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TECHNICAL NOTE

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OFF-DESIGN AERODYNAMIC CHARACTERISTICS AT MACH NUMBERS 1.61 AND 2.20 OF A SERIES OF HIGHLY SWEPT ARROW WINGS DESIGNED FOR MACH NUMBER 2.0 EMPLOYING VARIOUS DEGREES OF TWIST AND CAMBER

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SUMMARY

A series of five highly swept arrow wings was tested to investigate their respective "off-design" performance. Aerodynamic characteristics of the family of wings, which was designed for Mach number 2.0 employing design lift coefficients of 0, 0.08, and 0.16, were measured at Mach numbers of 1.61 and 2.20 and a Reynolds number, based on the mean aerodynamic chord, of 4.4×10^6.

A 70° swept arrow wing of aspect ratio 2.24 with moderate twist and camber (design lift coefficient of 0.08), which had produced the highest lift-drag ratio during design Mach number 2.0 tests, likewise produced the highest lift-drag ratios during the off-design tests. This wing gave maximum lift-drag ratios of 9.2, 8.8, and 8.4 at Mach numbers of 1.61, 2.05, and 2.20, respectively, compared with maximum lift-drag ratios of 8.1, 8.1, and 7.8 for the corresponding flat wing over the same Mach number range. Two twisted and cambered wings (of 70° and 75° leading-edge sweep) designed for a lift coefficient of 0.16 exhibited relatively minor superiority in lift-drag ratios over the flat wings throughout the Mach number range and became approximately equal in maximum lift-drag ratio to the flat wings at a Mach number of 2.20.

INTRODUCTION

Several tests of highly swept, twisted and cambered arrow wings have been conducted to investigate the aerodynamic efficiency of these wing shapes at the design Mach number. (For example, see refs. 1 and 2.) However, it has been realized that the tailoring of a wing through twist and camber techniques to produce low drag due to lift at some particular design point might penalize the wing during "off-design" operation to such an extent that its overall usefulness would be severely compromised.

Only moderate experimental success has been achieved in obtaining the low-drag-due-to-lift characteristics of warped arrow wings that are predicted by linear theory. (See ref. 2.) Sufficient response to the general twist and camber concept has been demonstrated, however, that the off-design performance of these wings has become of interest.

In order to establish some of the off-design characteristics of a twisted and cambered arrow-wing series, a family of five wings (three with 70° of sweep and an aspect ratio of 2.24 and two with 75° of sweep and an aspect ratio of 1.65) was tested in the Langley 4- by 4-foot supersonic pressure tunnel at Mach numbers of 1.61 and 2.20. These wings were originally developed and tested to investigate twist and camber effects at Mach number 2.0, employing design lift coefficients of 0 (flat wing), 0.08, and 0.16, as reported in references 1 and 3. Although the warped wings of this series failed to match their theoretical prediction, they did produce higher maximum lift-drag ratios at Mach number 2.0 than did the flat wings. In particular, the 70° sweptback wing employing a design lift coefficient of 0.08 produced a maximum lift-drag ratio of 8.8 compared with a value of 8.1 for the flat wing. (See ref. 1.)

SYMBOLS

All forces and moments were referred to the wind axis system with the moment center at the longitudinal station at which the 25-percent station of the mean aerodynamic chord is located.

$\bar{c}$ mean aerodynamic chord

C_D drag coefficient, $\frac{\text{Drag}}{qS}$

C_L lift coefficient, $\frac{\text{Lift}}{qS}$

$\frac{\Delta C_D}{\Delta C_L{}^2}$ slope of parabolic drag polar, referred to as drag-due-to-lift factor

C_{L_α} lift-curve slope, $\frac{dC_L}{d\alpha}$, per radian

C_m pitching-moment coefficient about $\bar{c}/4$, $\frac{\text{Pitching moment}}{qS\bar{c}}$

L/D lift-drag ratio, C_L/C_D

M free-stream Mach number

q free-stream dynamic pressure

R	free-stream Reynolds number based on $\bar{c}$
S	wing area, half-span model
α	angle of attack of wing reference plane (see ref. 1)
Λ	wing leading-edge sweepback angle

Subscripts:

max	maximum
min	minimum

MODELS AND INSTRUMENTATION

A sketch of the wing installations in the tunnel is shown in figure 1. The wings, all of which were half-span models, were mounted by means of a stub at the wing root to a four-component strain-gage balance located within a horizontal boundary-layer bypass plate, as shown schematically in the figure. In order to pitch the model, the entire plate-balance-model arrangement was rotated about an axis normal to the plate. A minimal clearance of 0.010 to 0.020 inch was provided between the wing root and the surface of the boundary-layer bypass plate (except where the wing attached to the balance) in order to minimize airflow bleeding through the root chord gap.

The aerodynamic description of the five wings (designated wings 1 to 5) is presented in figure 2. Wings 1 to 3 had a 70° swept leading edge and an aspect ratio (full span) of 2.24. These wings were designed, through use of a restricted twist and camber theory, to produce a minimum drag (in comparison with that produced for other wings in the family) at a certain lift coefficient. These design lift coefficients were 0, 0.08, and 0.16 for wings 1, 2, and 3, respectively. (A design lift coefficient of 0 corresponds to a flat wing.) Wings 4 and 5 had the same notch ratio (0.35) as the first three wings but had a 75° swept leading edge, which resulted in an aspect ratio of 1.65. The design lift coefficients for wings 4 and 5 were 0 and 0.16, respectively.

Thickness distributions for all the wings were determined by a 3-percent-thick biconvex airfoil section in the streamwise direction wrapped symmetrically about the wing camber surface. The design theory and a detailed description of the camber surfaces for the warped wings are presented in reference 1.

TEST CONDITIONS

The tests were conducted in the Langley 4- by 4-foot supersonic pressure tunnel at free-stream Mach numbers of 1.61 and 2.20 and a Reynolds number, based on the mean aerodynamic chord, of 4.4×10^6. This Reynolds number is the same as that used in the investigation reported in reference 1 at Mach number 2.05.

Boundary-layer transition was fixed on the wings by 1/8-inch-wide bands of sparsely distributed No. 80 carborundum grit located 1/4 inch behind the wing leading edge. Minimum drags of the wings were measured over a wide Reynolds number range to ensure that fully turbulent flow was established over the wing surfaces at the test conditions.

Angle of attack was measured optically through the use of prisms recessed in the wing surface.

From pretest calibrations and data repeatability (including repeat runs of the data reported in ref. 1), the Mach number, angle of attack, and aerodynamic coefficients were estimated to be accurate within the following limits:

M	±0.01
α, deg	±0.05
C_D	±0.0003
C_L	±0.003
C_m	±0.001

RESULTS AND DISCUSSION

In investigating the off-design performance of the arrow-wing family that was tested, the wing of particular interest was wing 2 (design lift coefficient of 0.08, 70° sweepback). This wing had demonstrated significantly improved performance over the corresponding flat wing 1 during design Mach number 2.0 tests and produced a maximum lift-drag ratio of 8.8 compared with 8.1 for wing 1 at the test Reynolds number of 4.4×10^6. (See ref. 1.) The wings designed for a lift coefficient of 0.16 (wings 3 and 5) with twice the twist and camber of wing 2 had shown only modest improvement in lift-drag ratio over the corresponding flat wings.

Typical transition check data, taken to ensure the effectiveness of the carborundum strips in tripping the boundary layer, is presented for the flat wing (wing 1) in figure 3. Measured minimum drag coefficients as a function of Reynolds number up to the test Reynolds number of 4.4×10^6 are shown for Mach numbers of 1.61 and 2.20. Estimated minimum drag coefficients based on smooth-turbulent skin friction and calculated wave drag are also shown for comparison. At both Mach numbers, it is considered that fully turbulent flow was established over the wing surfaces at the test Reynolds number.

Standard three-component force data for the five wings are plotted in figures 4 and 5 for Mach numbers of 1.61 and 2.20, respectively, with data for wings of the same planform plotted on a single set of axes to aid in comparisons. These data exhibit trends very similar to the data taken during the design Mach number 2.0 tests (ref. 1). Plots of lift coefficient against angle of attack are characterized by shifts in level as a function of design lift coefficient, with little difference in slopes. This result is true also of the pitching-moment data in the case of the 70° swept wings. However, in the 75° swept wing case, some nonlinearity in the pitching-moment data is apparent, with the flat wing (wing 4) exhibiting a gradual decrease in stability at the higher lift coefficients, in a manner similar to the Mach number 2.0 measurements.

Plots of lift-drag ratio for the five wings are included in figures 4 and 5 as a function of lift coefficient. Cross plots of maximum lift-drag ratio against Mach number, including data from reference 1, are presented in figure 6. Of the 70° swept-wing series, wing 2 consistently developed higher lift-drag ratios than the other two wings throughout the Mach number range. Values of $(L/D)_{max}$ of 9.2, 8.8, and 8.4 were obtained for wing 2 at Mach numbers of 1.61, 2.05, and 2.20, respectively; values of 8.1, 8.1, and 7.8 were obtained for the flat wing 1 over the same Mach number range. Wing 3 had demonstrated only slightly higher maximum lift-drag ratio than wing 1 during the Mach number 2.05 testing; the increment in maximum lift-drag ratio between wing 3 and wing 1 decreased essentially to zero at Mach number 2.20, but increased considerably at Mach number 1.61. This behavior is perhaps due to the alleviating effect of reduced Mach number on the local sonic pressure-coefficient restriction discussed in references 1 and 2. At a given sweep angle, as the free-stream Mach number is decreased, higher lift coefficients may be attained without incurring sonic cross flow. Wings 4 and 5, of the 75° sweptback series, exhibited characteristics that were closely similar to those observed for wings 1 and 3. Although a model with a design lift coefficient of 0.08 was not constructed in the 75° sweptback series, it would be expected that the performance of such a model would resemble the performance of wing 2 (design lift coefficient of 0.08) of the 70° sweptback series. This conclusion is based upon the observed similarity of the data for the 70° and 75° sweptback series for each of the other two design lift coefficients (0 and 0.16).

From the data of figure 6, it is concluded that the off-design performance of twisted and cambered wings that perform well at the design lift condition is likely to be superior to that of otherwise identical flat wings. Or, stated another way, twisting and cambering a wing to generate a high lifting efficiency at a particular design condition will not result in drastic off-design penalties.

The drag-due-to-lift characteristics of the 70° swept-wing series are also summarized in figure 6. The experimental drag-due-to-lift factors $\Delta C_D/\Delta {C_L}^2$ were based upon a parabolic envelope polar defined by the design point of wing 2 and the minimum drag point of wing 1. (The drag of wing 3 was too high at the design point to be used in defining an optimum envelope for the series.) The envelope drag-due-to-lift factors were defined according to the following equation:

$$\frac{\Delta C_D}{\Delta {C_L}^2} = \frac{\left(C_{D,\text{wing 2}}\right)_{C_L=0.08} - \left(C_{D,\text{wing 1}}\right)_{C_L=0}}{(0.08)^2}$$

In comparison, the values corresponding to the wings without leading-edge thrust component $\left(\frac{1}{C_{L_\alpha}}, \text{experimental}\right)$ and the theoretical envelope drag-due-to-lift factors for twist and camber wing design (from ref. 2) are also shown, where the theoretical drag-due-to-lift curves apply only to on-design wings. In figure 6, it is of interest to note the parallel nature of the theoretical and measured drag-due-to-lift factors for Mach numbers below design compared with the rather rapid divergence of these factors at Mach numbers above design. This behavior again tends to emphasize the critical nature of the local sonic pressure-coefficient restriction, and the associated limitations on the linear supersonic theory.

CONCLUSIONS

An experimental investigation to determine the "off-design" aerodynamic characteristics in pitch at Mach numbers 1.61 and 2.20 of a twisted and cambered arrow-wing family designed for Mach number 2.0 has provided the following conclusions:

1. Twisting and cambering a wing to generate a high lifting efficiency at a particular design condition will not result in drastic off-design penalties.

2. The twisted and cambered arrow wing, which had produced the highest lift-drag ratio during the design Mach number 2.0 tests, likewise produced the highest lift-drag ratios during the off-design tests. This wing gave maximum lift-drag ratios of 9.2, 8.8, and 8.4 at Mach numbers of 1.61, 2.05, and 2.20, respectively, compared with maximum lift-drag ratios of 8.1, 8.1, and 7.8 for the corresponding flat wing over the same Mach number range.

3. Two twisted and cambered wings (of 70° and 75° leading-edge sweep) designed for a lift coefficient of 0.16 exhibited relatively minor superiority in lift-drag ratios over the flat wings throughout the Mach number range and became approximately equal in maximum lift-drag ratio to the flat wings at a Mach number of 2.20.

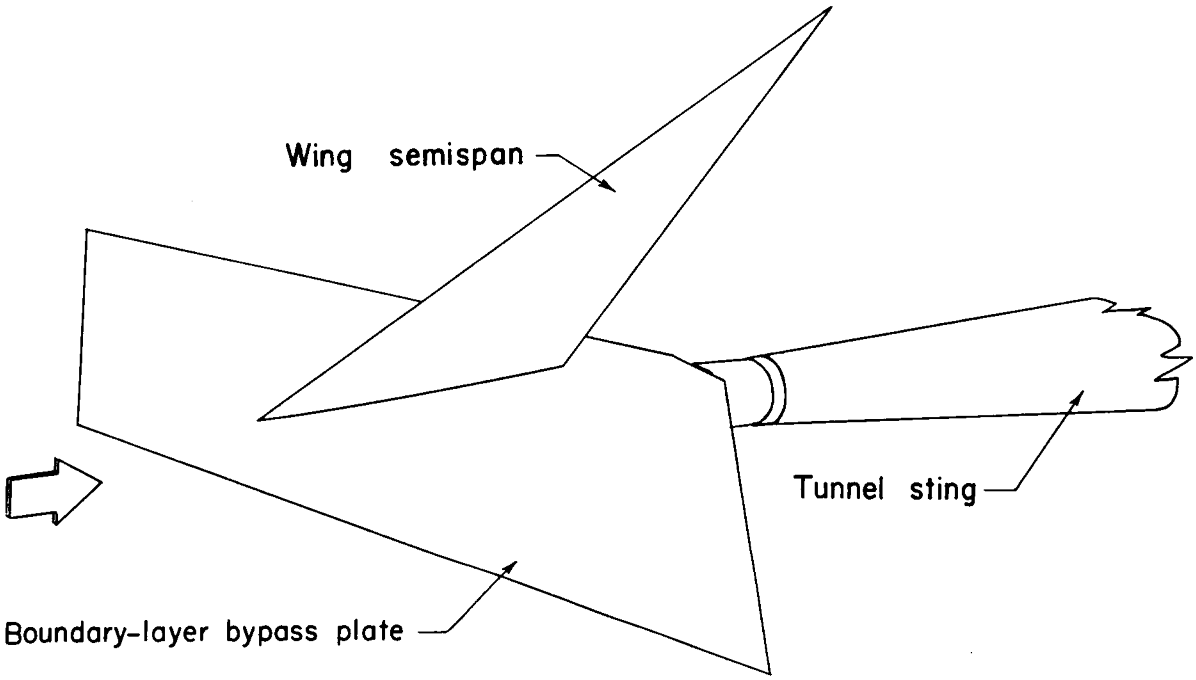
Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 14, 1963.

REFERENCES

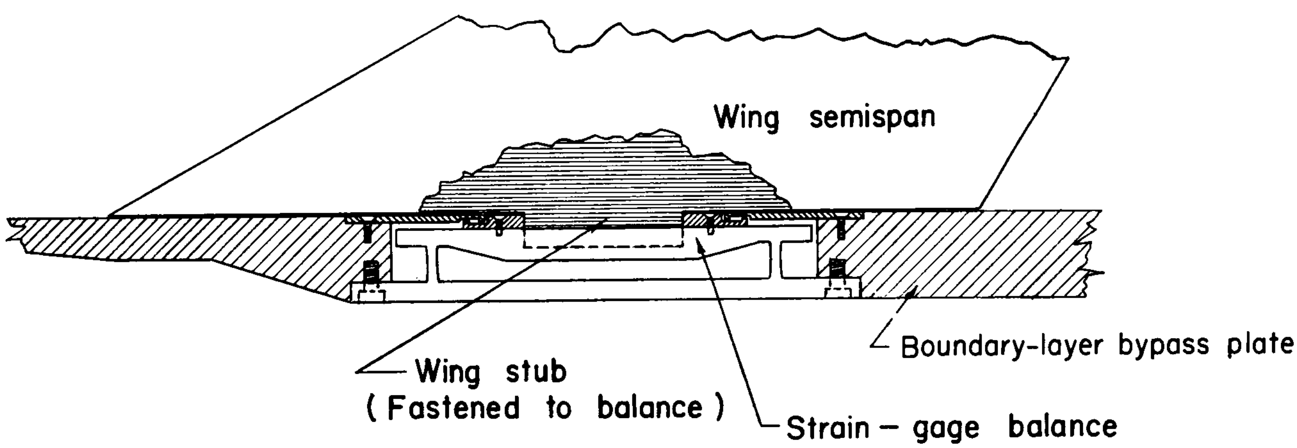
1. Carlson, Harry W.: Aerodynamic Characteristics at Mach Number 2.05 of a Series of Highly Swept Arrow Wings Employing Various Degrees of Twist and Camber. NASA TM X-332, 1960.

2. Brown, Clinton E., McLean, F. E., and Klunker, E. B.: Theoretical and Experimental Studies of Cambered and Twisted Wings Optimized for Flight at Supersonic Speeds. Advances in Aero. Sci., vol. 3, Pergamon Press (New York), 1961, pp. 415-430.

3. Carlson, Harry W.: Pressure Distributions at Mach Number 2.05 on a Series of Highly Swept Arrow Wings Employing Various Degrees of Twist and Camber. NASA TN D-1264, 1962.



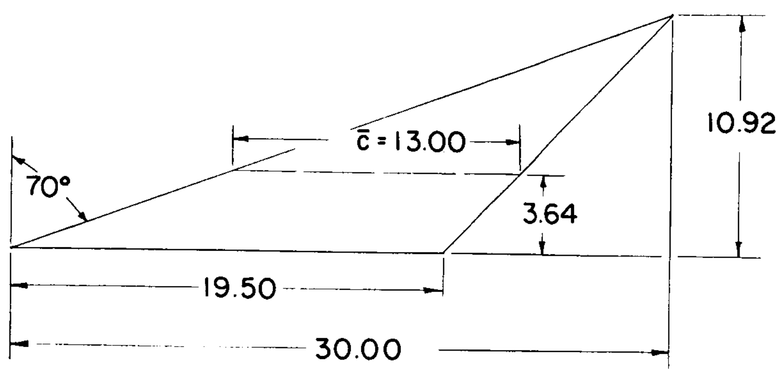
(a) Test rig in tunnel. Upper surface of boundary-layer bypass plate is parallel to tunnel flow.



(b) Plate-balance-model details.

Figure 1.- Sketch of test setup.

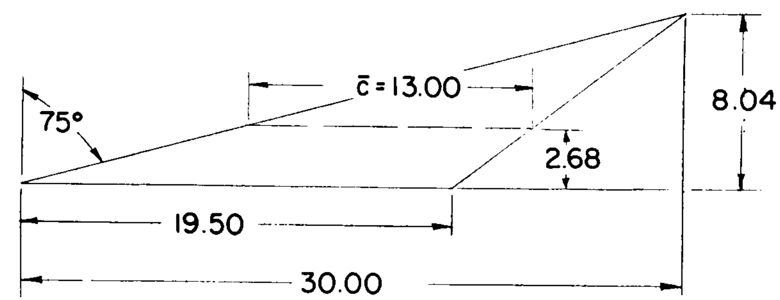
70° swept wing



Planform of wings 1, 2, and 3

Aspect ratio = 2.24
Notch ratio = 0.35
Design lift coefficient (Mach = 2.0):
Wing 1 = 0
Wing 2 = 0.08
Wing 3 = 0.16

75° swept wing



Planform of wings 4 and 5

Aspect ratio = 1.65
Notch ratio = 0.35
Design lift coefficient (Mach = 2.0):
Wing 4 = 0
Wing 5 = 0.16

Figure 2.- Aerodynamic description of arrow-wing family. All wings employed a 3-percent-thick biconvex streamwise airfoil section. (All dimensions in inches; see ref. 1 for ordinates of wing camber surfaces.)

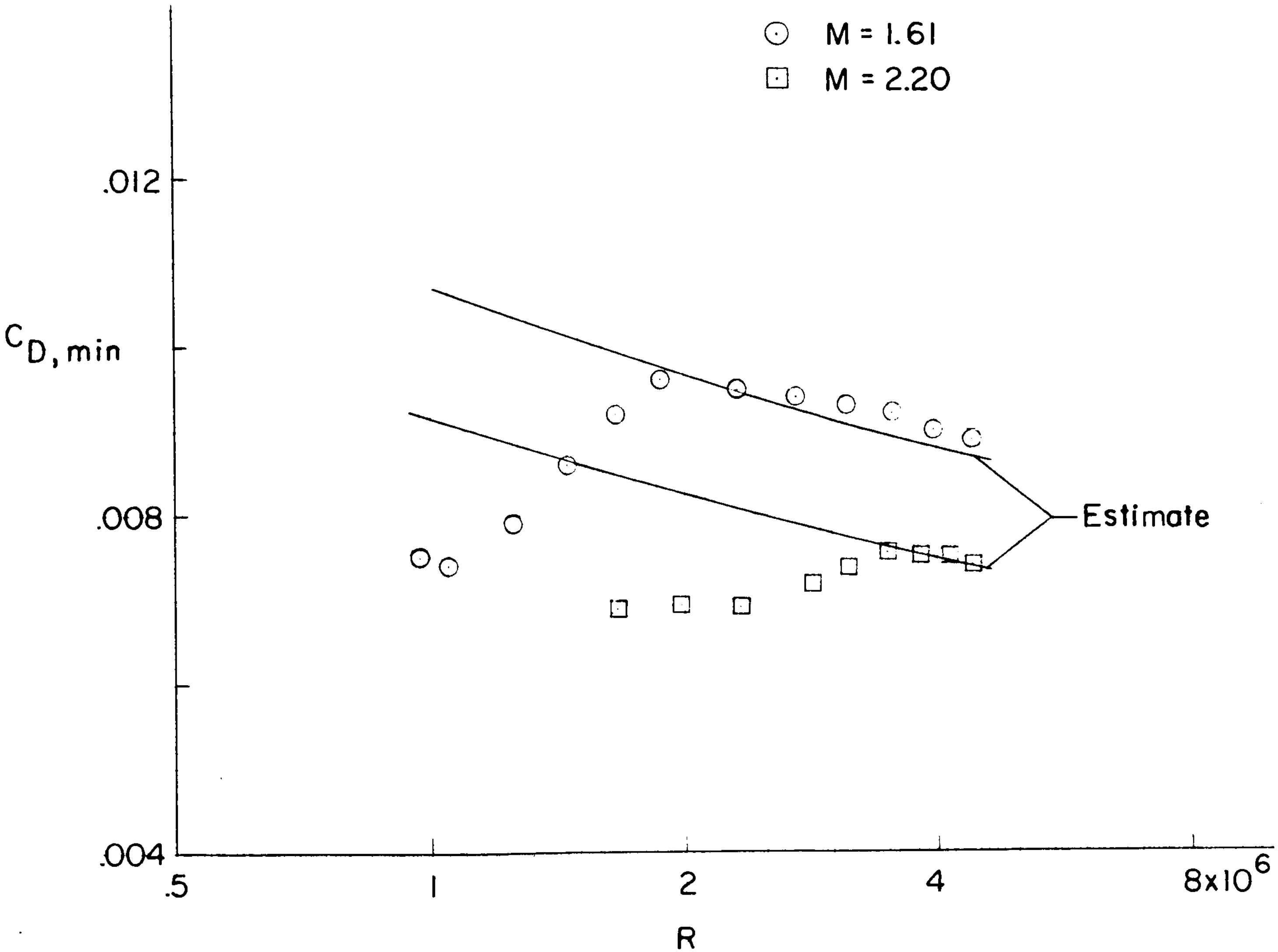
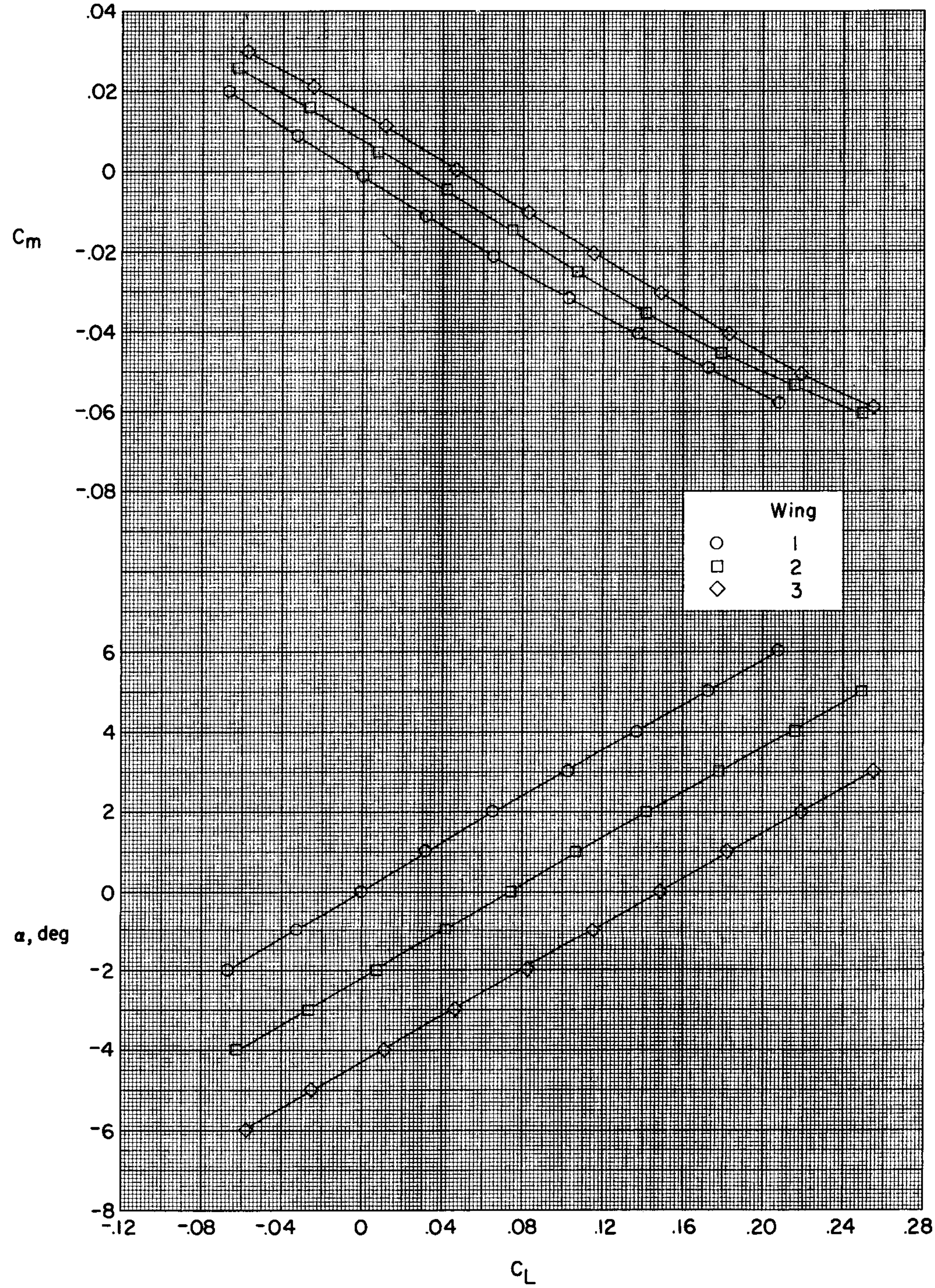
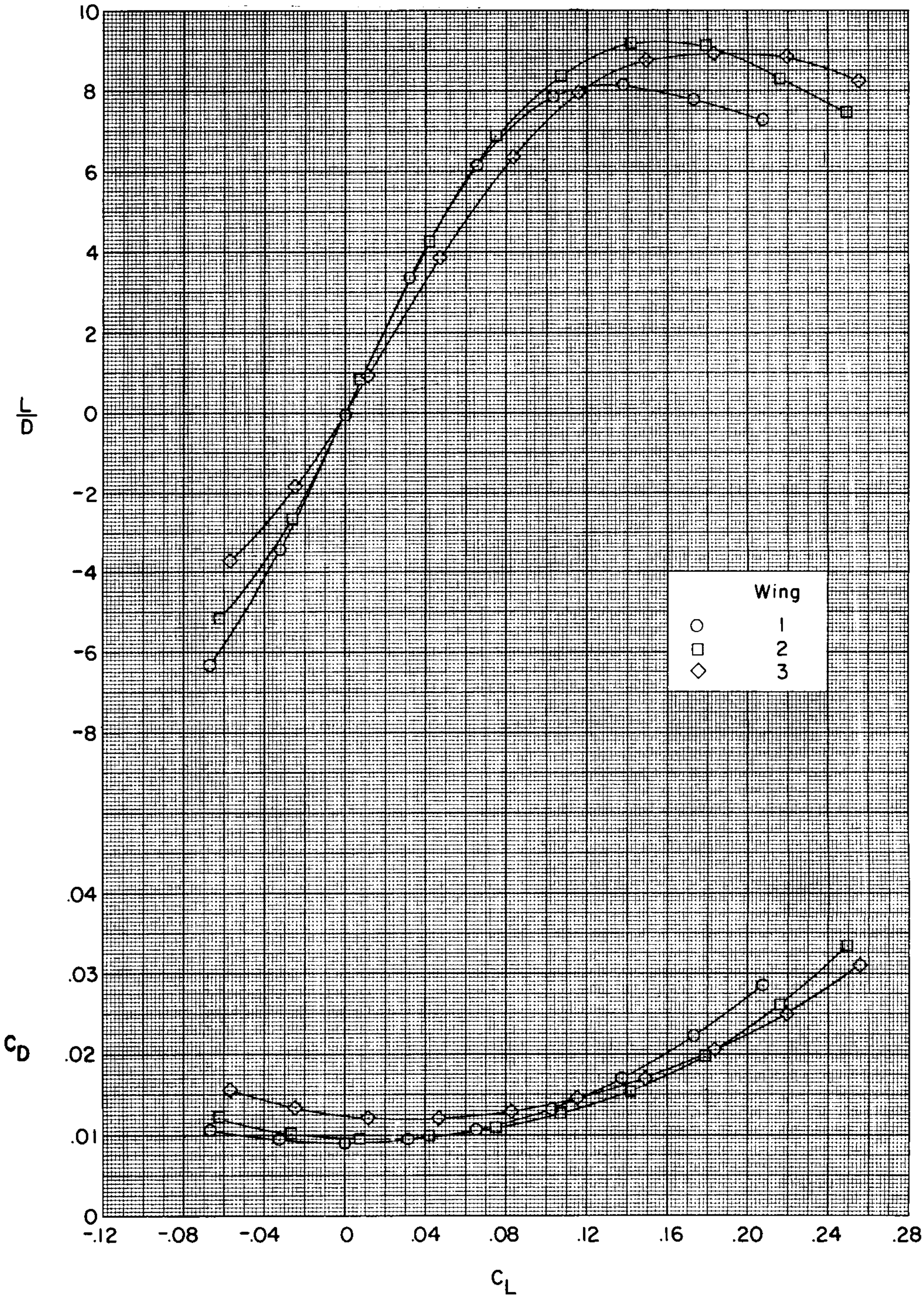


Figure 3.- Variation of minimum drag coefficient with Reynolds number. Wing 1.



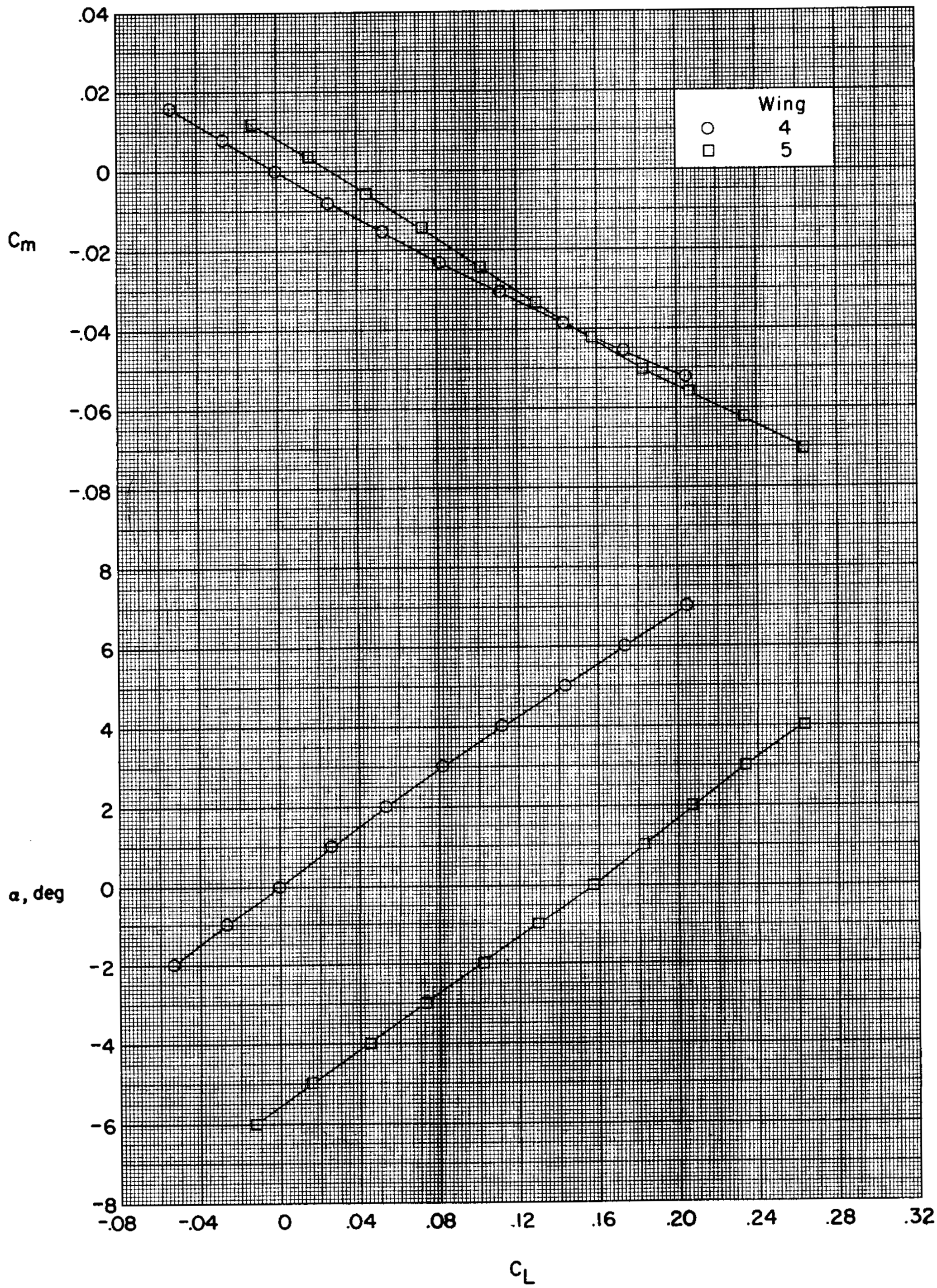
(a) $\Lambda = 70^{\circ}$.

Figure 4.- Effect of twist and camber on the aerodynamic characteristics in pitch. M = 1.61.



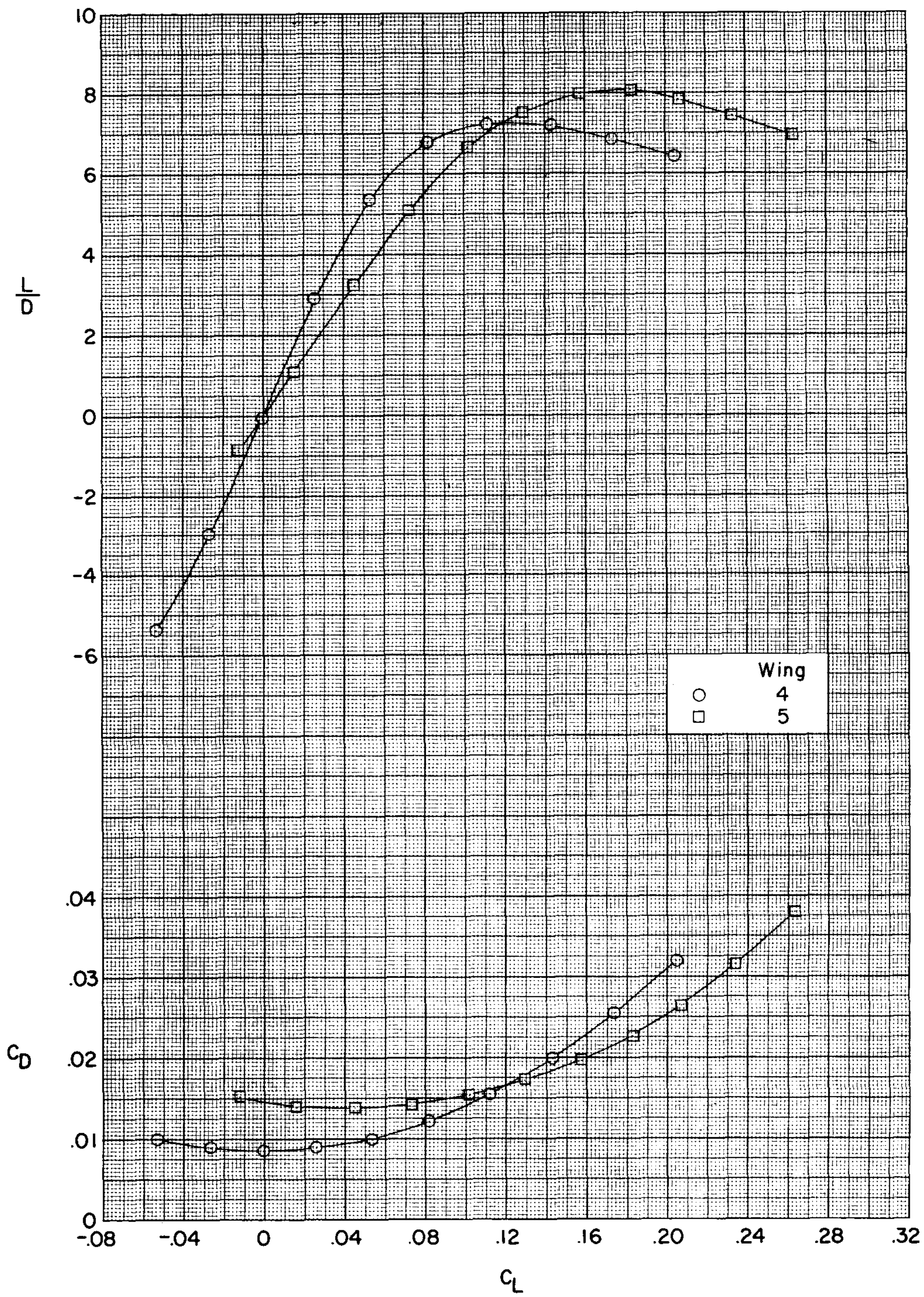
(a) $\Lambda = 70^{\circ}$. Concluded.

Figure 4.- M = 1.61. Continued.



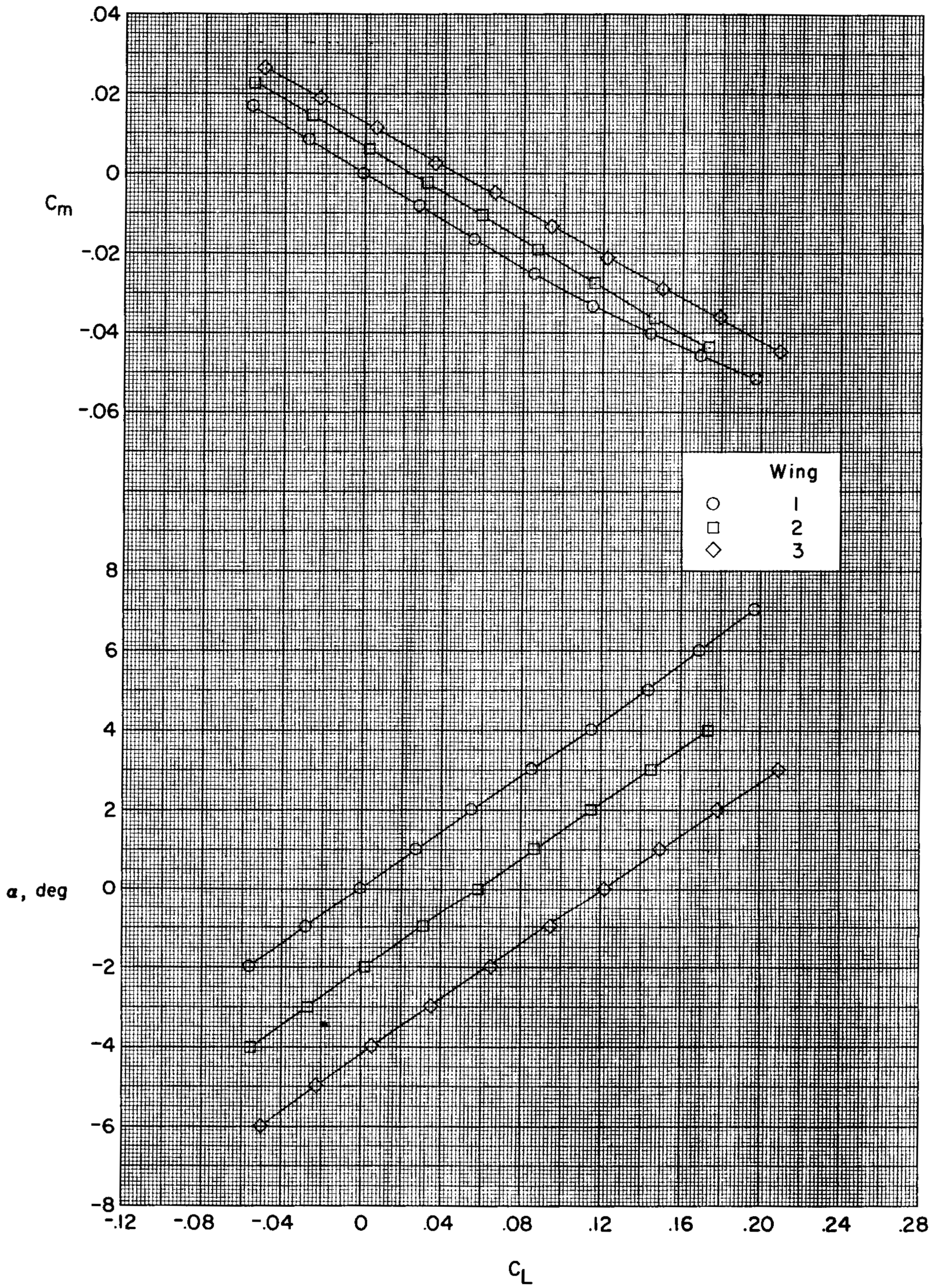
(b) $\Lambda = 75^{\circ}$.

Figure 4.- M = 1.61. Continued.



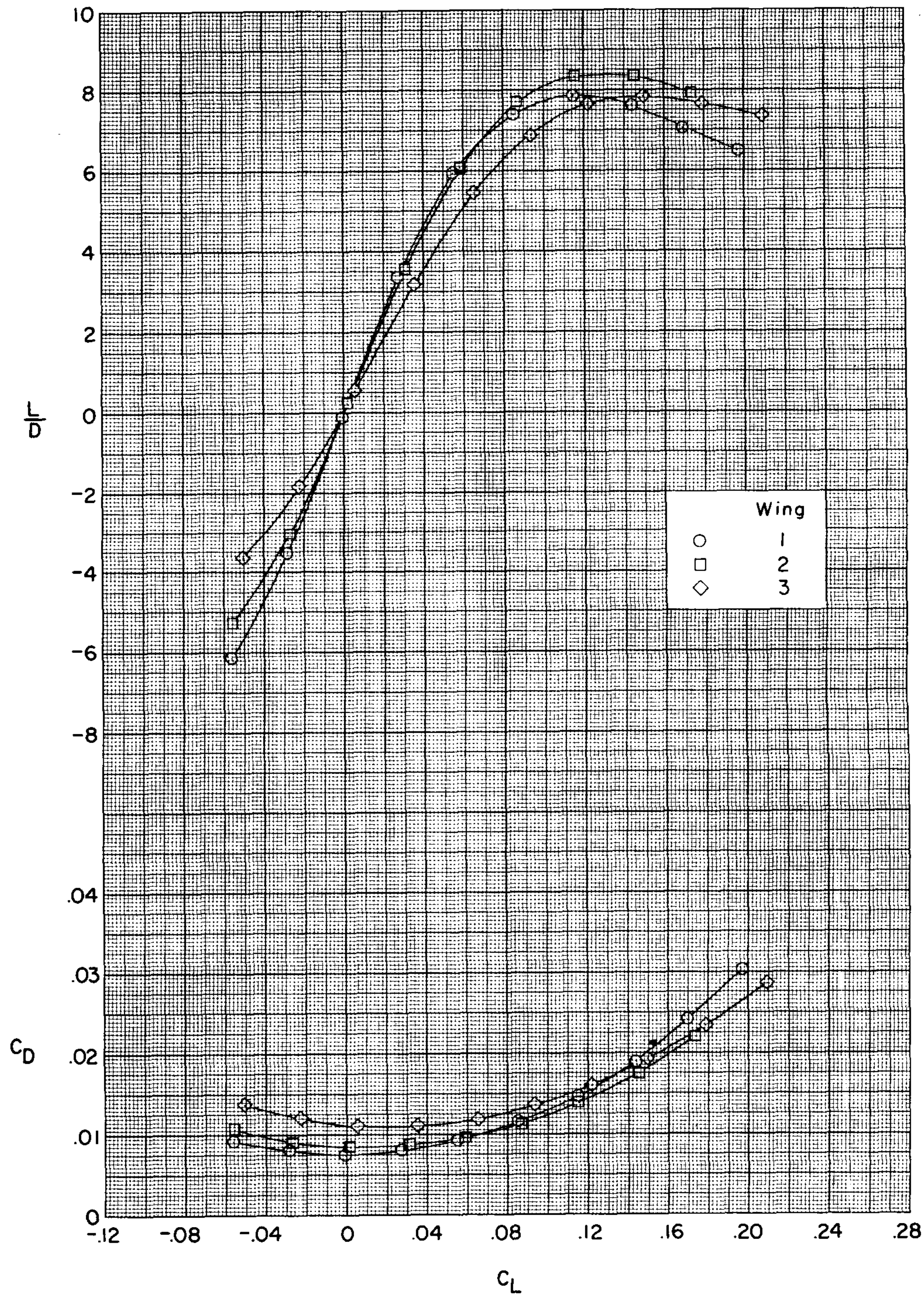
(b) $\Lambda = 75^\circ$. Concluded.

Figure 4.- M = 1.61. Concluded.



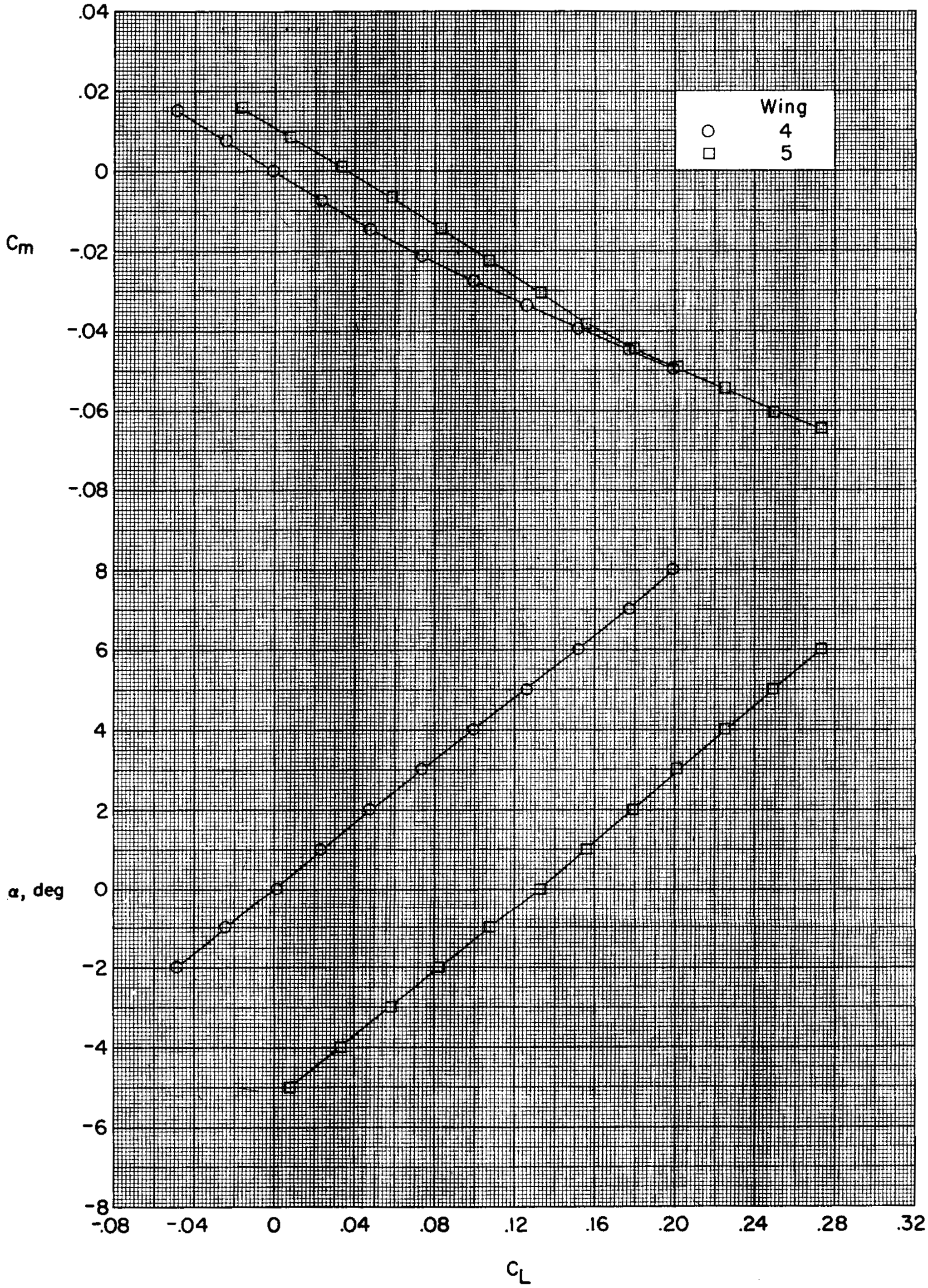
(a) $\Lambda = 70^{\circ}$.

Figure 5.- Effect of twist and camber on the aerodynamic characteristics in pitch. M = 2.20.



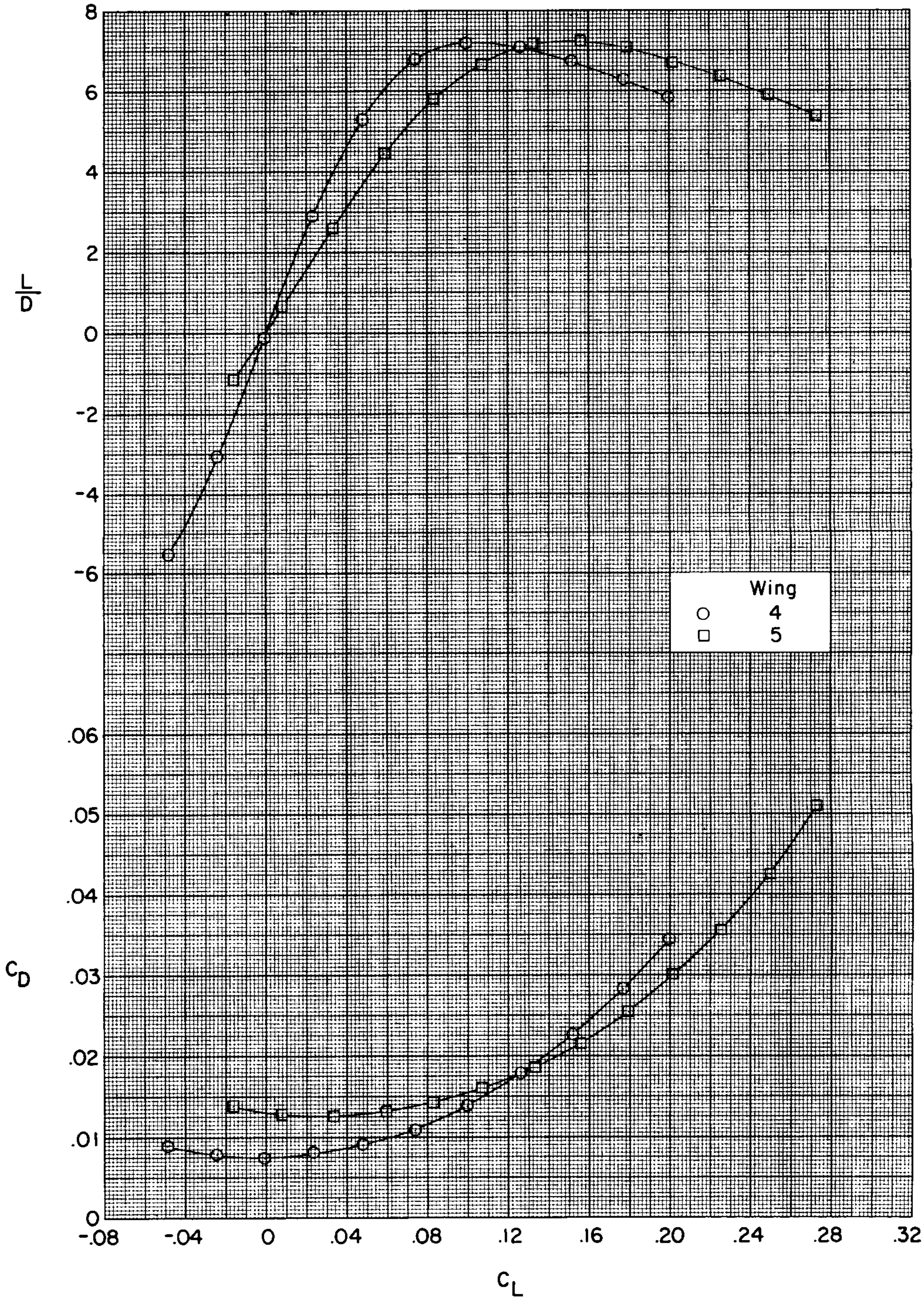
(a) $\Lambda = 70^{\circ}$. Concluded.

Figure 5.- M = 2.20. Continued.



(b) $\Lambda = 75^{\circ}$.

Figure 5.- M = 2.20. Continued.



(b) $\Lambda = 75^{\circ}$. Concluded.

Figure 5.- M = 2.20. Concluded.

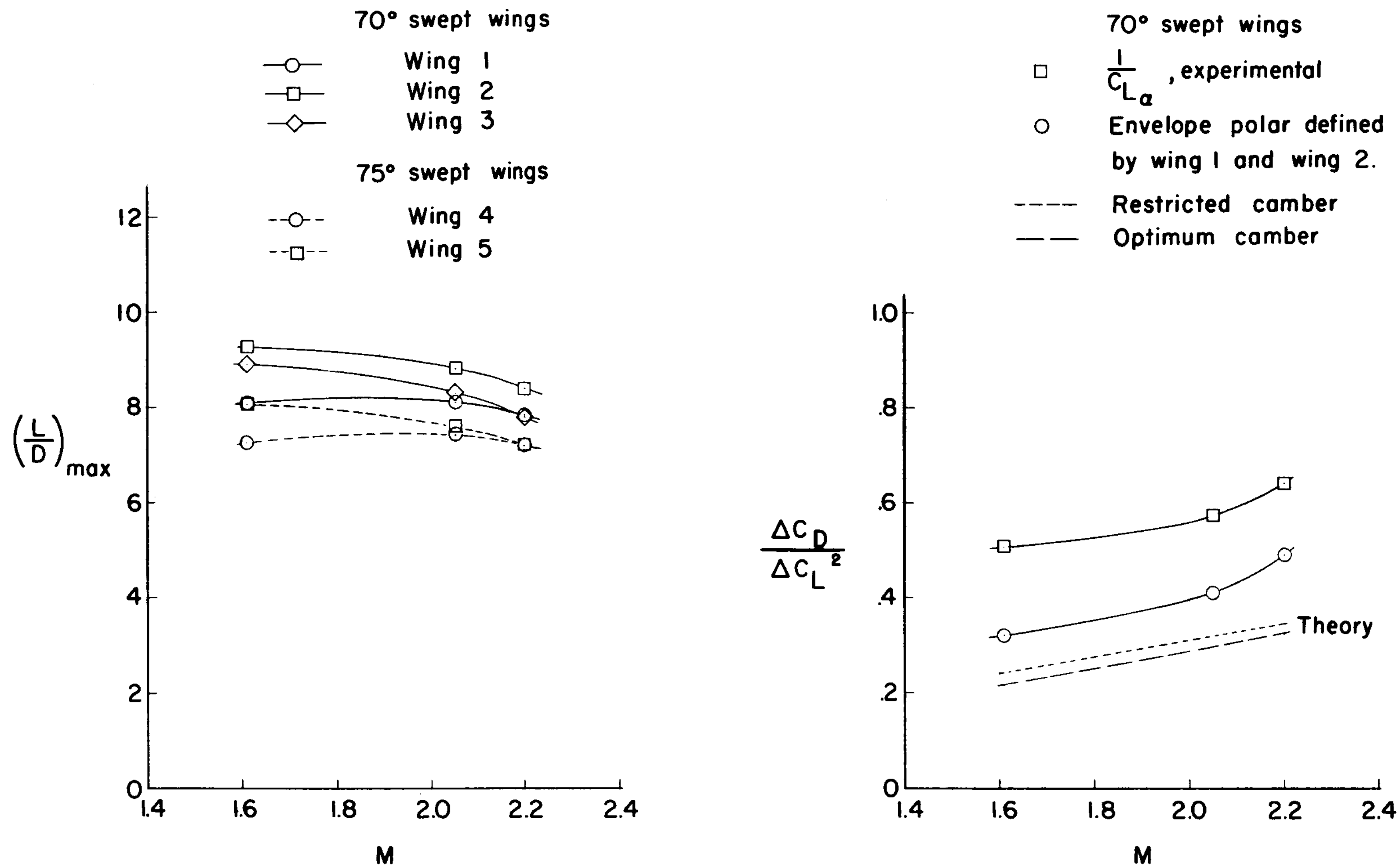


Figure 6.- Maximum lift-drag ratio and drag-due-to-lift factor for arrow-wing series. Notch ratio = 0.35; R = 4.4×10^6. (Data at Mach 2.05 from ref. 1; theoretical drag-due-to-lift factors from ref. 2.)