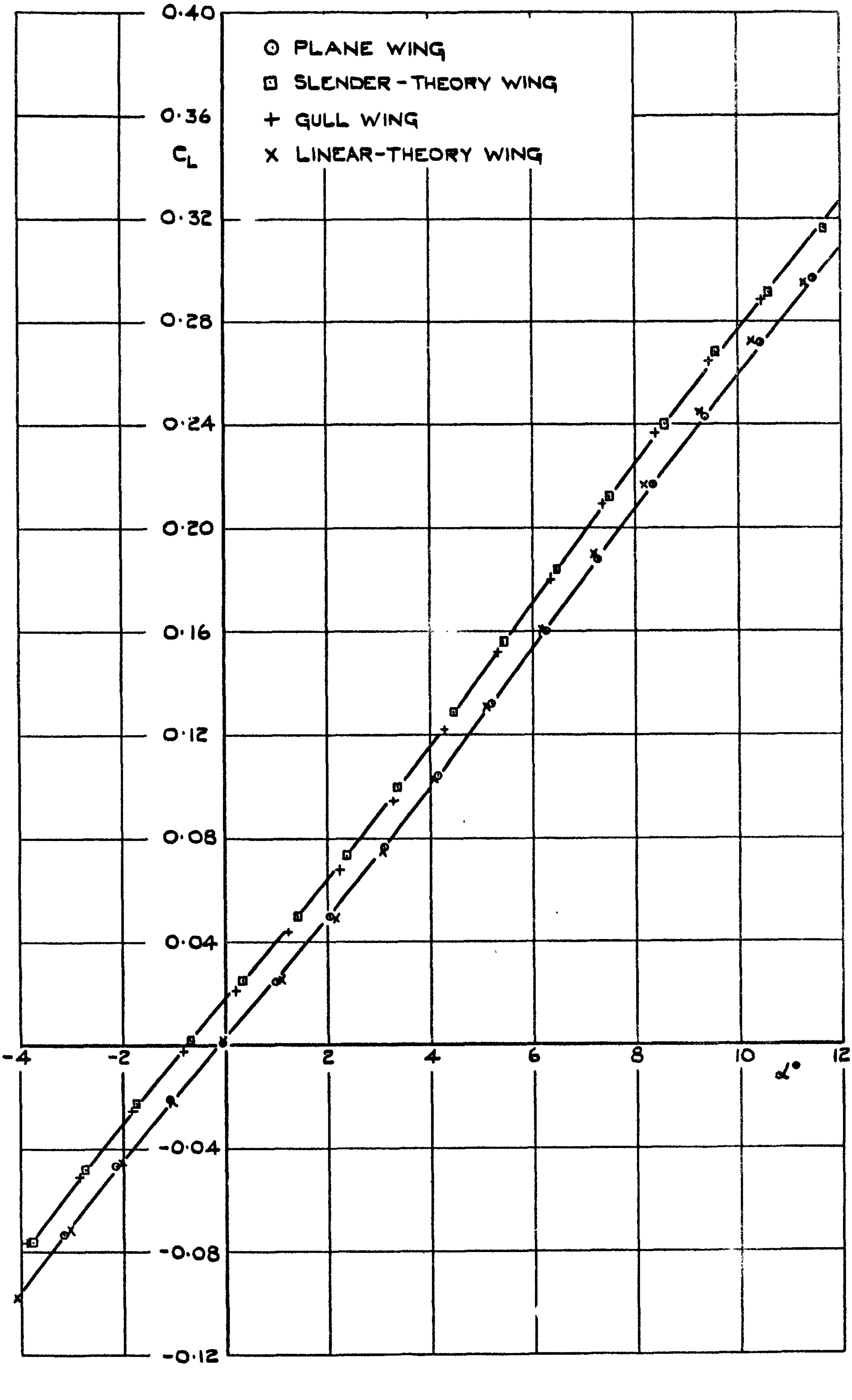


FIG. 7(c) VARIATION OF C_L WITH α: M=1·82.

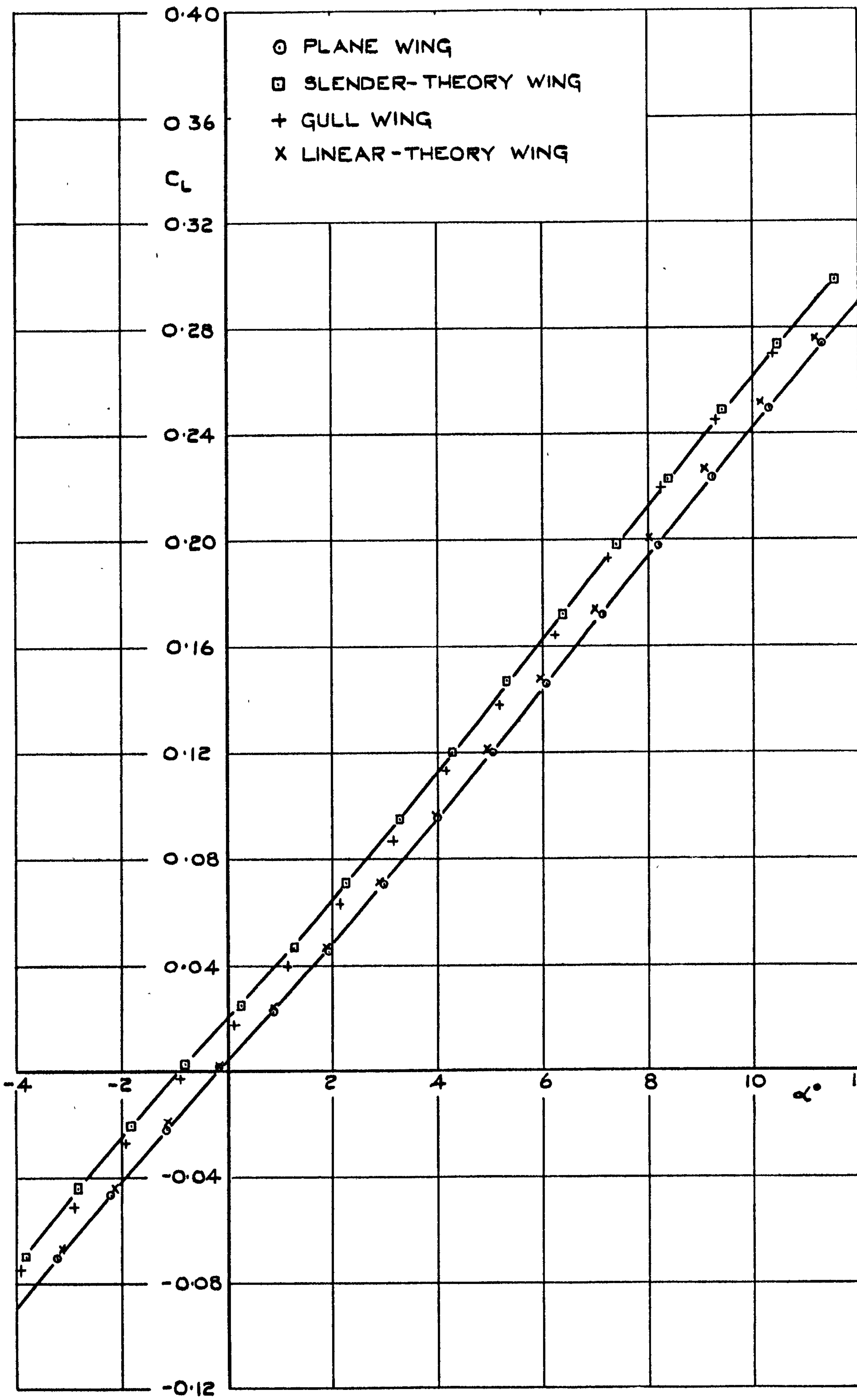
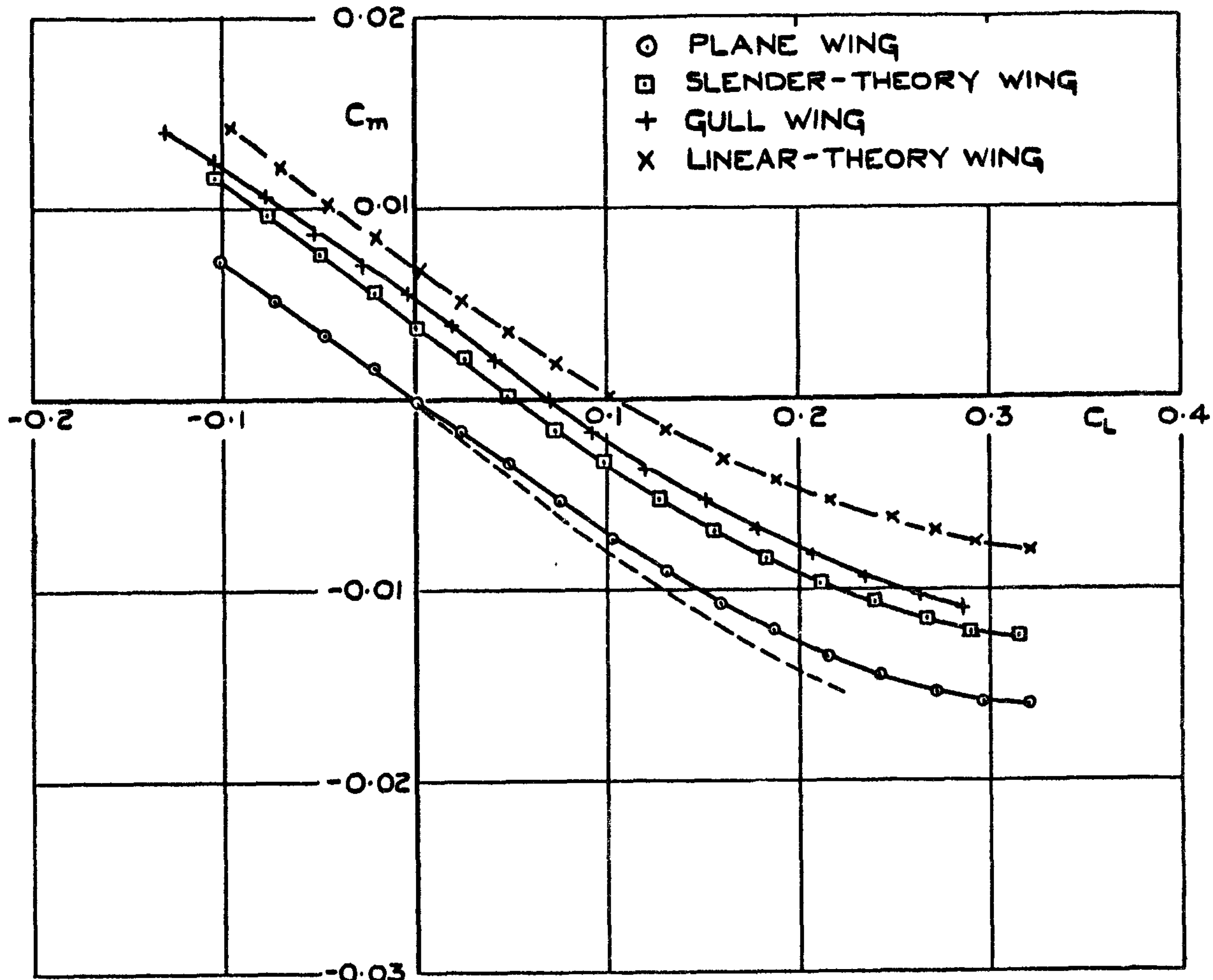
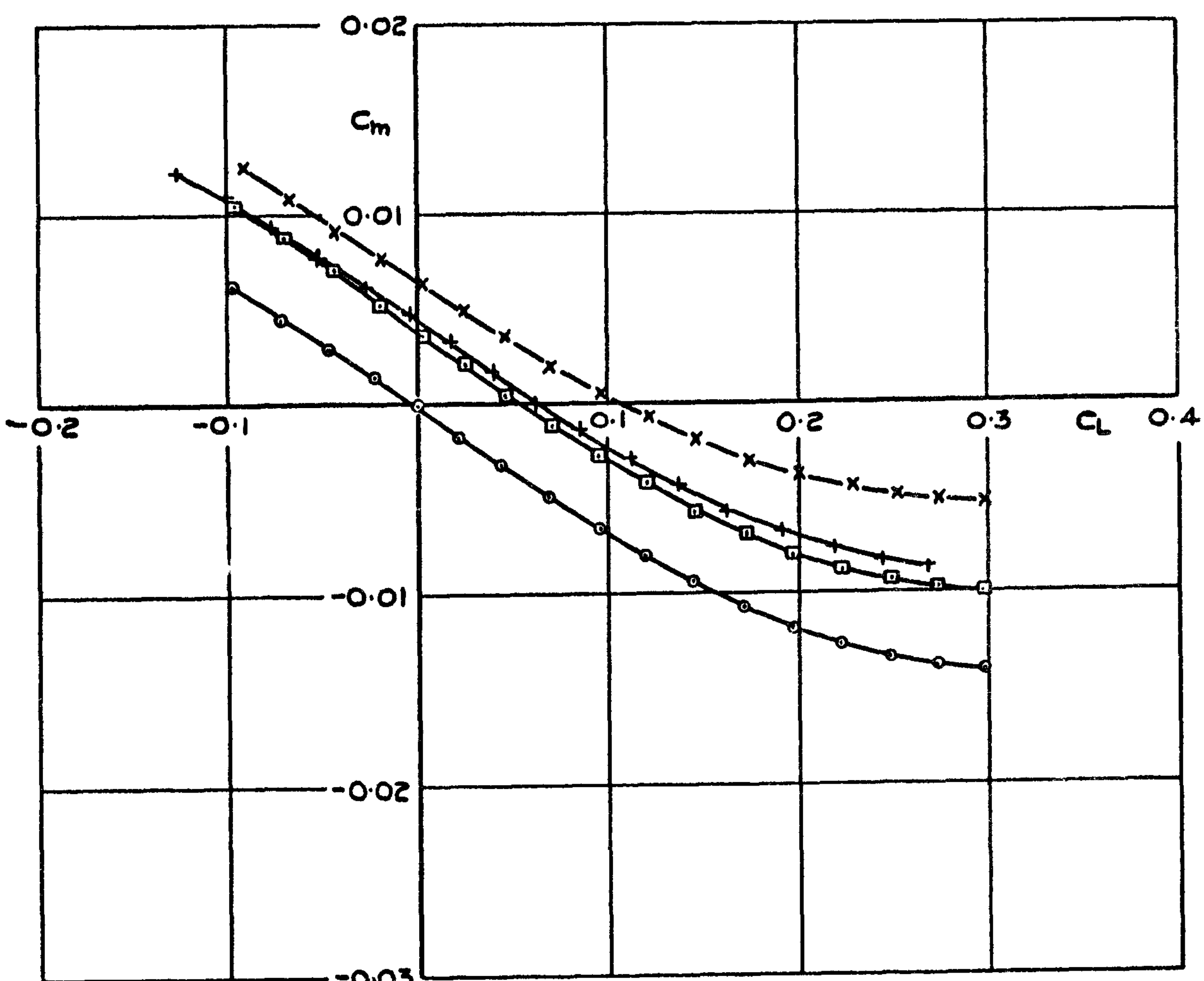


FIG. 7(d) VARIATION OF C_L WITH α: M = 2·0.

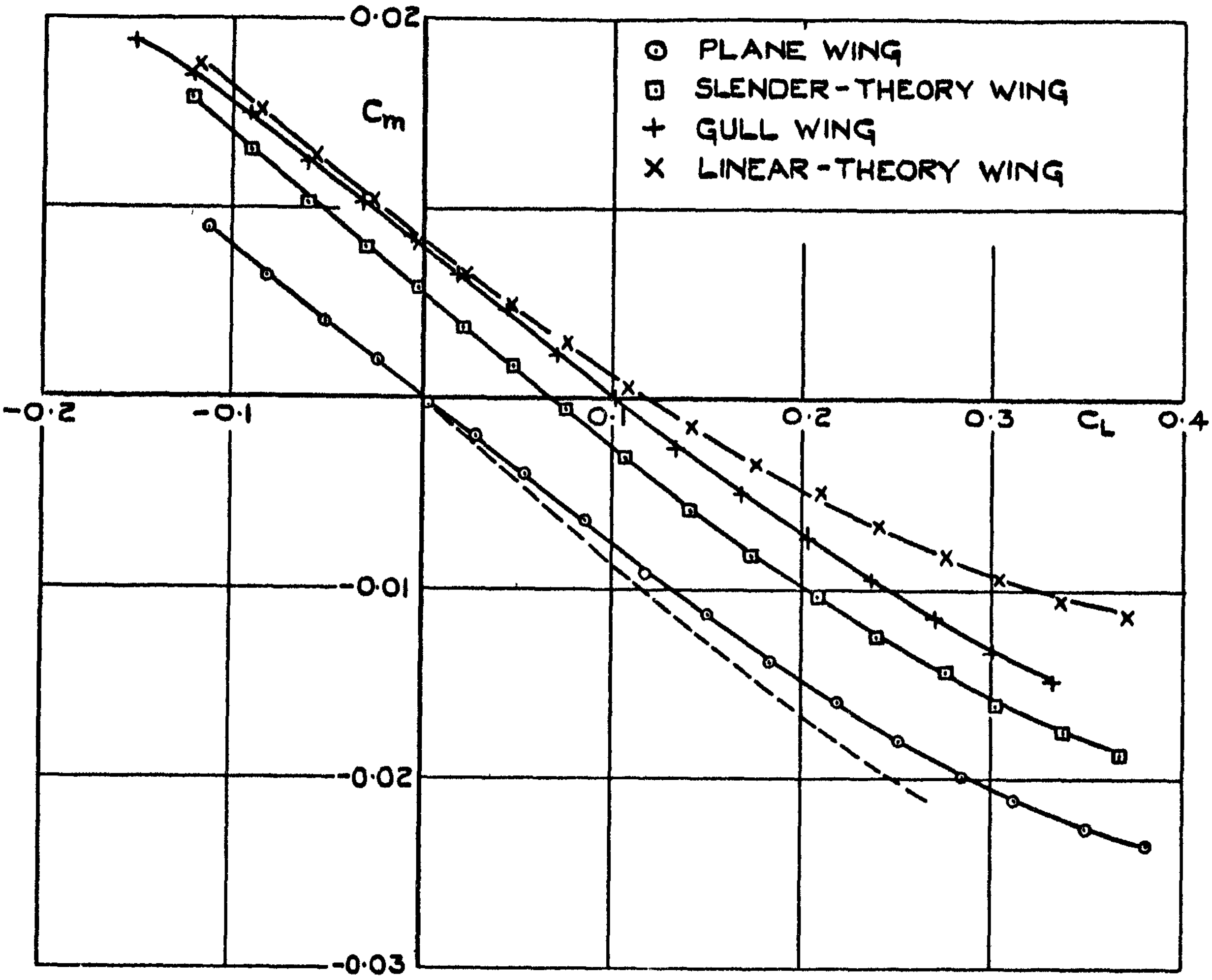


(C) M = 1·82.

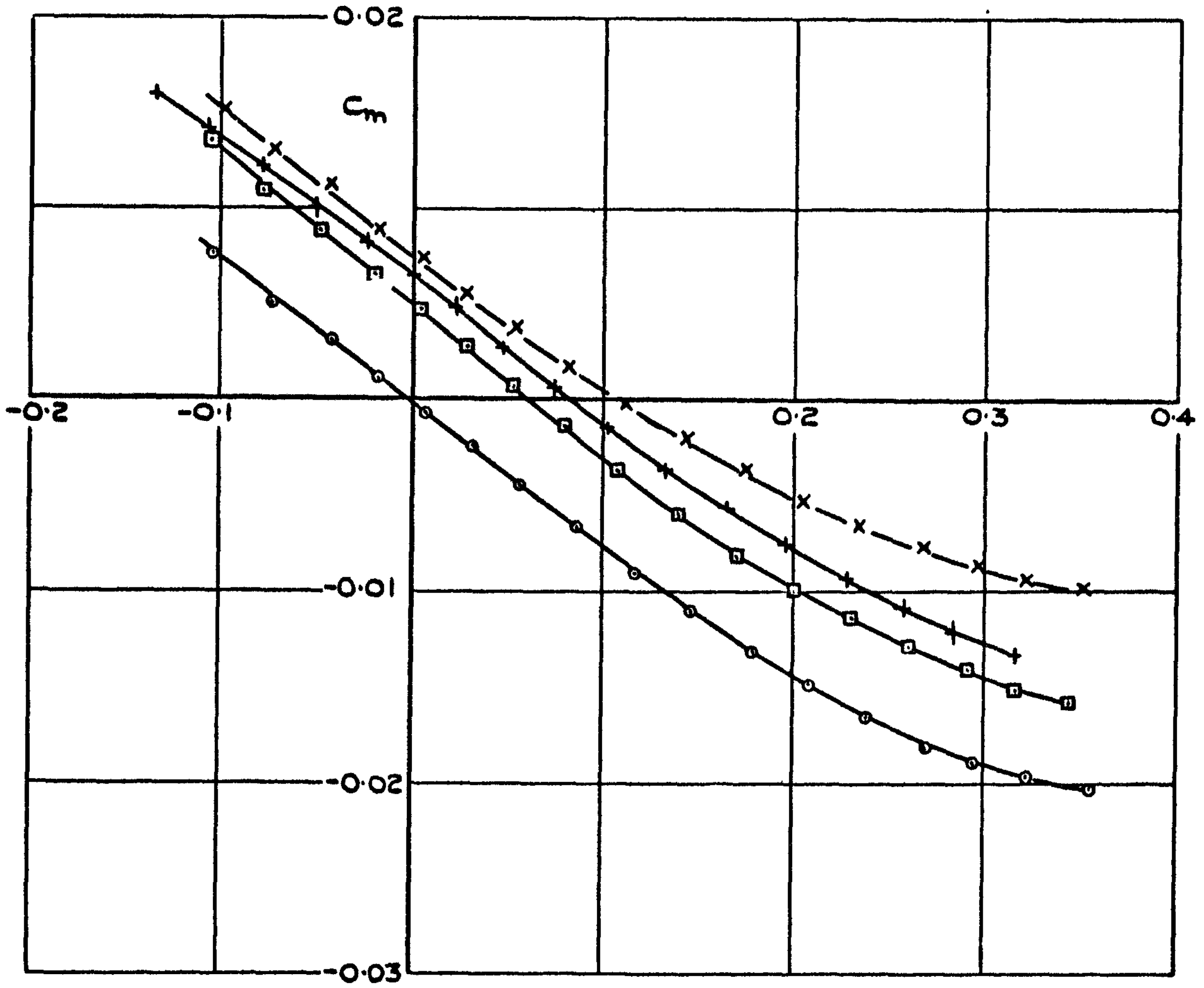


(d) M = 2·0.

FIG. 8. VARIATION OF C_m WITH C_L.



(a) M = 1·42.



(b) M = 1·61.

FIG. 8. VARIATION OF C_m WITH C_L.

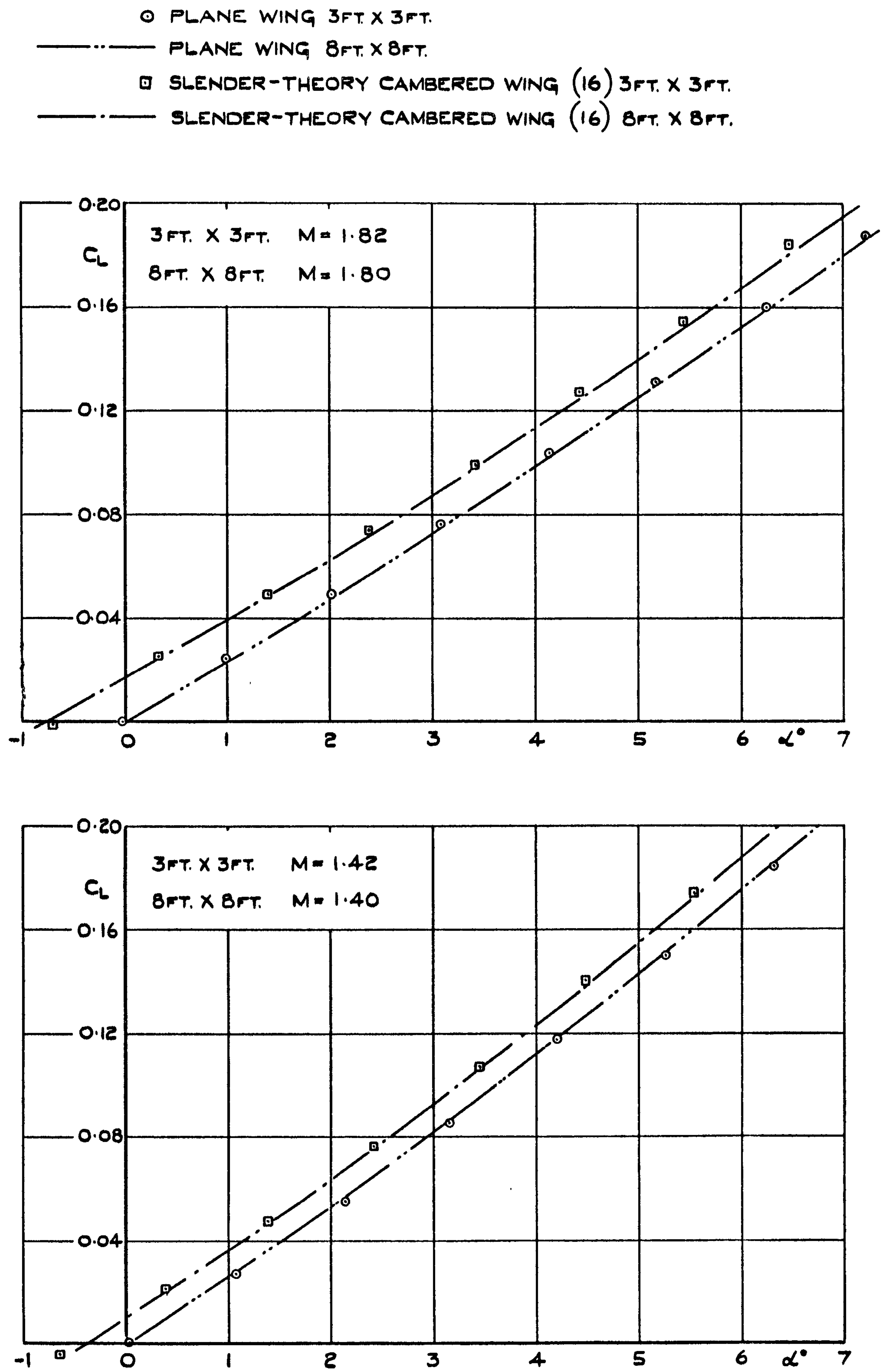


FIG. 9. COMPARISON OF 3FT. X 3FT. AND 8FT. X 8FT. RESULTS: LIFT.

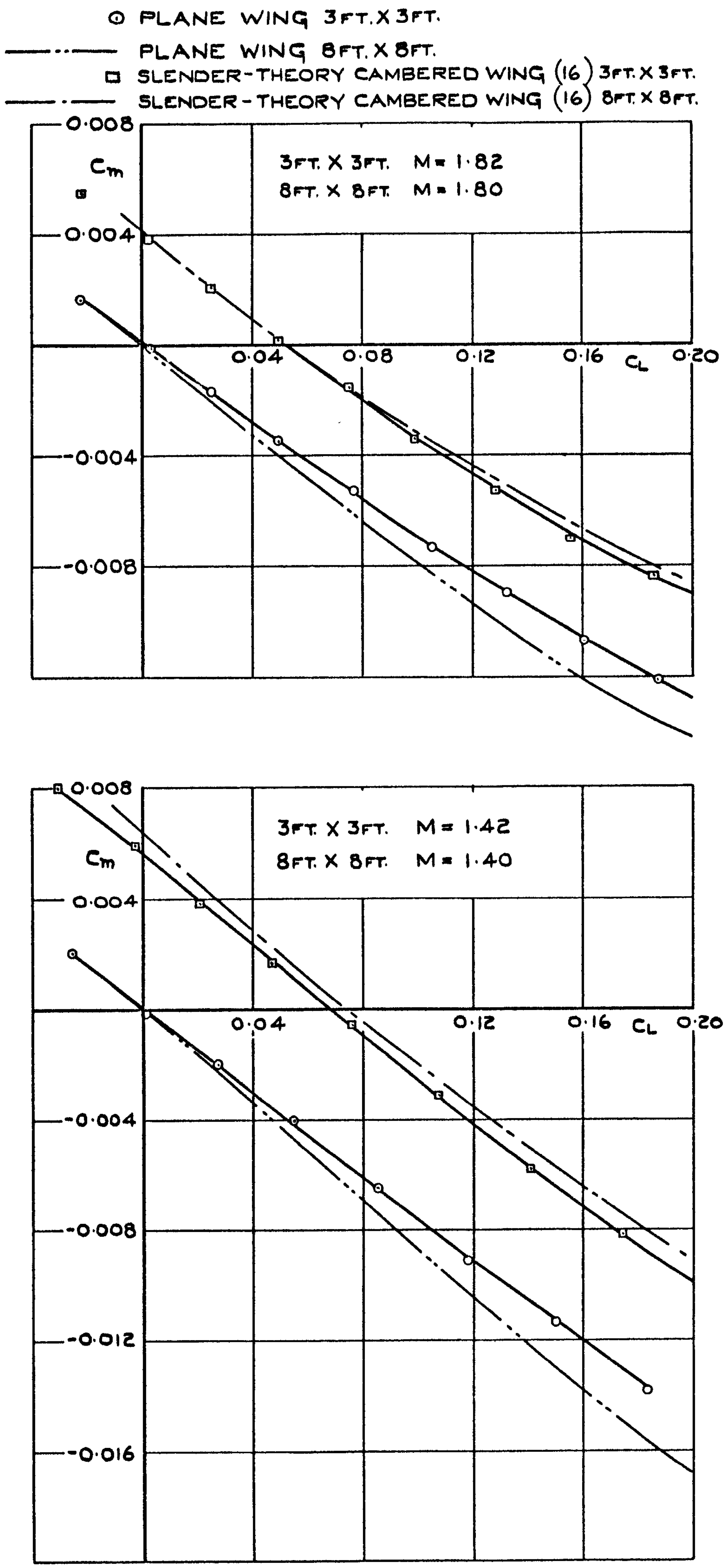


FIG. 10. COMPARISON OF 3FT. X 3FT. AND 8FT. X 8FT. RESULTS: PITCHING MOMENT.

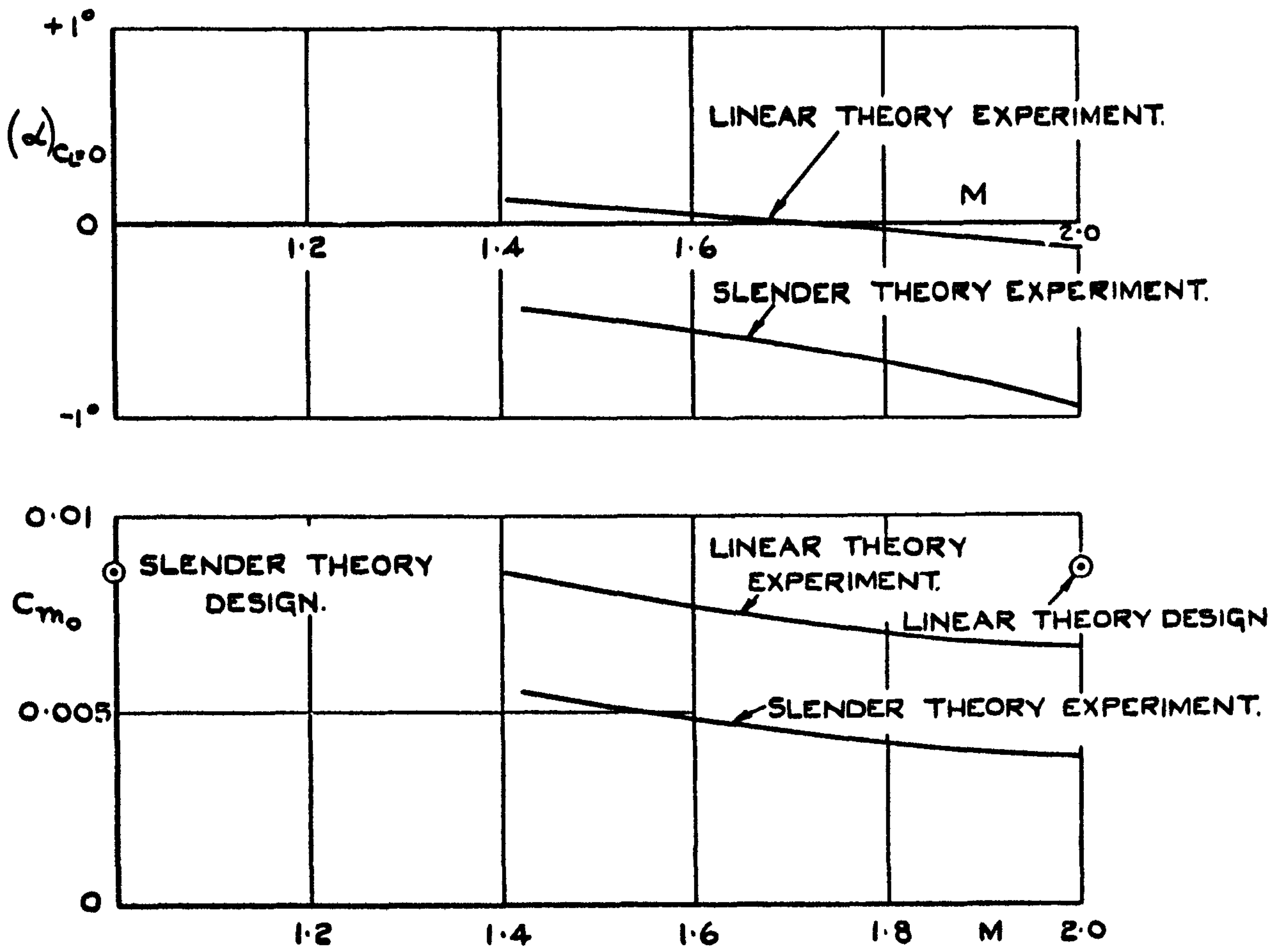


FIG. 11. VARIATION OF $(\alpha)_{C_L=0}$, AND C_{m_0} WITH M: SLENDER AND LINEAR THEORY WINGS.

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