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Wind Tunnel Measurements at Mach Numbers up to 2.80 of the Effects of Gulling on the Longitudinal and Lateral Stability and Drag of a Cambered, Slender Ogee Wing

by

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WIND TUNNEL MEASUREMENTS AT MACH NUMBERS UP TO 2.80 OF THE EFFECTS OF GULLING ON THE LONGITUDINAL AND LATERAL STABILITY AND DRAG OF A CAMBERED, SLENDER OGEE WING

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SUMMARY

Tests have been made at M = 0.31, 1.40, 1.80, 2.20, 2.40 and 2.80 on a cambered, slender ogee wing with spanwise camber designed to reduce the size of rolling moment due to sideslip at low speed. The results are compared with those for a similar model without spanwise camber and show that, at M = 0.31, gulling has resulted in loss of $-\ell_v$ as required, together with reductions in y_v and n_v and an increase in non-linear lift, probably at the drooped tips. Similar effects are obtained at supersonic speeds, though the effect of gulling on $-\ell_v$ diminishes with increasing Mach number.

At supersonic speeds, there is a small increase of drag at zero lift, which appears to be explained by the increase of surface area of the gulled wing.

Replaces R.A.E. Tech. Note No. Aero.2974 - A.R.C. 26,700.

CONTENTS

ILLUSTRATIONS

1 INTRODUCTION

As part of an extensive programme of research to assist the design of a supersonic transport aircraft, a series of slender wings, described in a memorandum by Evans and Squire, has been tested in the 3 ft × 3 ft and 8 ft × 8 ft wind tunnels at the Royal Aircraft Establishment, Bedford. Some of the tests made in the 8 ft × 8 ft wind tunnel were intended to examine the properties of shapes closely resembling realistic aircraft configurations. One wing in particular was examined in detail and the effects of engine installations, controls, and various design modifications were investigated. The basic wing was Wing 16 of the series and had an 'ogee' planform ($p = 0.45$) with camber designed by slender-wing theory to give a pitching moment coefficient of 0.00853 at zero lift. Measurements of camber effectiveness and other longitudinal characteristics of Wing 16 are reported in Ref.1, while the effects of controls, engine nacelles, etc, are reported in Ref.2.

The test described here was made using a model which represented a further development of Wing 16, the present model being added to the initially-proposed programme as Wing 21 of the series. This development was to droop the tip of Wing 16 in order to improve its low speed lateral characteristics, the tip anhedral being coupled with an inboard dihedral to maintain adequate ground clearance. The amount of gulling was decided by the change in rolling moment due to sideslip required, using the results described in Ref.3. The test was made in October, 1960.

2 THE MODEL

The model is sketched in Fig.1 and basic model details are listed in Table 1. Fig.2 shows the effects of spanwise camber on some model sections. The planform and camber and thickness distributions were the same as those of Wing 16[1,2], but an additional spanwise camber was made, so that outboard of a line parallel to the centre-line, and at a distance 0.1 S_T from it, there was a dihedral angle of 8.5°, and outboard of a line at 0.667 S_T there was an anhedral angle of 15°. Suitable 'rounding-off' at the dihedral and anhedral lines eliminated discontinuities in local surface slopes. The model was sting-mounted and, in order to include a sting shroud of diameter 2.60 inches, was distorted near the centre-line aft of $x/c_o \simeq 0.7$.

The fin shown in Fig.1 was mounted on the sting shroud and was similar to that fitted to Wing 16. The model was thus identical to the fin-on, no-canopy configuration of Ref.2 with the exception of the spanwise camber. Manufacture was from glass cloth and araldite and, as a result, the model was more flexible than Wing 16, which was made of steel, (corrections for this increased flexibility were made - see Section 3).

3 TEST DETAILS

Six-component balance measurements were made at Mach numbers 0.31, 1.40, 1.80, 2.20, 2.40 and 2.80, and at a constant Reynolds' number of 10^7, based on model length. The model was tested at zero sideslip at 0.5° intervals in incidence, and over a range of sideslip angles at every 2° of incidence.

Zero incidence was defined as the model attitude at which there was zero lift according to slender-wing theory. Model attitude angles were corrected for balance and sting deflections under load, and the model was tested both right way up and inverted in the tunnel in order to make allowance for free-stream flow deflections by averaging the results.

The moment reference point for both Wing 21 and Wing 16 was at $\bar{\bar{c}}/2$, while the reference length used to non-dimensionalise pitching moment coefficients was $\bar{\bar{c}}$ and that for rolling moment and yawing moment coefficients the wing span, b. The lateral derivatives y_v, n_v and ℓ_v have been defined as $\partial C_y/\partial\beta$, $\partial C_n/\partial\beta$ and $\partial C_\ell/\partial\beta$ respectively, where β is expressed in radians; slopes have been measured graphically over the range $-2^\circ \leqslant \beta \leqslant +2^\circ$. All coefficients refer to stability axes.

Axial force measurements were corrected for the difference between free-stream static pressure and the measured pressures within the sting shroud. No correction to axial force was made for the effect of the shroud on the drag of the model but pitching moments at supersonic speeds were corrected using the method of the Appendix to Ref.1: this correction was $\Delta C_m = 0.0007/\beta$, where $\beta = \sqrt{M^2-1}$. (The corresponding correction to Wing 16 results was $\Delta C_m = 0.0003/\beta$.) As in the case of Wing 16 the shroud was symmetrical about the trailing edge and there was therefore no correction to lift.

Corrections for the flexibility of Wing 21 were assumed to be the same as those derived in the tests of Ref.1, and were:-

$$\Delta\alpha^\circ = -1.5\, C_L \; ; \qquad \Delta C_m = -0.010\, C_L$$

Results at M = 0.31 were corrected for tunnel constraint and blockage effects. The constraint corrections were:-

$$\Delta\alpha^\circ = 0.73\, C_L \; ; \qquad \Delta C_m = 0.057\, C_L^2/\alpha \; ; \qquad \Delta C_D = 0.010\, C_L^2 \; ;$$

while blockage corrections were made to the free-stream static and dynamic pressures used in computing the results, (the corrected Mach number is that quoted, viz 0.31).

The location of boundary layer transition was fixed on the model by means of bands of 60 grade carborundum particles on an Araldite base. Each band was 0.5 inches wide and started at a line 0.1 inches from and measured normal to the leading edge.

Possible errors in the results were estimated to be as follows. At supersonic speeds:-

$$\Delta C_L = \pm 0.001 \pm 0.006\, C_L,$$

$$\Delta C_m = \pm 0.0002 \pm 0.005\, C_m,$$

$$\Delta C_D = \pm 0.0005 \pm 0.008\, C_L^2 \; .$$

At M = 0.3, due to lower dynamic pressure,

$$\Delta C_L = \pm 0.002 \pm 0.006\, C_L$$

$$\Delta C_m = \pm 0.0003 \pm 0.005\, C_m$$

$$\Delta C_D = \pm 0.0008 \pm 0.008\, C_L^2$$

At all Mach numbers,

$$\Delta y_v = \pm 0.005$$

$$\Delta n_v = \pm 0.004$$

$$\Delta \ell_v = \pm 0.005$$

$$\Delta \alpha = \pm 0.05^\circ$$

4 DISCUSSION OF RESULTS

The results are presented graphically as a comparison between the 'gulled' and the 'ungulled' wings: Figs.3 to 7 show results at M = 0.31 and Figs.8 to 18 results at supersonic speeds.

4.1 Results at M = 0.31

Figs.3(a) and 4(a) show that spanwise camber has reduced the effect of incidence on ℓ_v. At zero and low incidence the effect is small, about +0.01: this is because the inboard dihedral effect very nearly cancels that of the anhedral tip, as is apparent from an estimate of the change in ℓ_v using Equation 17 of Ref.4. This estimate indicates an increase in ℓ_v due to gulling of +0.0033, if it is assumed that the dihedral commences at the centre-line. The effect of incidence cannot be estimated using the theoretical methods of Ref.4, but the reduction at $\alpha = 14^\circ$ ($C_L \simeq 0.5$) of 0.077 is approximately that designed for by the empirical method of Ref.3.

The remaining graphs of Figs.3 and 4 show the effects of gulling on y_v and n_v: losses in both derivatives occur with increasing incidence. As Fig.4(c) illustrates, the change in n_v can be broken down into a component due to the change in ℓ_v ($\Delta n_v = -\Delta \ell_v \tan \alpha$) and a component due to the change in y_v acting at a constant chordwise position, viz $x/c_o = 0.57$. (The assumption of a fixed point of action for side-force has been found, in general, to satisfy yawing moment measurements on slender wings without fins[5].) In the present case it is not possible to establish the precise source of the loss of y_v. Drooped tips alone result in negative y_v at incidence as has been shown in some unpublished low-speed tests by Maltby and Hay on a simple model with no chordwise camber.

However, some changes in y_v can be expected from the effect of overall gulling on vortex behaviour when the model is sideslipped. A further unknown factor in the present tests is the effect of gulling on fin effectiveness - some results quoted in Ref.4 (for a wing with anhedral) suggest that inboard dihedral might result in a loss of fin effectiveness.

Fig.5 shows that gulling has resulted in an increase in non-linear lift on the model and Fig.6 that there has been a reduction in 'pitch-up'. This indicates that anhedral has improved the lift characteristics of the tip at high incidence, probably as a result of separation of the flow across the anhedral line with consequent, additional non-linear lift. This effect has been observed in the tests by Maltby and Hay and in tests on a gulled wing described in Refs.6 and 7. A further feature of the increase in non-linear lift is a reduction in the drag due to lift, evident in Fig.7, amounting to about 3% at $C_L = 0.5$. A slight increase in minimum drag coefficient due to gulling was measured and, though the difference is less than the estimated accuracy of drag measurements, this is consistent with an estimated increase in skin friction drag coefficient of 0.0002 due to increased wetted area.

4.2 Results at supersonic speeds

At $M = 1.40$, the effects of spanwise camber on the lateral derivatives ℓ_v, y_v and n_v are similar to and have roughly the same magnitude as those at $M = 0.31$, within the reduced incidence range covered at supersonic speeds. Fig.8(a) shows a decrease both of $-\ell_v$ at zero incidence and of the variation of $-\ell_v$ with increasing incidence. Gulling results in an increasing negative increment in y_v above about 7° incidence (Fig.9(a)) and an increasing loss of n_v with incidence (Fig.10(a)).

The result of increasing Mach number above 1.40 is to reduce the size of the effect of gulling on ℓ_v (Fig.8), so that at a possible cruise attitude of about 3° at $M = 2.20$ the influence is negligible, and at $M = 2.80$ the effect is very small at all angles of incidence. Mach number effects on y_v and n_v (Figs.9 and 10) are more complicated, though in general, at all Mach numbers, gulling results in an increase in $-y_v$ at high incidence and a loss of n_v at all incidences. At $M = 2.20$ and $\alpha = 3^\circ$, about 50% of n_v is lost.

Fig.11 shows that spanwise camber has effected a small increase in lift-curve slope at zero incidence at most Mach numbers and that a small increase in non-linear lift is also in general obtained (Fig.13). An analysis of pitching moment results (Fig.12) shows that the gulled wing has a zero-lift aerodynamic centre aft of that of Wing 16 (Fig.14). The difference in aerodynamic centre position increases with increasing lift (Fig.15), indicating that the additional non-linear lift is generated over the drooped tips as at low speed.

Drag results are plotted in Figs.16, 17 and 18 showing that, again as at $M = 0.31$, gulling results in an increase in minimum drag and a reduction in drag due to lift, both effects being insensitive to Mach number variation.

As Fig.17 illustrates the increase in minimum drag can largely be attributed to the increase in skin friction drag due to the increased wetted area of Wing 21 compared with Wing 16. As is apparent from Fig.16, the reduction in lift-induced drag does not offset the increase in minimum drag until high values of C_L are reached: at $M = 2.20$ this value of C_L is about 0.16. However, it should be borne in mind that the differences under discussion are of the same magnitude as the estimated accuracy and too much significance should not be placed upon them.

5 CONCLUSIONS

A comparison of the results of wind tunnel tests on a cambered ogee wing, with and without an additional spanwise camber, has shown the following results.

At $M = 0.31$, due to gulling:-

(1) There is a reduction in $-\ell_v$, increasing with incidence, providing approximately the reduction designed for at $C_L \simeq 0.5$.

(2) Both y_v and n_v are reduced above about 4° incidence.

(3) There is an increase in non-linear lift, a reduction in pitch-up and a reduction in lift-induced drag, suggesting additional separation effects on the drooped tips.

(4) A small increase in minimum drag has been measured.

At supersonic speeds, due to gulling:-

(1) Effects on ℓ_v, y_v and n_v similar to those at $M = 0.31$ have been obtained at $M = 1.40$. The effect on ℓ_v decreases with increasing Mach number: the effects on y_v and n_v vary irregularly with Mach number, though it should be noted that n_v invariably decreases.

(2) In general, there are increases in lift-curve slope and non-linear lift together with rearward movements of aerodynamic centre, implying additional lift on the tips similar to that at $M = 0.31$.

(3) There is an increase in minimum drag, corresponding approximately to the expected increase in skin friction drag due to additional wetted area, and a reduction in lift-dependent drag.

<u>SYMBOLS</u>

M	Mach number
α	angle of incidence, zero when there is zero lift according to slender body theory
β	angle of sideslip
x	chordwise distance from model nose
c_o	centre-line chord length, i.e. model length
$\bar{\bar{c}}$	aerodynamic mean chord
s	local semi-span
S_T	trailing edge semi-span
S	planform area
p	planform parameter $= S/2S_T\ c_o$
C_ℓ	rolling moment coefficient
C_y	side force coefficient
C_n	yawing moment coefficient
ℓ_v	$\partial C_\ell/\partial\beta$, between $\beta = -2^\circ$ and $+2^\circ$
y_v	$\partial C_y/\partial\beta$, between $\beta = -2^\circ$ and $+2^\circ$
n_v	$\partial C_n/\partial\beta$, between $\beta = -2^\circ$ and $+2^\circ$
C_L	lift coefficient
C_m	pitching moment coefficient
C_D	drag coefficient

REFERENCES

No.	Author	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. ARC R. & M. 3328. December 1961
2	Isaacs, D.	Measurements at subsonic and supersonic speeds of the longitudinal and lateral stability of a slender cambered ogee wing including the effects of a fin, canopy nose and trailing edge controls. ARC R. & M. 3390 September 1963
3	Kirby, D.A. Trebble, W.J.G.	Low speed wind tunnel tests of the effects of anhedral and dihedral on the lateral and longitudinal stability of slender wings. Unpublished M.O.A. Report
4	Ross, A.J.	The calculation of lateral stability derivatives of slender wings at incidence, including fin effectiveness, and correlation with experiment. RAE Report No. Aero 2647. ARC R. & M. 3402. March 1961
5	Spence, A. Lean, D.	Some low-speed problems of high-speed aircraft. AGARD Report 357. 1961
6	Howard, M.B.	The effects of combined dihedral and anhedral on the static stability of the HSA.1000 aircraft at subsonic speeds. AVRO Report ARD/WT/HSA.1000/4. August 1960
7	Howard, M.B.	Flow patterns on the upper surface of a model of the HSA.1000 aircraft having combined dihedral and anhedral. AVRO Report ARD/WT/HSA.1000/5. August 1960

TABLE 1

Model details

Planform equation:

$$\frac{s(x)}{S_T} = \frac{x}{c_o}\left\{1.2 - 2.4\frac{x}{c_o} + 2.2\frac{x^2}{c_o^2} + 3\frac{x^3}{c_o^3} - 3\frac{x^4}{c_o^4}\right\} ,$$

where $\frac{S_T}{c_o} = 0.208$

Planform parameter, p	0.45	
Length, c_o	60	inches
Span, $2S_T$	24.96	inches
Plan area, S	674	in.^{2}
Aspect ratio	0.924	
Aerodynamic mean chord, $\bar{\bar{c}}$	36.96	inches
Fin area	45.56	in.^{2}
Dihedral/anhedral details → see Section 2		
Ratic of total wetted area of wing and sting shroud to twice plan area	1.086	

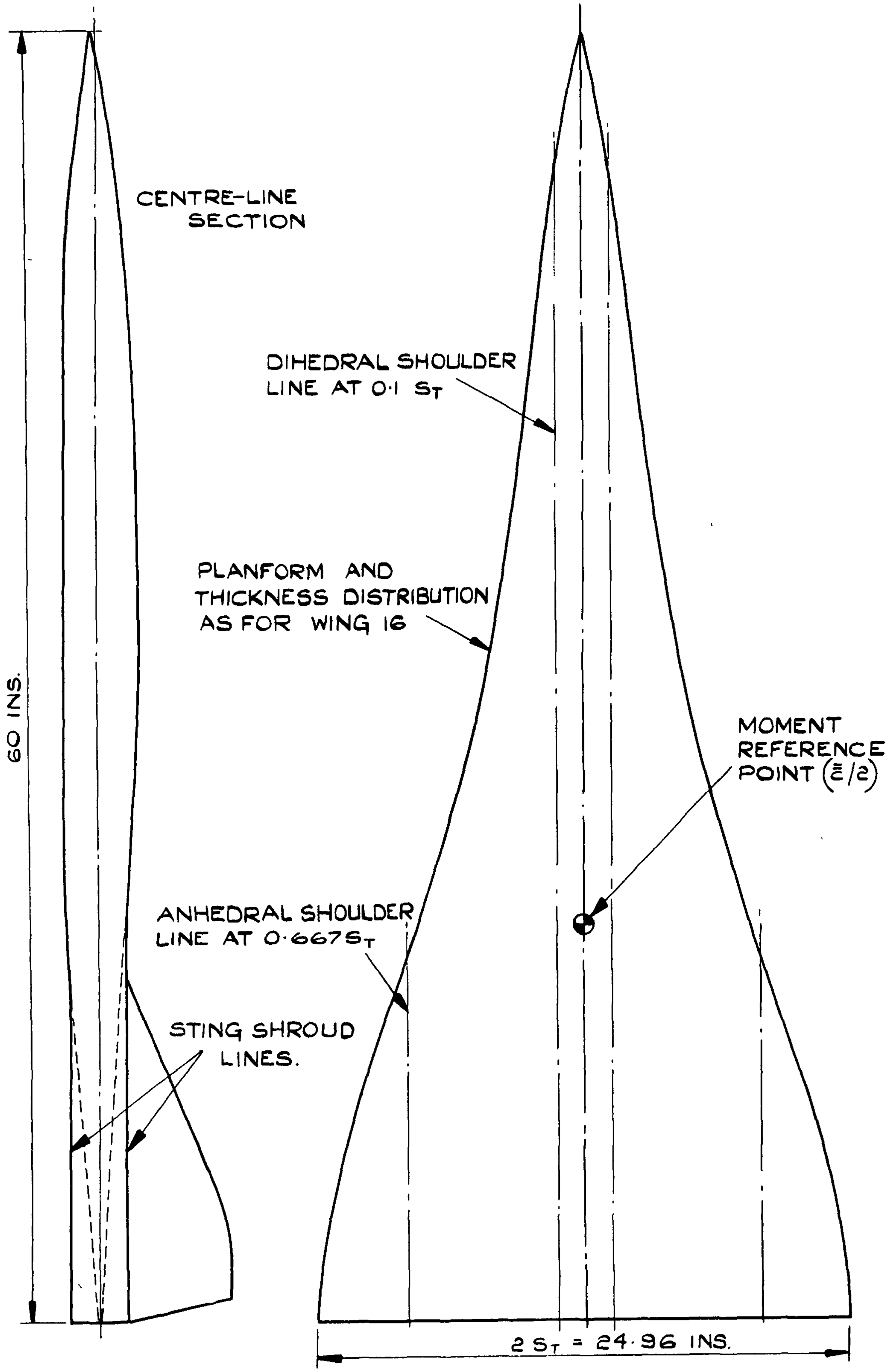
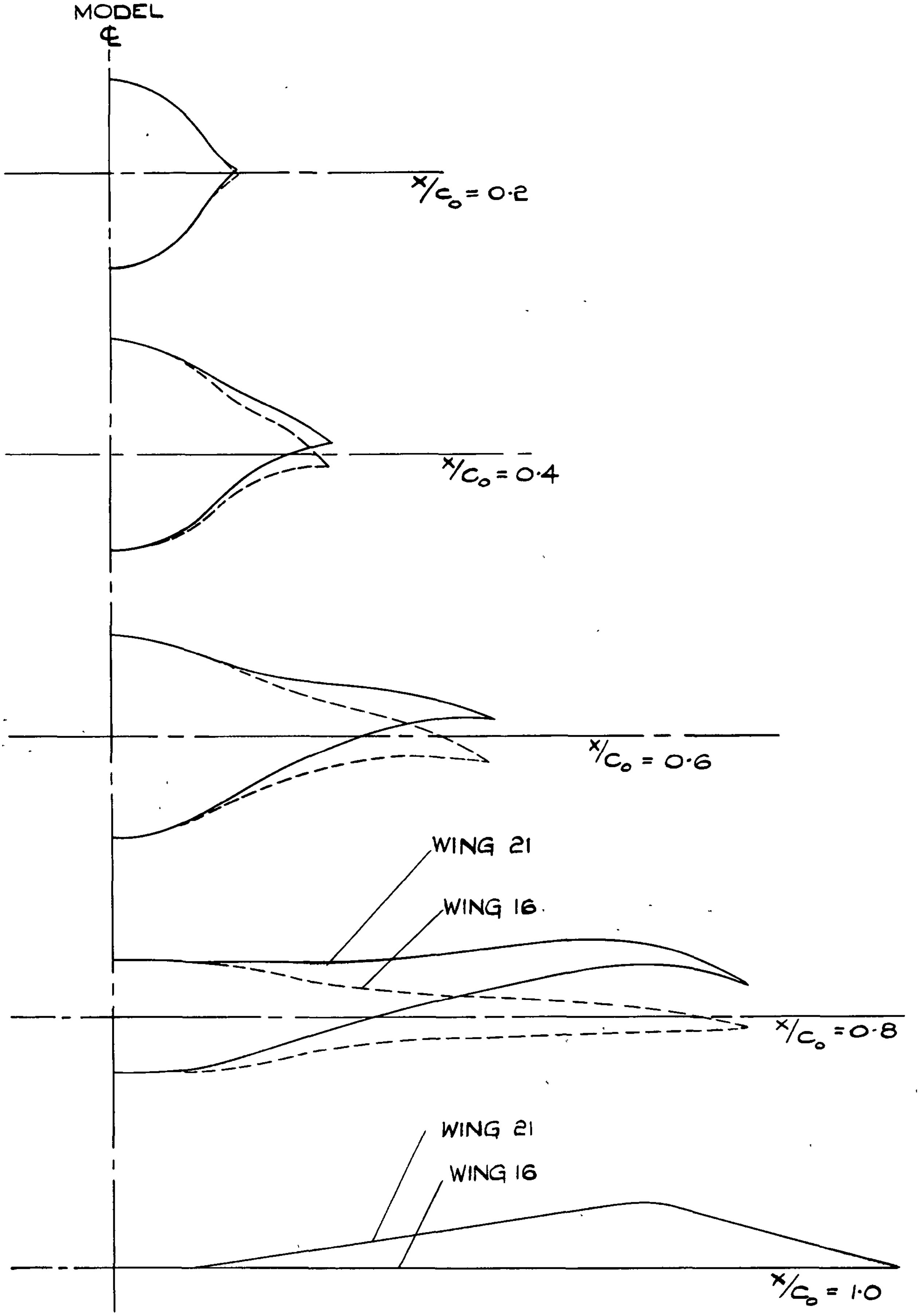
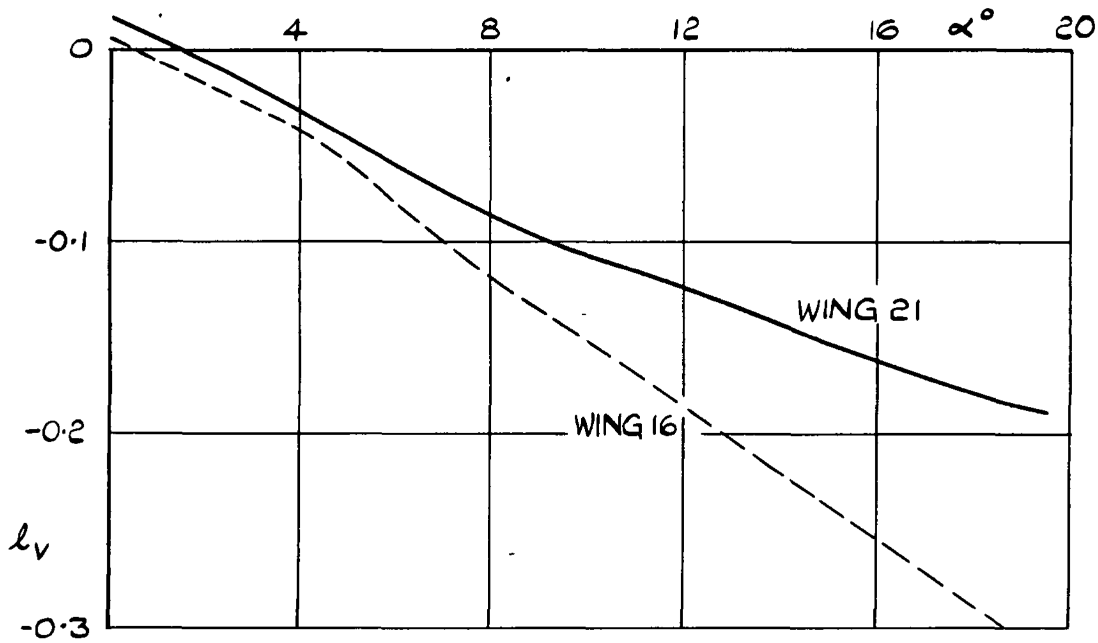


FIG.1. DETAILS OF THE MODEL.

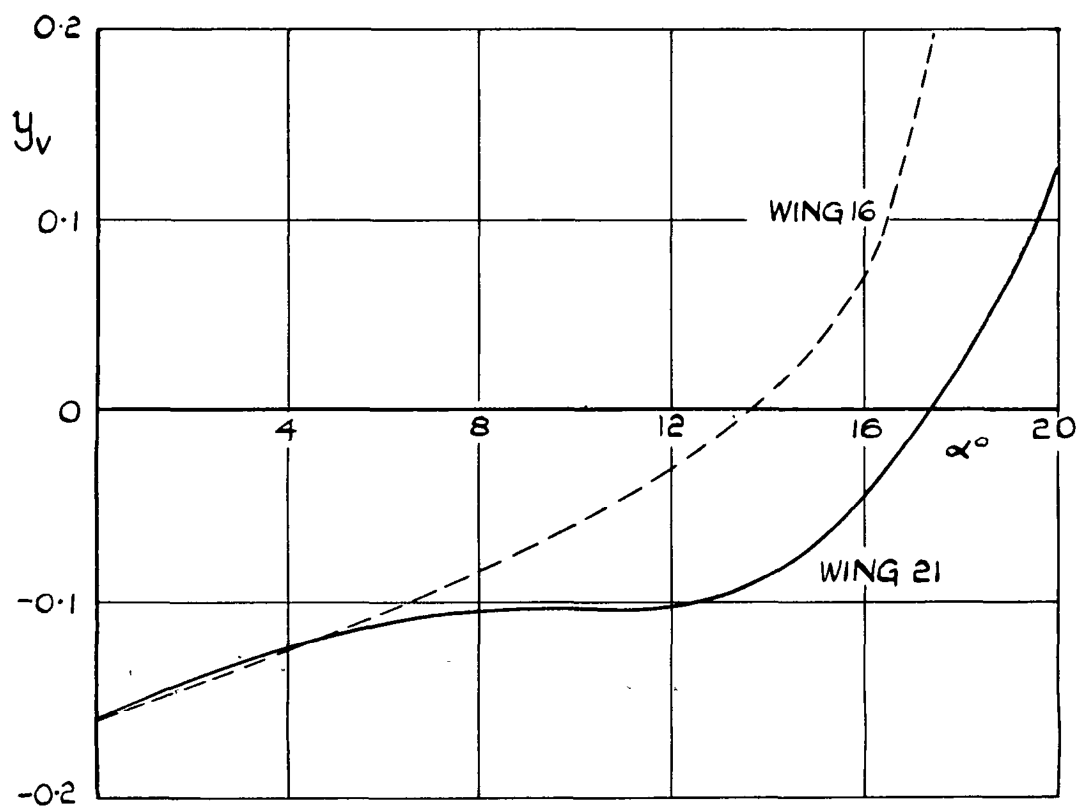


NOTE: FIN AND STING SHROUD ARE NOT SHOWN

FIG.2. WING SECTIONS.

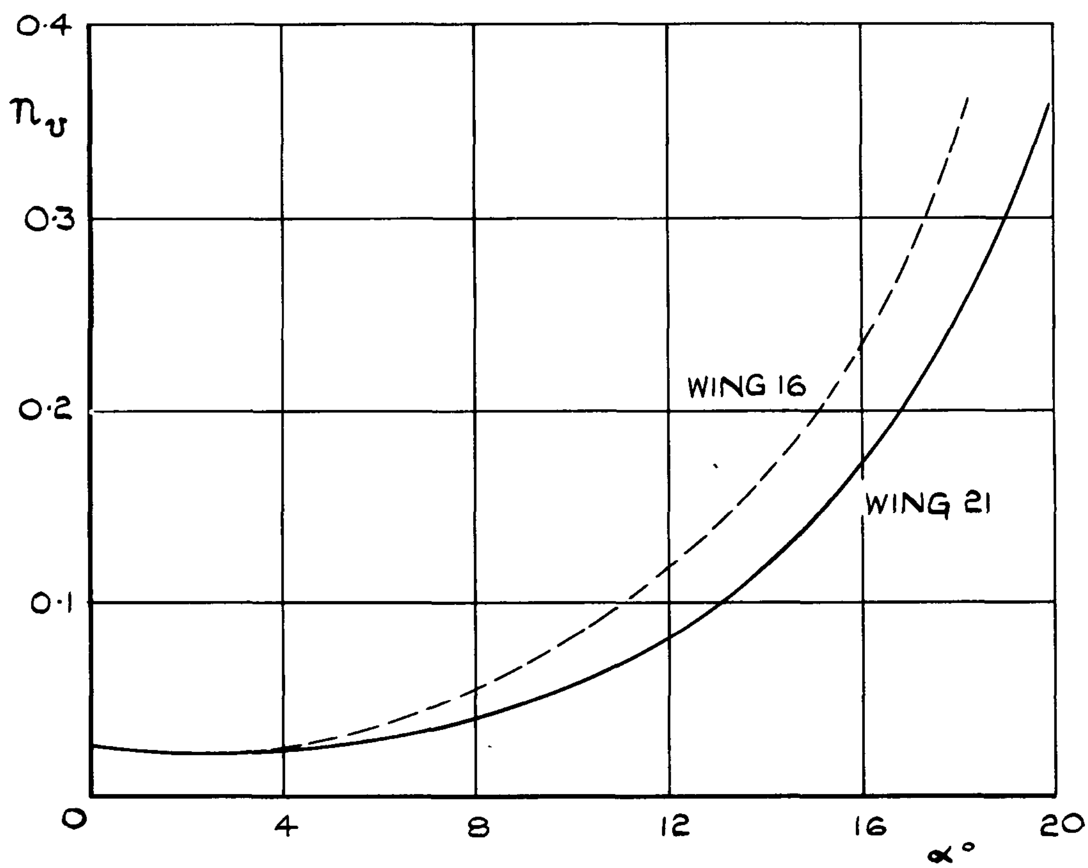


(a) $\ell_v \sim \alpha$



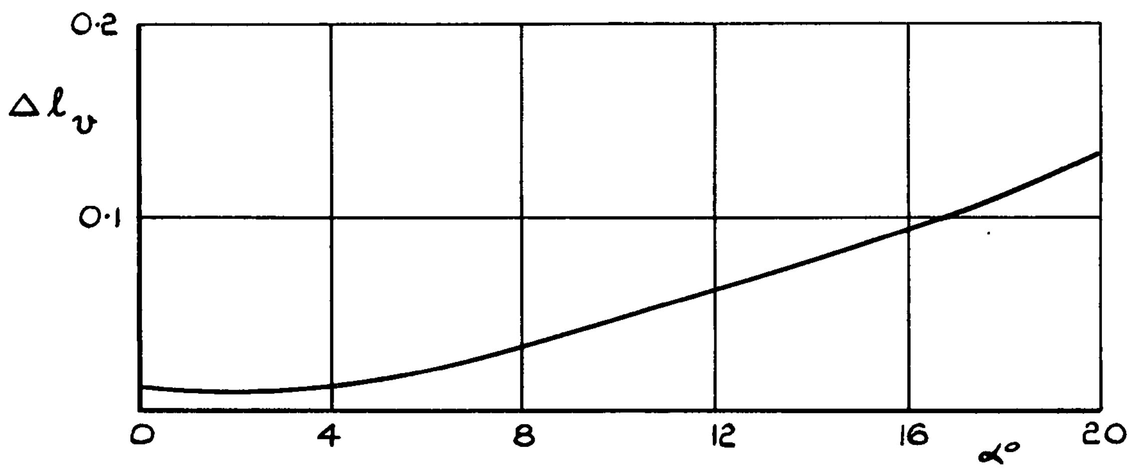
(b) $y_v \sim \alpha$

FIG. 3. LATERAL DERIVATIVES AT M=0·31.

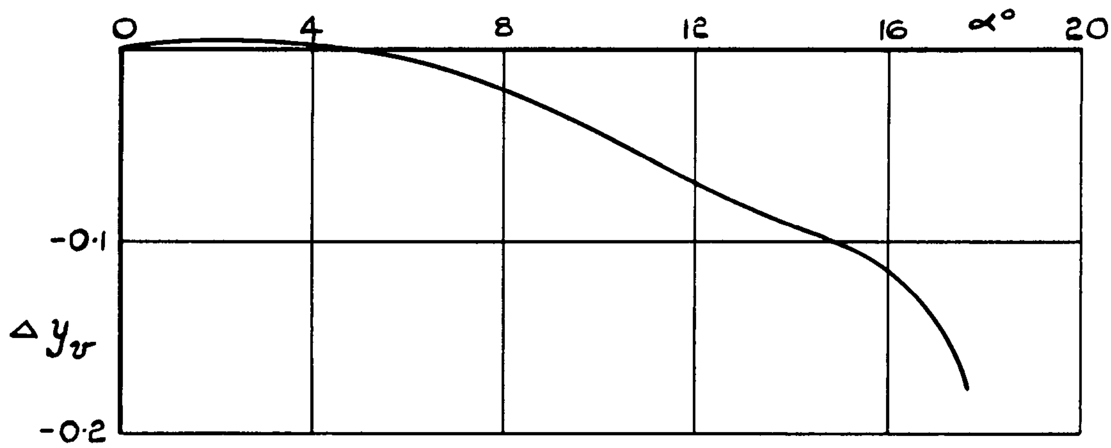


(c) $n_v \sim \alpha$

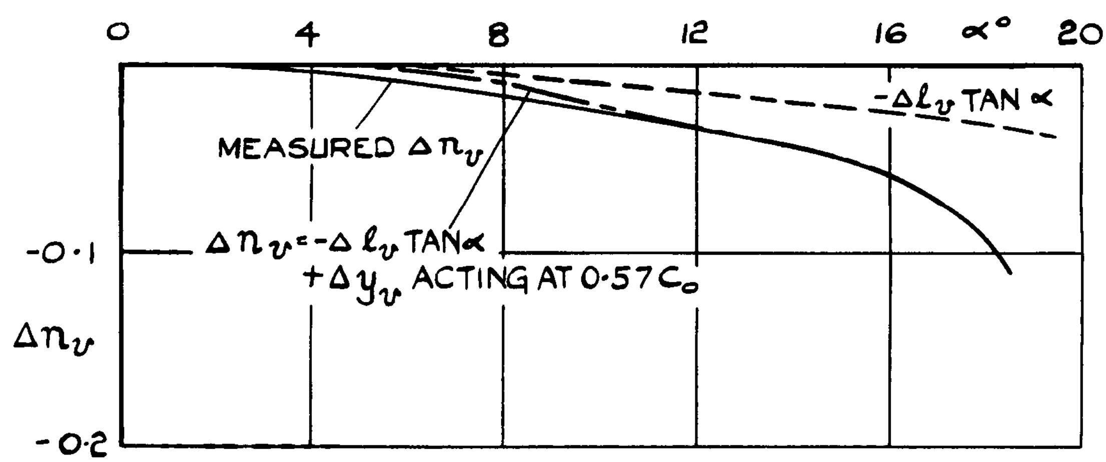
FIG. 3. (Concld.)



(a) $\Delta l_v \sim \alpha$



(b) $\Delta y_v \sim \alpha$



(c) $\Delta n_v \sim \alpha$

FIG. 4. EFFECTS OF SPANWISE CAMBER ON LATERAL DERIVATIVES AT M=0·31.

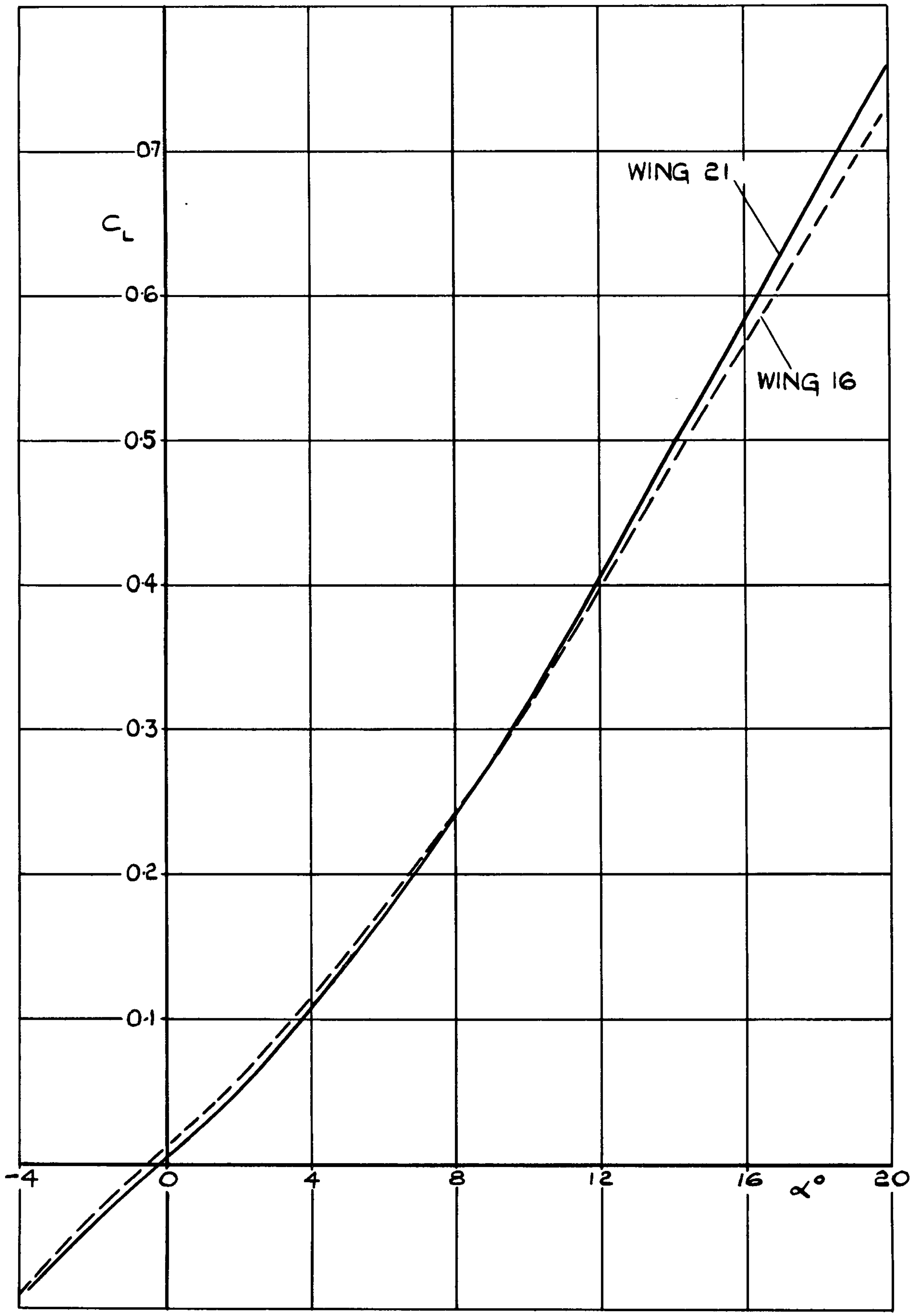


FIG.5. VARIATION OF C_L WITH α AT M=0·31.

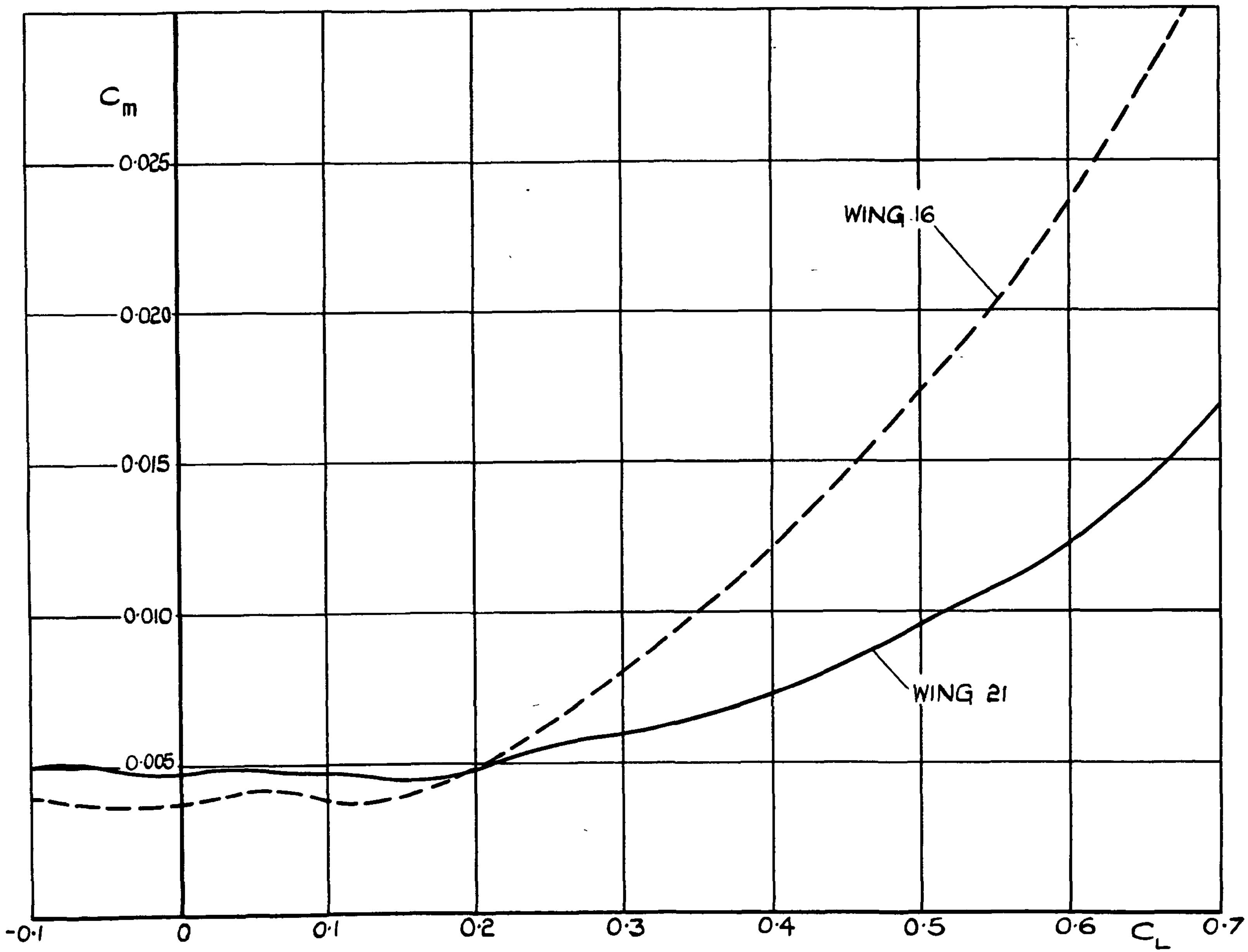


FIG. 6. VARIATION OF C_m WITH C_L AT M=0·31

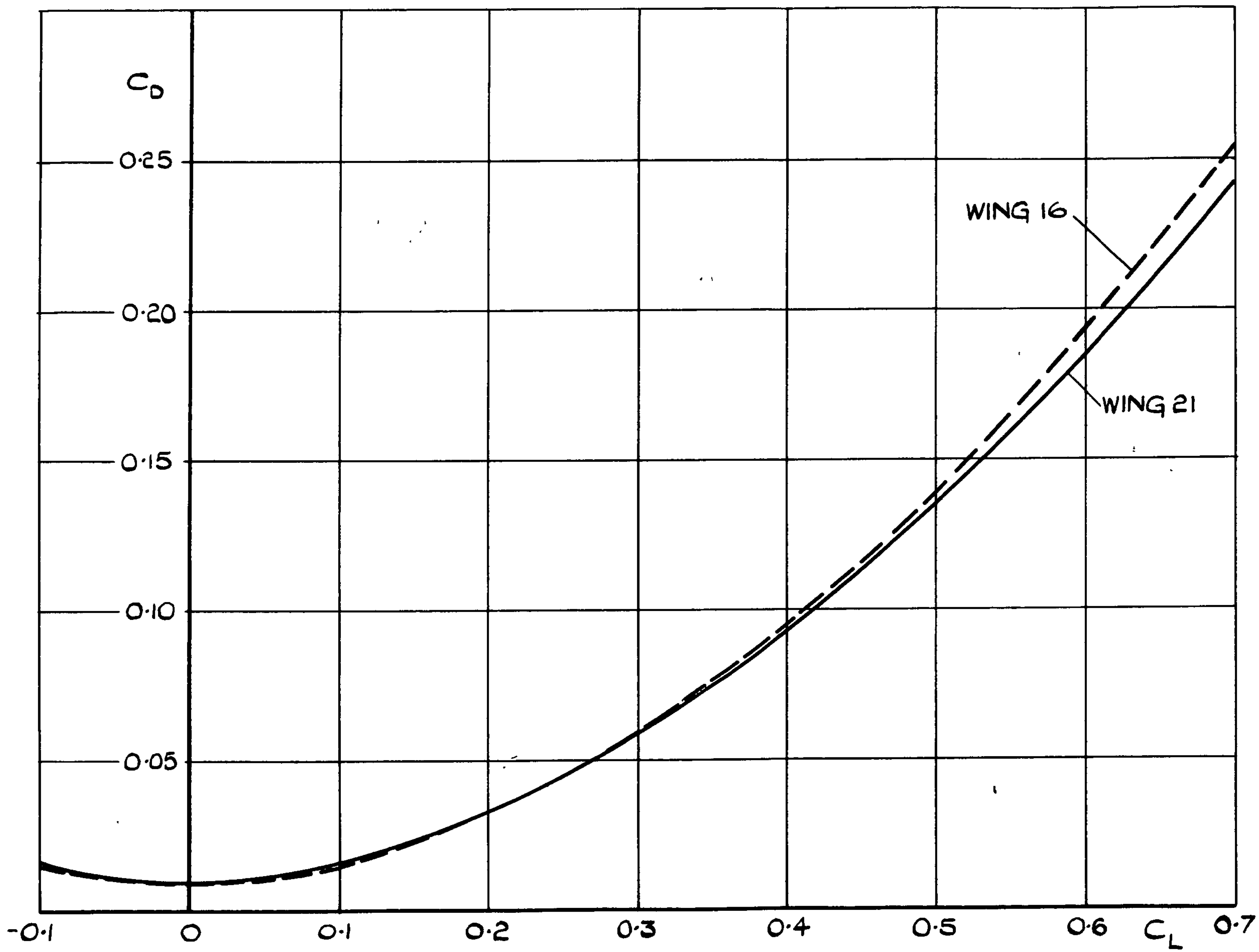
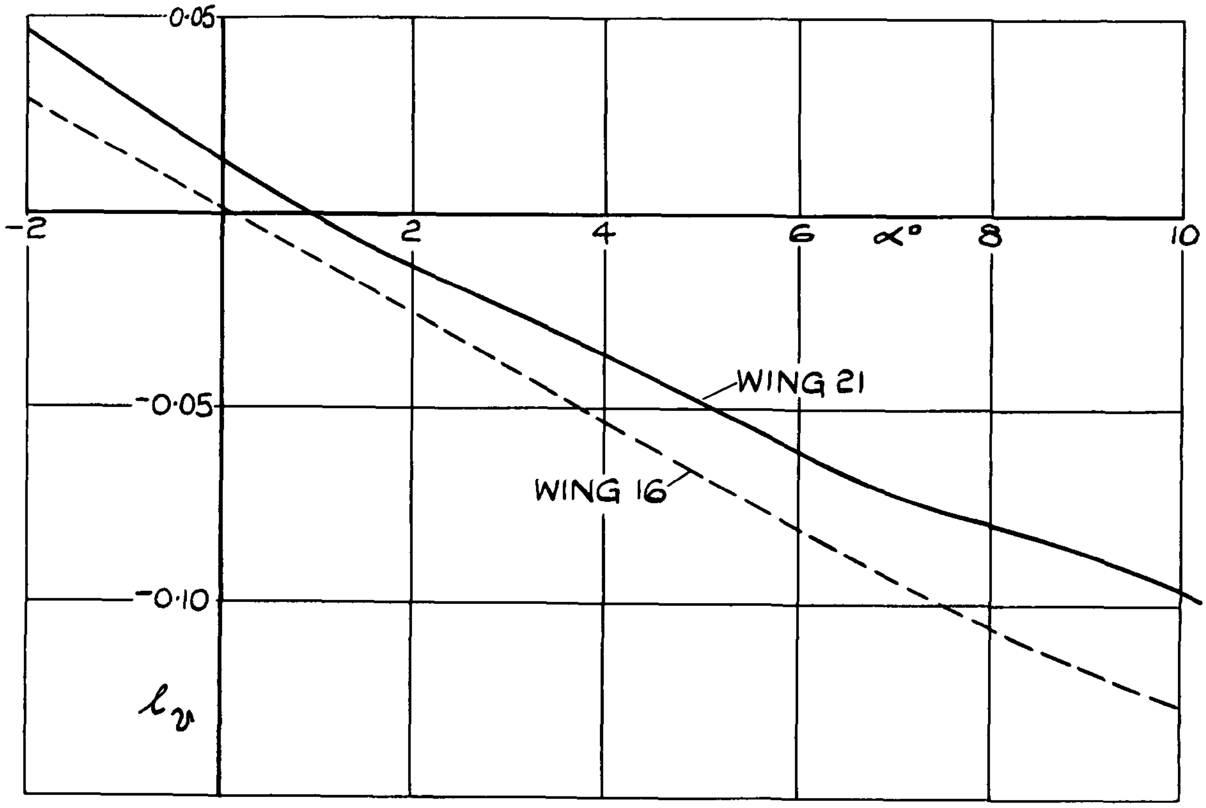
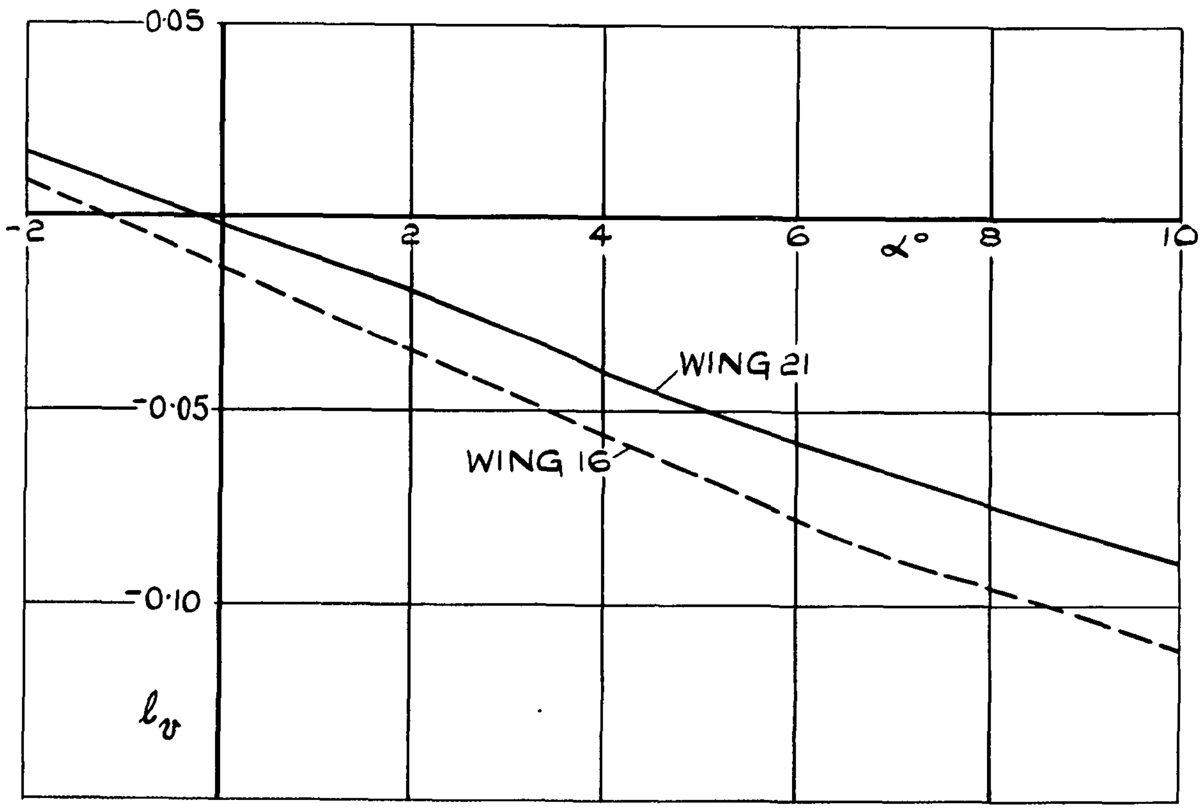


FIG.7. VARIATION OF C_D WITH C_L AT $M=0\cdot31$.



(a) M = 1·40



(b) M = 1·80

FIG. 8. l_v v. α AT SUPERSONIC SPEEDS.

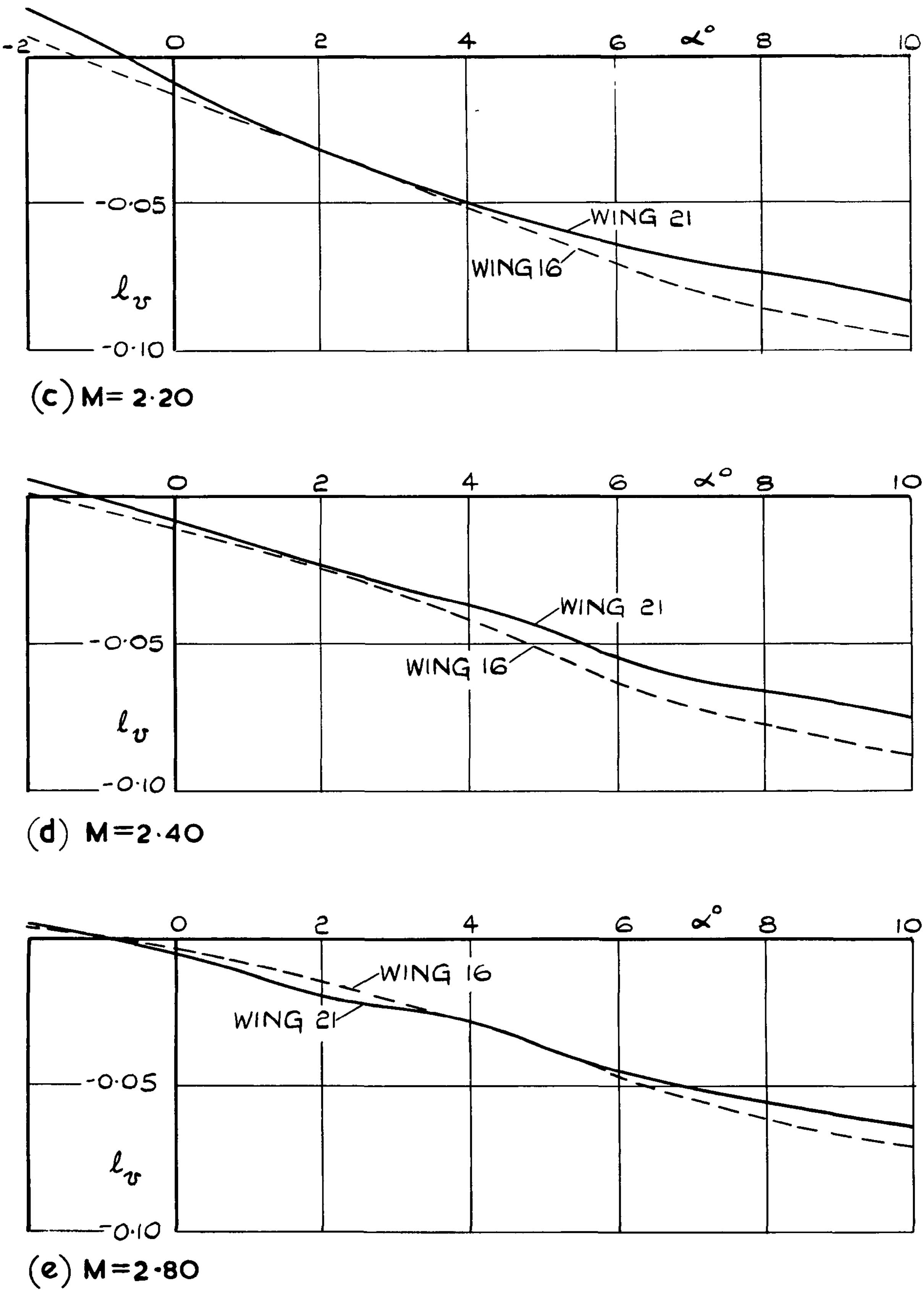
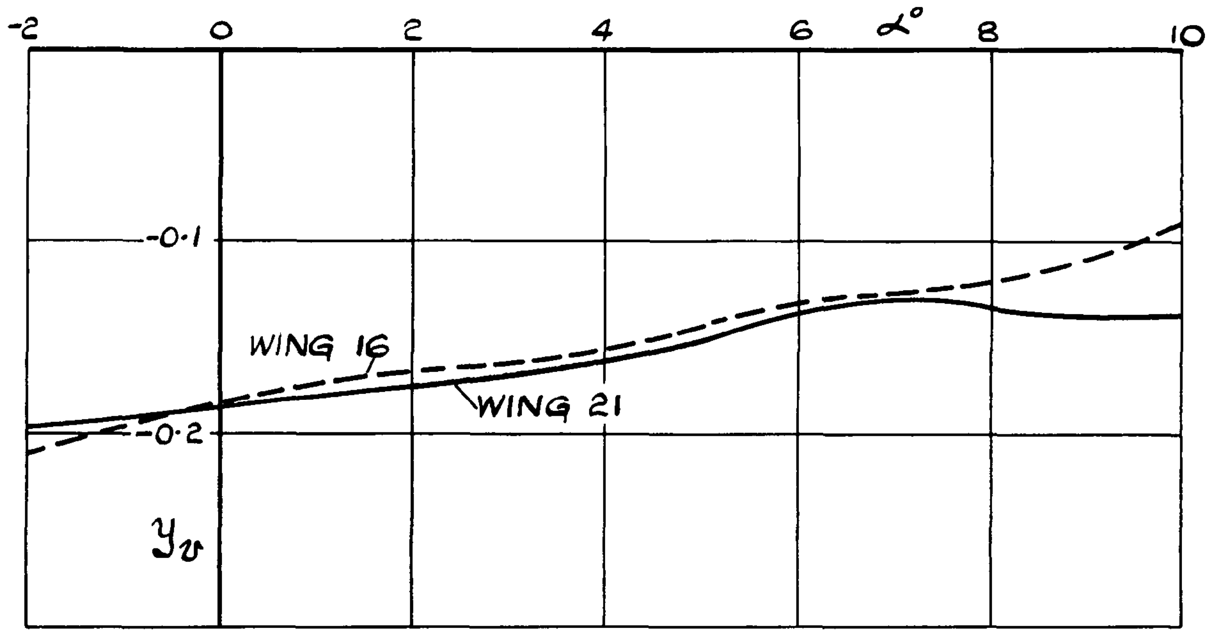
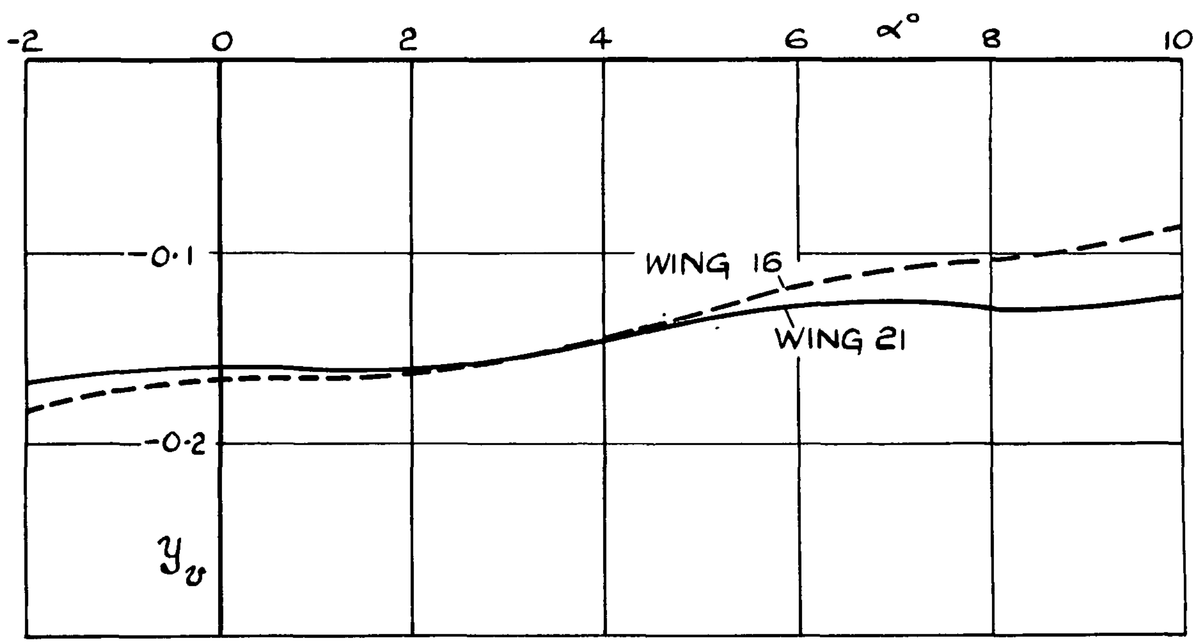


FIG. 8. l_v V α AT SUPERSONIC SPEEDS.

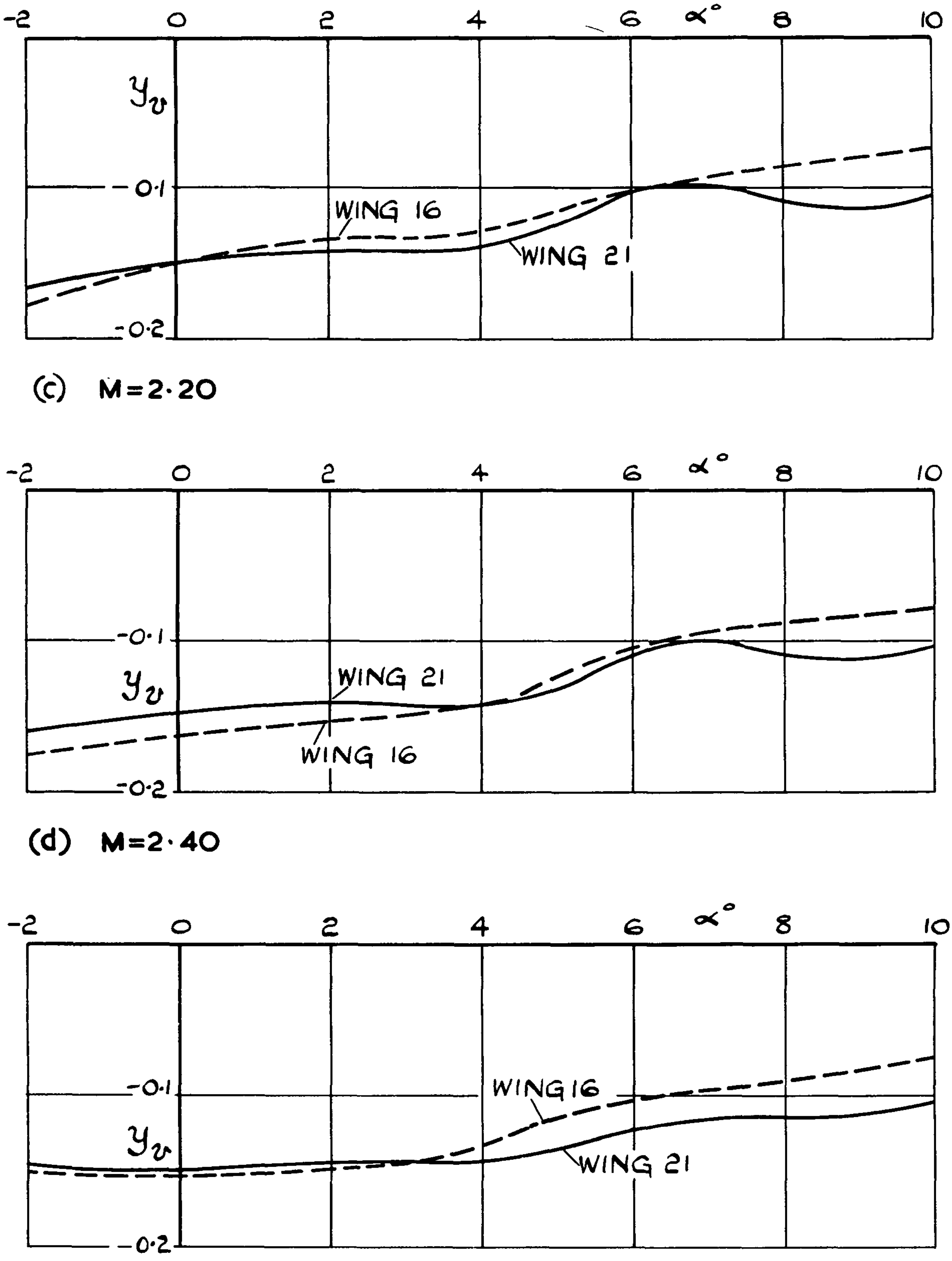


(a) M = 1·40



(b) M=1·80

FIG.9. y_v V. α AT SUPERSONIC SPEEDS.



(c) M=2·20

(d) M=2·40

(e) M=2·80

FIG.9. y_v V. α AT SUPERSONIC SPEEDS.

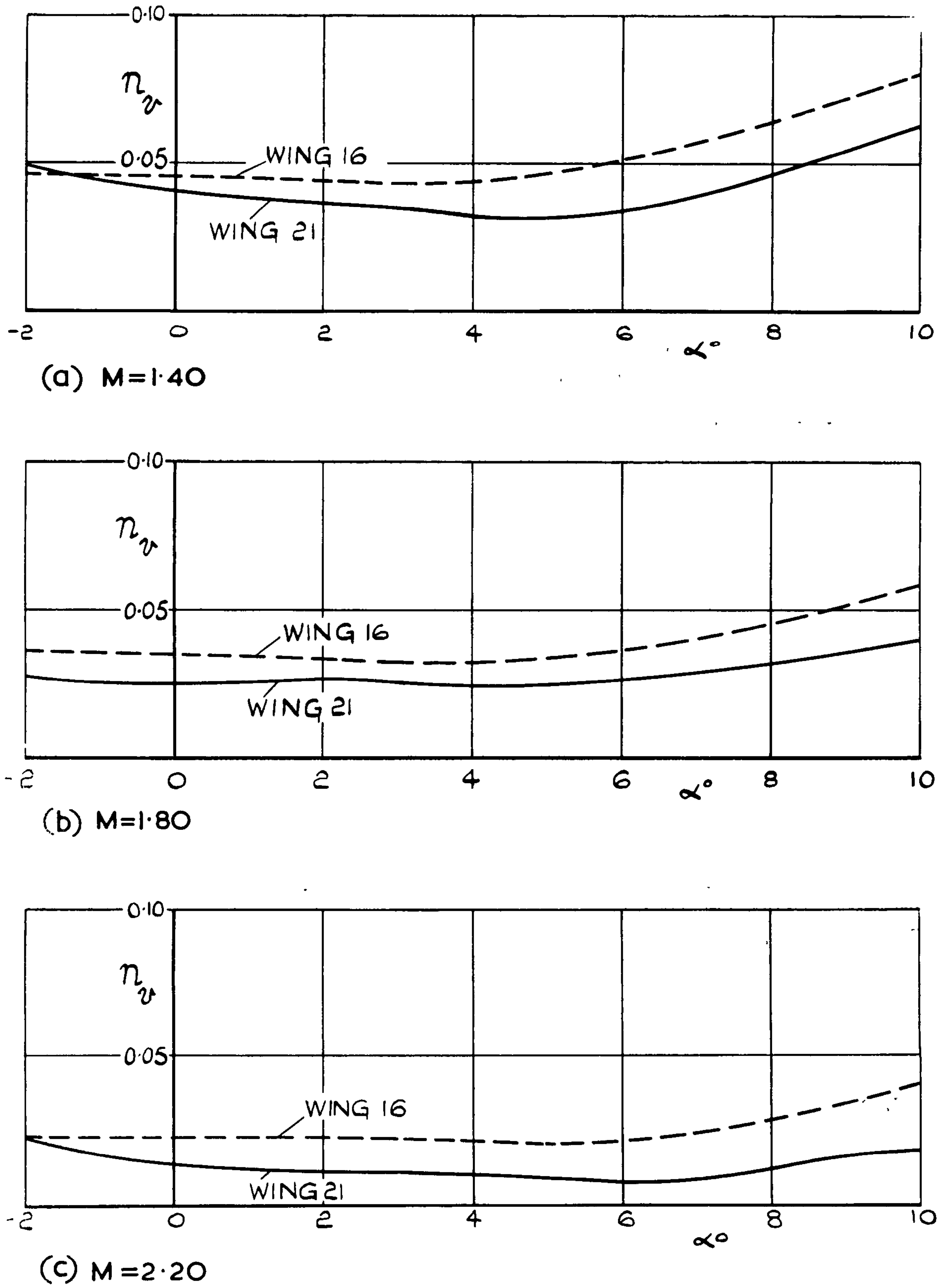
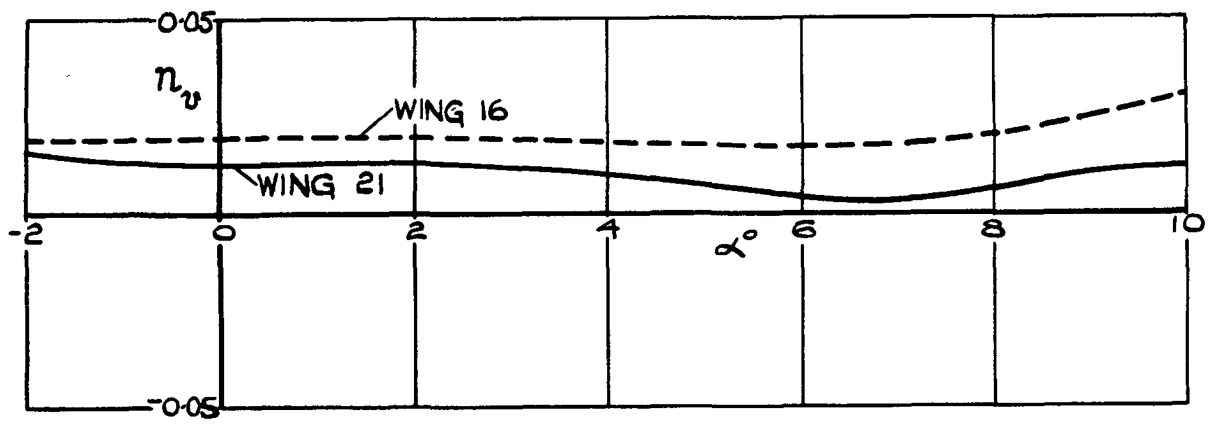
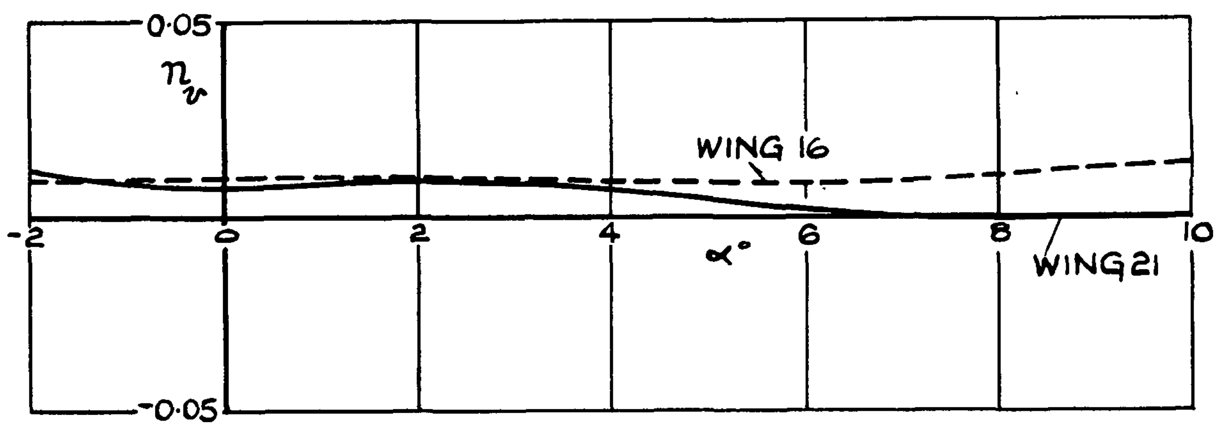


FIG.10. n_v V. α AT SUPERSONIC SPEEDS.



(d) M = 2·40



(e) M = 2·80

FIG. 10. (CONCLD.)

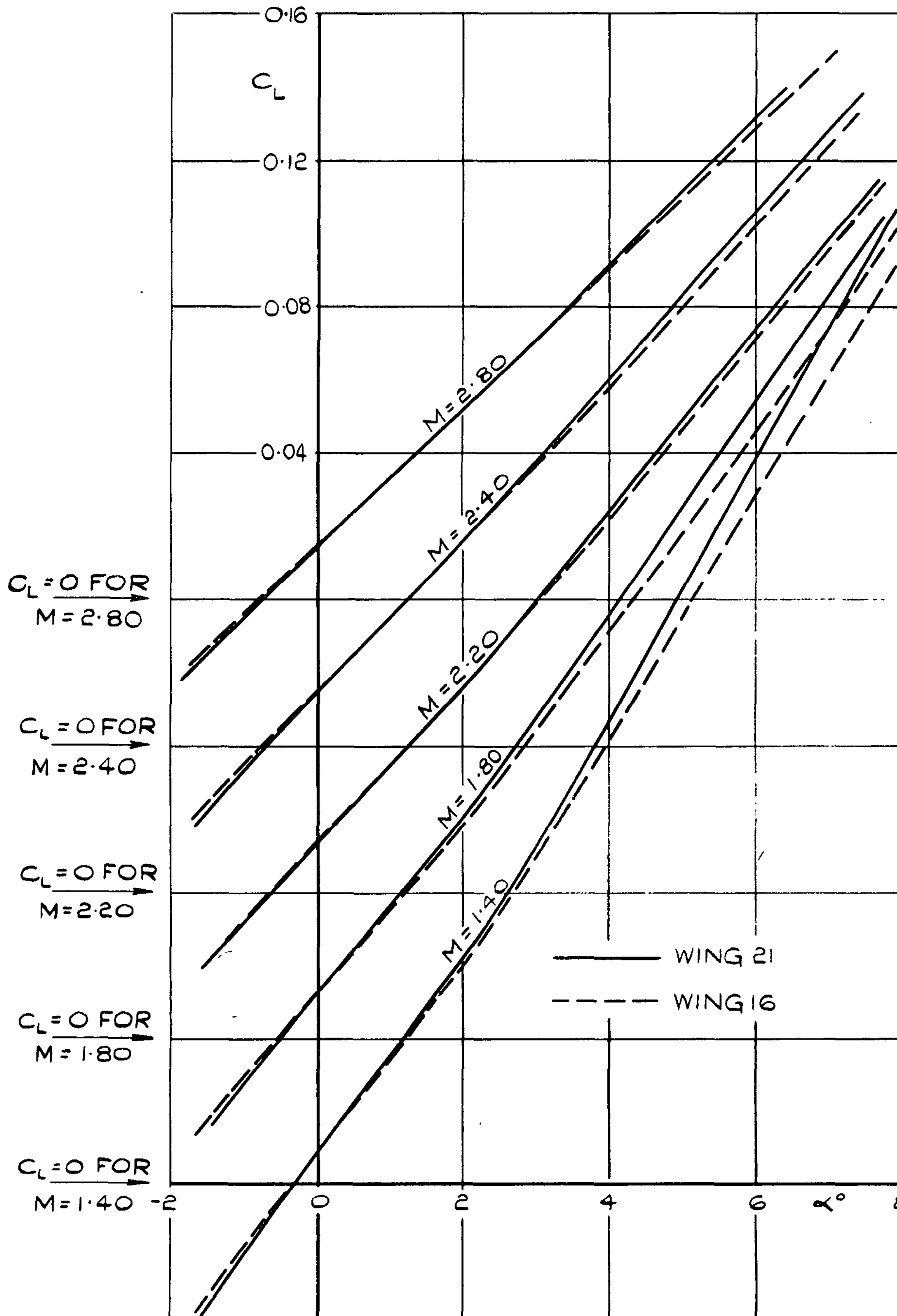


FIG. 11. VARIATION OF C_L WITH α AT SUPERSONIC SPEEDS.

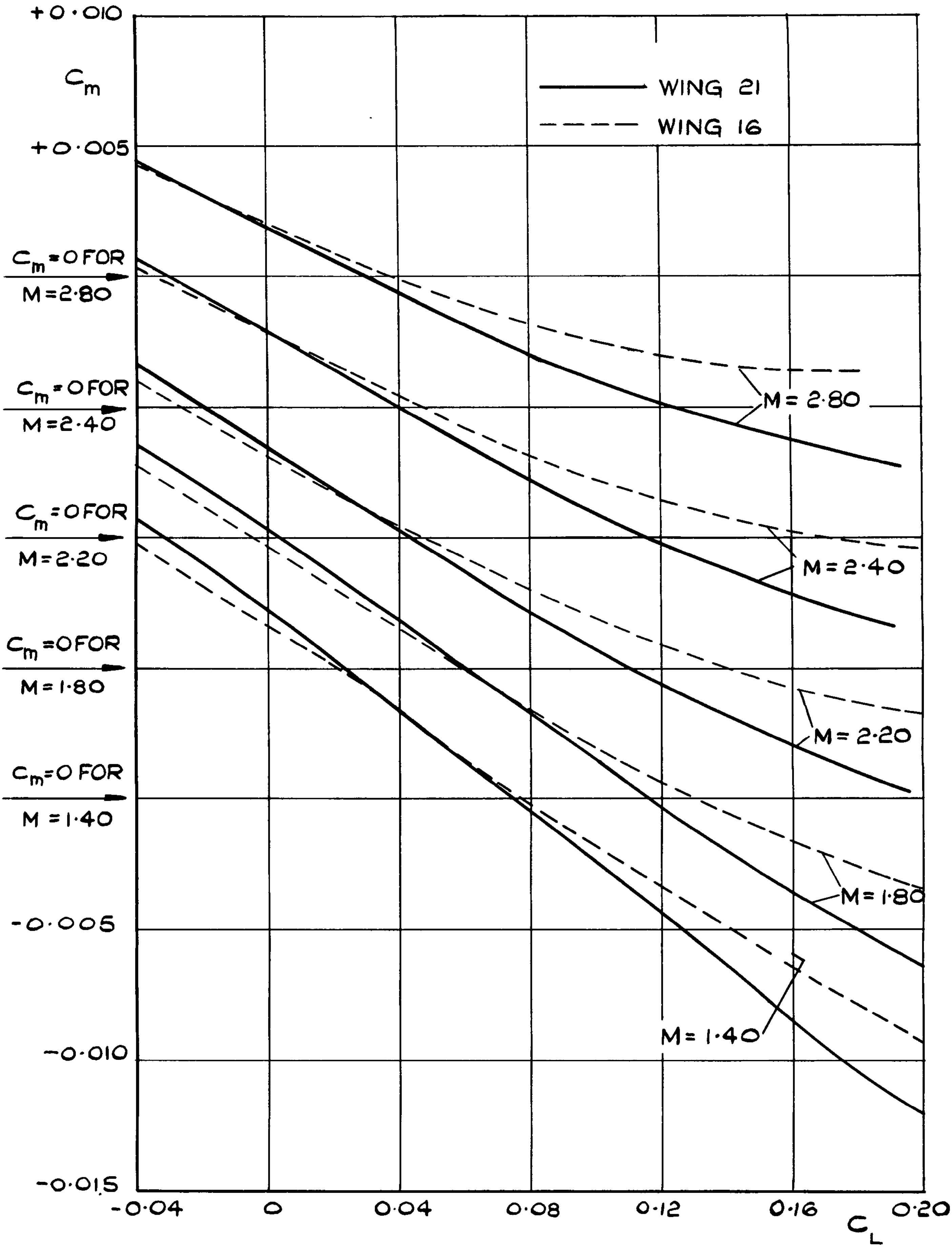


FIG. 12. VARIATION OF C_m WITH C_L AT SUPERSONIC SPEEDS.

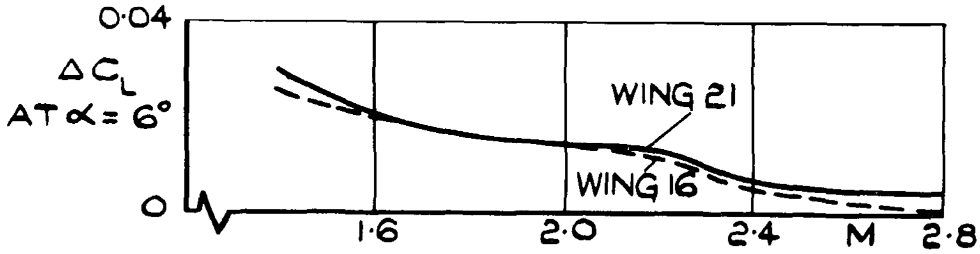


FIG.13. NON-LINEAR LIFT AT $\alpha = 6°$

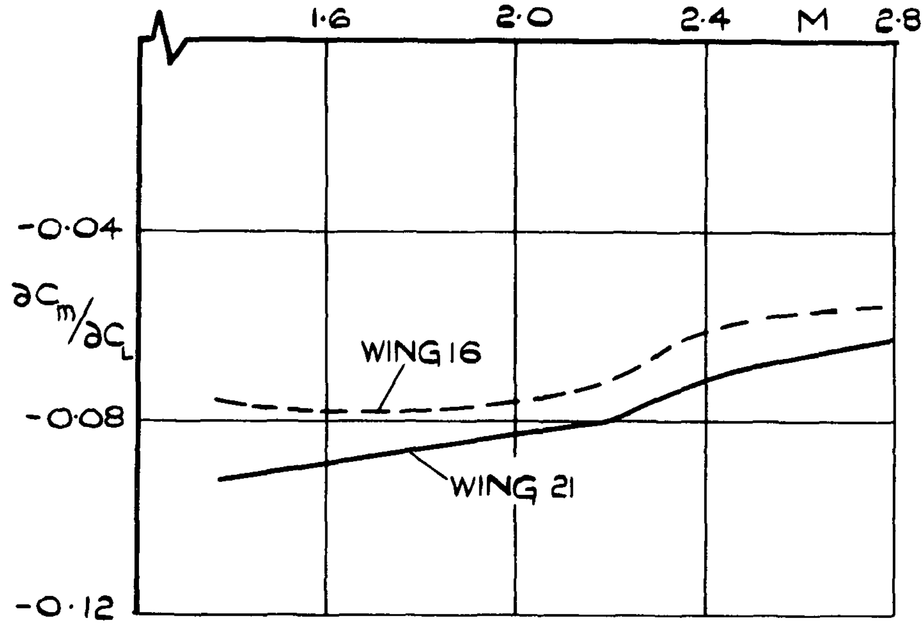
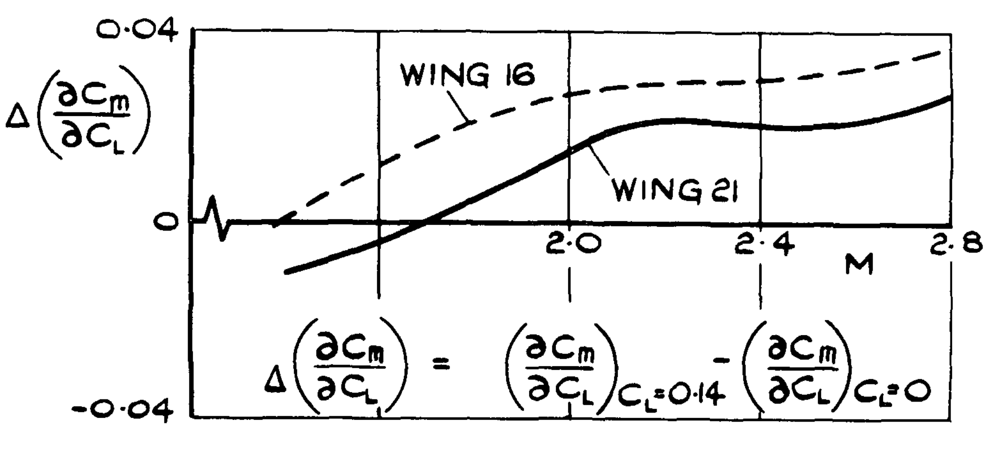


FIG.14. LONGITUDINAL STABILITY SLOPES AT ZERO LIFT.



$$\Delta\left(\frac{\partial C_m}{\partial C_L}\right) = \left(\frac{\partial C_m}{\partial C_L}\right)_{C_L=0\cdot14} - \left(\frac{\partial C_m}{\partial C_L}\right)_{C_L=0}$$

FIG.15. CHANGE IN $\partial C_m/\partial C_L$ DUE TO LIFT

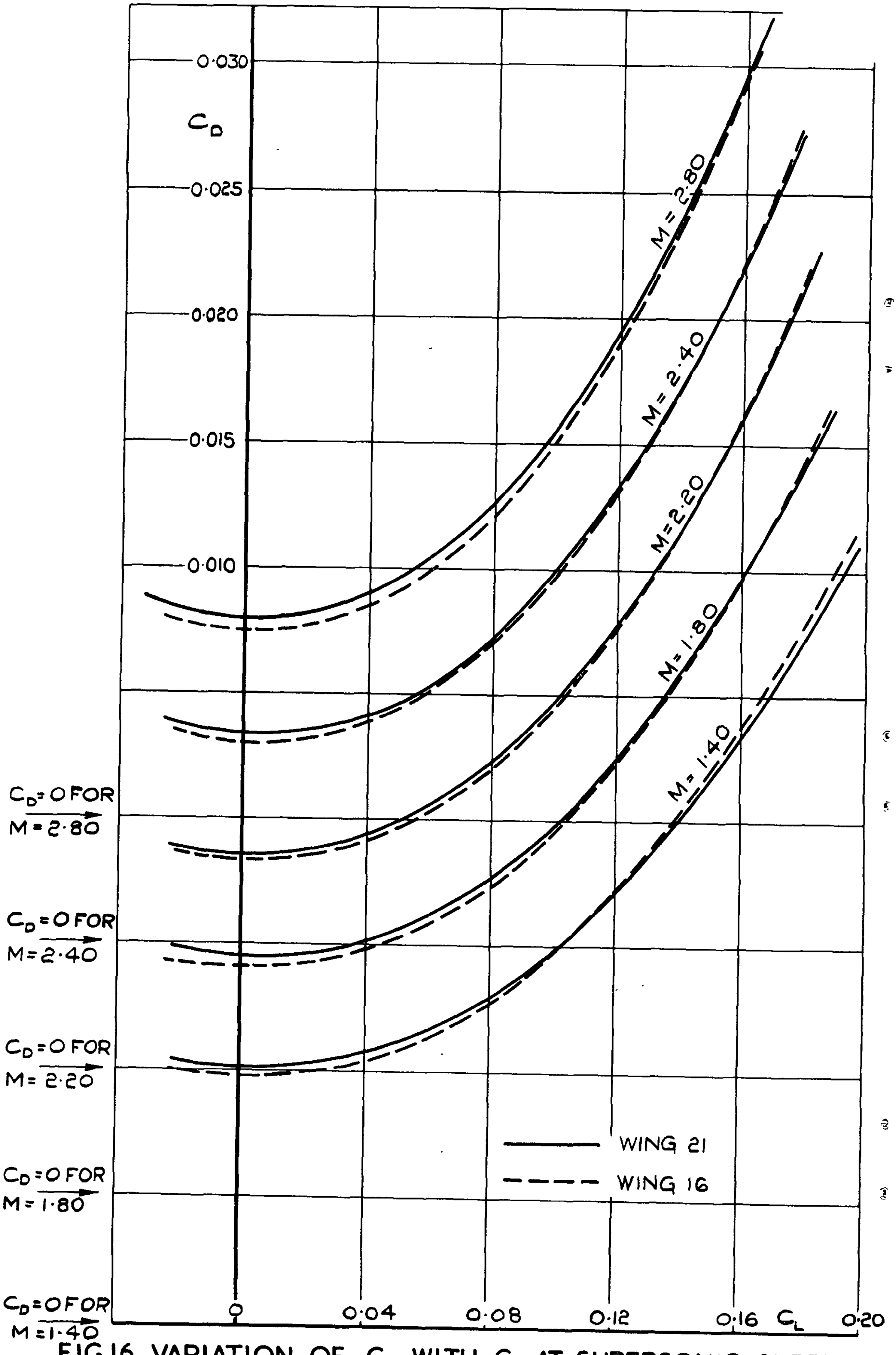


FIG.16. VARIATION OF C_D WITH C_L AT SUPERSONIC SPEEDS.

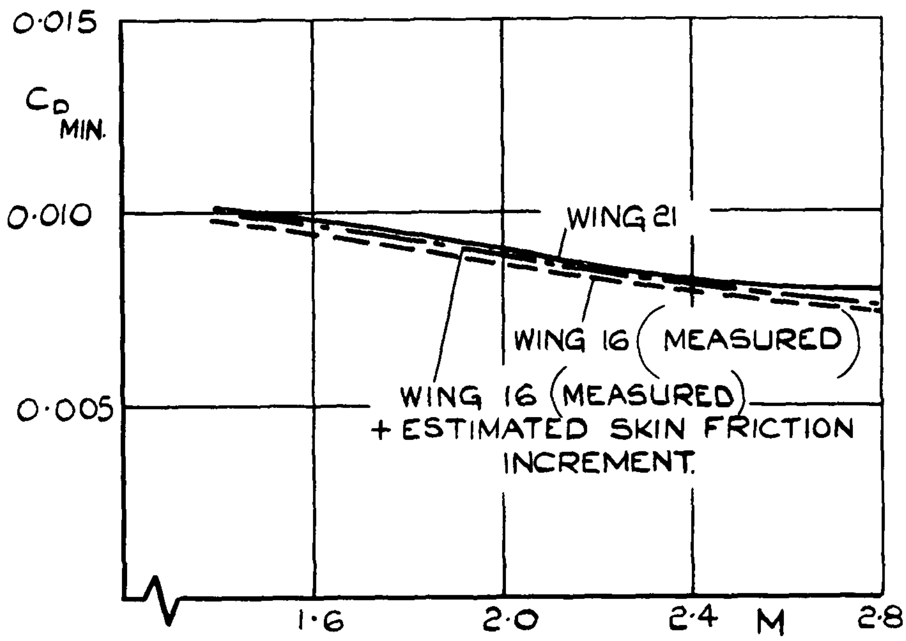


FIG.17. MINIMUM DRAG COEFFICIENTS.

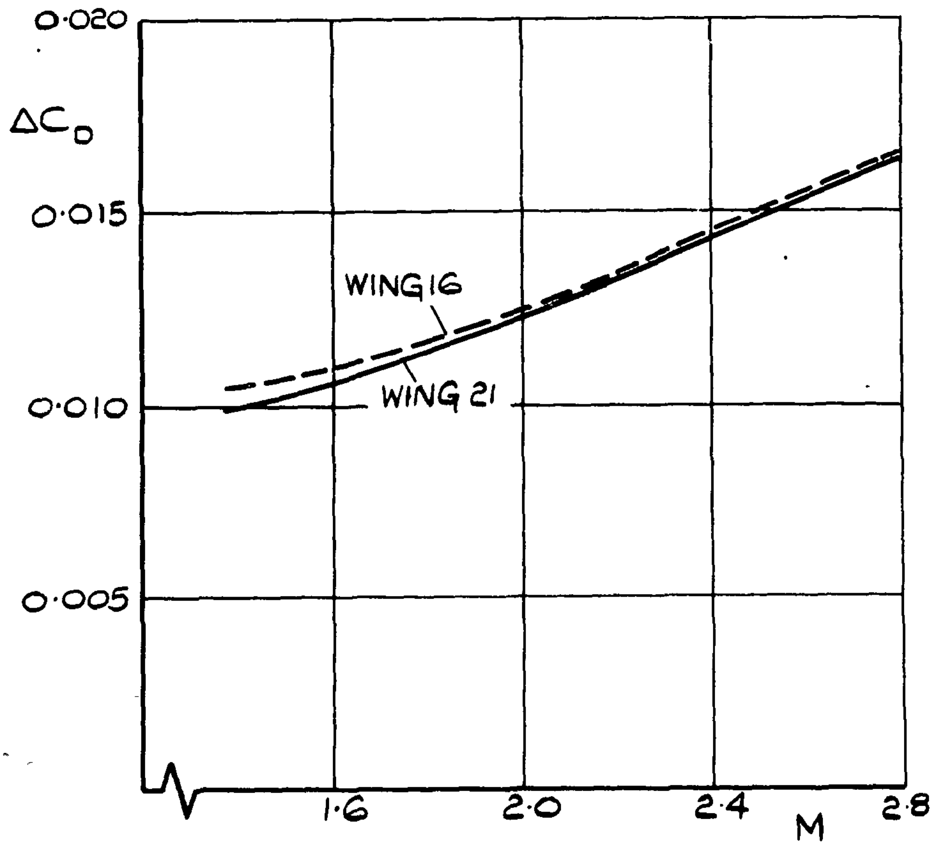


FIG.18. DRAG DUE TO LIFT AT $C_L = 0·14$.

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WIND TUNNEL MEASUREMENTS AT MACH NUMBERS UP TO 2.80 OF THE EFFECTS OF GULLING ON THE LONGITUDINAL AND LATERAL STABILITY AND DRAG OF A CAMBERED, SLENDER OGEE WING. Cook, T.A. August 1964.

Tests have been made at M = 0.31, 1.40, 1.80, 2.20, 2.40 and 2.80 on a cambered, slender ogee wing with spanwise camber designed to reduce the size of rolling moment due to sideslip at low speed. The results are compared with those for a similar model without spanwise camber and show that, at M = 0.31, gulling has resulted in loss of $-\ell_v$ as required, together with reductions in y_v and n_v and an increase in non-linear lift, probably at the drooped tips. Similar effects are obtained at supersonic speeds, though the effect of gulling on $-\ell_v$ diminishes with increasing Mach number.

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(Over)

At supersonic speeds, there is a small increase of drag at zero lift, which appears to be explained by the increase of surface area of the gulled wing.

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