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AERODYNAMIC CHARACTERISTICS OF AN OBLATE SPHEROID AND A SPHERE AT MACH NUMBERS FROM 1.70 TO 10.49

by Lloyd S. Jernell

Langley Research Center
Langley Station, Hampton, Va.

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16. Abstract

A wind-tunnel investigation was conducted to determine the stability and drag characteristics of an oblate spheroid at angles of attack from approximately -4° to 12°. Drag coefficients on spheres were obtained for comparison. The results are compared with modified Newtonian theory and several empirical expressions.

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AERODYNAMIC CHARACTERISTICS OF AN OBLATE SPHEROID AND A SPHERE AT MACH NUMBERS FROM 1.70 TO 10.49

By Lloyd S. Jernell
Langley Research Center

SUMMARY

An investigation has been conducted in the Langley Unitary Plan wind tunnel and the Langley continuous-flow hypersonic tunnel to determine the aerodynamic characteristics of an oblate spheroid at angles of attack from approximately -4° to 12° and Mach numbers from 1.70 to 10.49. Drag coefficients on spheres were obtained for comparison.

Both the pitching-moment and lift coefficients of the oblate spheroid show small nonlinearities with angle of attack at the lower test Mach numbers. However, for the test Mach numbers of 2.96 and greater, these data are linear and essentially unaffected by Mach number.

The center-of-pressure location of the oblate spheroid exhibits some effect of angle of attack and Mach number at the lower test Mach numbers. However, for Mach numbers from approximately 2.7 to 10.5, the center-of-pressure location is invariant at 0.575 body diameter rearward of the theoretical sphere stagnation point.

The empirical expression developed in the present investigation for the pressure distribution over a hemispherical forebody is in good agreement with the experimental data for the following approximate ranges: θ from 0° to 60° for a Mach number from 3 to 10, and θ from 0° to 90° for a Mach number from 6 to 10, where θ is the angle between a normal to the local surface and the model center line.

The experimental total drag coefficients of the oblate spheroid are approximately 10 percent greater than those of the sphere throughout the Mach number range. The data for both configurations exhibit maximum values at the lower test Mach numbers, a decrease with increasing Mach number in the supersonic range, and little change throughout the hypersonic range. The empirical expression developed in the present investigation for the total drag coefficient of the oblate spheroid agrees well with the experimental data for Mach numbers from approximately 2.3 to 10.5.

INTRODUCTION

In the design of recoverable spacecraft, the resolution of the well-known aerodynamic heating problem encountered during atmospheric entry generally requires the incorporation of a high degree of nose bluntness, particularly for nonlifting vehicles. One configuration of an orbital, ballistic-entry vehicle which has attracted attention is the oblate spheroid. It would be expected that this configuration would afford a higher volume-weight ratio and greater static stability than the cone-shaped-afterbody vehicles such as the Apollo command module; however, the oblate spheroid would realize less drag for vehicle deceleration.

The attempt to predict the local flow properties for this type of body raises the question of accuracy, especially with regard to the subsonic flow field behind the detached bow shock wave. References 1 to 3 are examples of the numerous studies which have been devoted to developing theories to describe blunt body flow. However, as pointed out in reference 4, the methods which have evolved to date may differ greatly in the values predicted. Hence, in order to obtain reliable data, investigations were undertaken to determine experimentally the aerodynamic characteristics of the oblate spheroid for angles of attack from about -4° to 12° at Mach numbers from 1.70 to 10.49. Drag coefficients on spheres were obtained for comparison.

Other experiments which have been conducted to determine the drag and/or local flow properties of spheres and related blunt bodies are reported in references 5 to 13.

SYMBOLS

The data are referred to the stability-axis system with the moment center located as shown in figure 1.

A	frontal area
C_D	drag coefficient, Drag/qA
$C_{D,f}$	forebody drag coefficient
$C_{D,a}$	afterbody drag coefficient
C_L	lift coefficient, Lift/qA
C_m	pitching-moment coefficient, Pitching moment/qAd

C_p local pressure coefficient

$C_{p,max}$ maximum (stagnation point) pressure coefficient

d body diameter

d_b diameter of balance cavity

M Mach number

q dynamic pressure

R Reynolds number, based on body diameter

x axial coordinate measured from stagnation point of sphere and from stagnation point of theoretical sphere for oblate spheroid (see fig. 1)

x_{cp} location of center of pressure

α angle of attack, deg

θ angle between normal to local surface and model center line, deg or rad

APPARATUS AND METHODS

Models

A drawing of the models is shown in figure 1. Two models, the 9-inch-diameter (22.86 cm) oblate spheroid and the 6-inch-diameter (15.24 cm) sphere, were constructed of wood and fiber glass and were tested in the Langley Unitary Plan wind tunnel. The 5.75-inch-diameter (14.61 cm) oblate spheroid and sphere models, constructed of stainless steel, were tested in the Langley continuous-flow hypersonic tunnel.

Tunnels

The Langley Unitary Plan wind tunnel is a variable-pressure, return-flow tunnel which has two test sections. Each section is 4 feet (121.9 cm) square by approximately 7 feet (213 cm) long. The nozzles leading to the test sections are of the asymmetric sliding-block type and permit continuous variations in Mach number from about 1.5 to 2.9 and 2.3 to 4.7.

The Langley continuous-flow hypersonic tunnel is a variable-pressure, return-flow facility which has two 31-inch-square (78.7 cm) interchangeable test sections with Mach numbers of approximately 10 and 12.

Measurements, Corrections, and Tests

Aerodynamic forces and moments were measured by means of a sting-supported, six-component, strain-gage balance mounted within the models. Base pressure measurements were obtained by means of a static pressure orifice located within the balance cavity. No attempt was made to induce boundary-layer transition by artificial means.

Aerodynamic characteristics were obtained for the oblate spheroid at angles of attack from about -4° to 12° for Mach numbers from 1.70 to 10.49 and Reynolds numbers from 0.97×10^{6} to 3.75×10^{6}. Drag coefficients for the spheres were obtained at Mach numbers from 1.90 to 4.63 and a Reynolds number of 2.00×10^{6}, and at a Mach number of 10.49 and a Reynolds number of 0.97×10^{6}.

The angles of attack have been corrected for tunnel flow misalinement and model support system deflection due to aerodynamic load. The stagnation dewpoint was maintained sufficiently low to insure negligible condensation effects.

DISCUSSION

Schlieren photographs which depict typical flow patterns for both the oblate spheroid and sphere models are shown in figure 2. These and numerous unpublished photographs obtained during the investigation indicate that flow separation from the model surface occurs at θ from approximately 95° to 105°. The variation of the separation point was random rather than the result of distinct Mach number or Reynolds number effects.

The basic aerodynamic characteristics of the oblate spheroid model are presented in figure 3. The data, which were obtained at several Reynolds numbers for some Mach numbers, indicate no measurable Reynolds number effects. Both the pitching-moment and lift coefficients show small nonlinearities with angle of attack at the lower test Mach numbers. However, for Mach numbers of 2.96 and greater, these data are linear and essentially unaffected by Mach number. Although the pitching-moment curves reflect longitudinal instability (positive slope), the moment reference center employed herein (fig. 1) is located 0.75d rearward of the theoretical sphere stagnation point. This position corresponds to the balance moment center. The lift curve exhibits a slightly negative slope throughout the Mach number range. The drag coefficient is not noticeably affected by angle of attack, but it shows the expected decrease with increasing Mach number.

The effects of angle of attack and Mach number on the center-of-pressure location for the oblate spheriod are shown in figure 4. Although some variation with angle of attack and Mach number exists at the lower test Mach numbers, these effects diminish rapidly as Mach number is increased. For the Mach number range from about 2.7 to 10.5, the center-of-pressure location for the oblate spheriod is invariant at 0.575d rearward of the theoretical sphere stagnation point, as compared with the location at 0.50d for the sphere.

In order to assess the relative merits of several methods commonly used to predict the pressure distribution over a hemispherical forebody, the experimental pressure data obtained over the forebody of the hemisphere-cylinder model of reference 11 and unpublished data obtained over a sphere at $M = 10.0$ by Robert L. Stallings, Jr., at the Langley Research Center are presented in figure 5. Values predicted by the modified Newtonian theory $\left(C_p = C_{p,max} \cos^2\theta\right)$ and by the empirical method of reference 5 $\left(C_p = 2 \cos^2\theta - \left(2 - C_{p,max}\right)\cos \theta\right)$ are included for comparison. Presented in this form, the experimental values of $\frac{C_p}{C_{p,max}}$ are essentially invariant with Mach numbers greater than about 3 for values of θ to approximately 60°. At Mach numbers greater than approximately 6, the pressure ratio may be considered invariant with Mach number over the entire forebody. Both the modified Newtonian method and the empirical method overestimate the local pressure at the lower values of θ and, with the exception of the data at lower Mach numbers, underestimate in the shoulder region.

In the regions where the experimental data may be considered invariant with Mach number, the pressure distribution can be more accurately described by the empirical expression

$$\frac{C_p}{C_{p,max}} = \cos^8 0.55\theta \tag{1}$$

This equation was obtained by assuming that the pressure distribution could be approximated by the expression $\frac{C_p}{C_{p,max}} = \cos^n k\theta$. Various values of n and k were assumed and the results were compared with the experimental data of figure 5. Only integer values were used for n because no practical method was found for integrating the expression involving fractional exponents to obtain the drag coefficient. As shown in figure 5, equation (1) is in good agreement with the experimental data for the following approximate ranges: θ from 0° to 60° for a Mach number from 3 to 10, and θ from 0° to 90° for a Mach number from 6 to 10.

The forebody drag coefficient of a spherical segment may be expressed as

$$C_{D,f} = \int C_p \sin 2\theta \, d\theta$$

Substituting equation (1) into this expression yields

$$C_{D,f} = C_{p,max} \int \cos^8 0.55\theta \sin 2\theta \, d\theta \tag{2}$$

By integrating equation (2) between the limits $\theta = 0$ and $\theta = \pi/2$, the forebody drag coefficient of the sphere may be expressed as

$$C_{D,f} = 0.482C_{p,max} \tag{3}$$

Although no experimental pressure data are available for confirmation, equation (1) should apply equally well to the spherically blunted section of the oblate spheriod. The validity of the expression in the forebody region beyond the oblate section cannot presently be ascertained, but the effect of any discrepancy on drag should be negligible because the oblate section produces the major portion of the overall forebody drag. Hence, by integrating equation (2) using the appropriate limits (θ varies from 0 to approximately 0.915 radian for the oblate section) and reference areas, the forebody drag coefficient of the oblate spheroid may be expressed as

$$C_{D,f} = 0.540C_{p,max} \tag{4}$$

In figure 6, the results of the theoretical and empirical methods are compared with the experimental drag coefficients of the present investigation and sphere drag coefficients of reference 8. The experimental afterbody drag coefficients were obtained by applying the single balance-cavity pressure measurement over the entire afterbody. This procedure was considered justified on the basis of unpublished experimental data (by Stallings) which indicate that the pressure is essentially invariant throughout the separated-flow region and that very small errors would be incurred by assuming the separated-flow region to act over the entire afterbody. The afterbody drag coefficients for the two configurations are about equal and exhibit rapidly decreasing values at the lower Mach numbers to near-zero values in the hypersonic range. The expression for the afterbody drag coefficient $C_{D,a} = 1/M^2$, which results from the commonly employed approximation $C_{p,base} = -1/M^2$ (in the present investigation, $C_{D,a} = -C_{p,base}$), is shown in comparison with the experimental data. Although it provides good agreement over most of the Mach number range, the expression overestimates considerably at the lower Mach numbers.

The experimental total drag coefficients of the oblate spheroid are approximately 10 percent greater than those of the sphere throughout the Mach number range. The data for both configurations exhibit maximum values at the lower test Mach numbers, a decrease with increasing Mach number in the supersonic range, and little change throughout the hypersonic range. Because the theoretical and empirical methods represent forebody drag coefficient only, the $1/M^2$ approximation of afterbody drag coefficient has been added for comparison with the experimental values of total drag coefficient. The trends of the theoretical and empirical data parallel those of the experimental data for Mach numbers above approximately 2.5. Below this Mach number, the drag coefficient is increasingly overestimated as Mach number is decreased primarily due to the ineffectiveness of the $1/M^2$ approximation. Throughout the Mach number range, the modified Newtonian predictions (adjusted for afterbody drag) are consistently higher than the experimental data, particularly those for the oblate spheroid. Although the sphere drag coefficients predicted by the empirical methods of both reference 5 and the present investigation (equation (3) + $1/M^2$) are in agreement with the experimental data throughout most of the Mach number range, the values are slightly low in comparison with the experimental average in the hypersonic range. The drag coefficient of the oblate spheroid as predicted by the method of reference 5 is in agreement with experiment at supersonic Mach numbers above approximately 2 but is slightly high in the hypersonic range. Of the approximate methods, the empirical method developed as equation (4) + $1/M^2$ most accurately describes the total drag coefficient of the oblate spheroid and provides good agreement at Mach numbers from approximately 2.3 to 10.5.

CONCLUSIONS

An investigation has been conducted to determine the aerodynamic characteristics of models of an oblate spheroid and a sphere at Mach numbers from 1.70 to 10.49 and at angles of attack from approximately -4° to 12°. The investigation resulted in the following conclusions:

1. Both the pitching-moment and lift coefficients of the oblate spheroid show small nonlinearities with angle of attack at the lower test Mach numbers. However, for the test Mach numbers of 2.96 and greater, these data are linear and essentially unaffected by Mach number.

2. The center-of-pressure location of the oblate spheroid exhibits some effect of angle of attack and Mach number at the lower test Mach numbers. However, for Mach numbers from approximately 2.7 to 10.5, the center-of-pressure location is invariant at 0.575 body diameter rearward of the theoretical sphere stagnation point.

3. The empirical expression developed in the present investigation for the pressure distribution over a hemispherical forebody is in good agreement with the experimental data for the following approximate ranges: θ from 0° to 60° for a Mach number from 3 to 10, and θ from 0° to 90° for a Mach number from 6 to 10, where θ is the angle between a normal to the local surface and the model center line.

4. The experimental total drag coefficients of the oblate spheroid are approximately 10 percent greater than those of the sphere throughout the Mach number range. The data

for both configurations exhibit maximum values at the lower test Mach numbers, a decrease with increasing Mach number in the supersonic range, and little change throughout the hypersonic range.

5. The empirical expression developed in the present investigation for the total drag coefficient of the oblate spheroid agrees well with the experimental data for Mach numbers from approximately 2.3 to 10.5.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 26, 1969.

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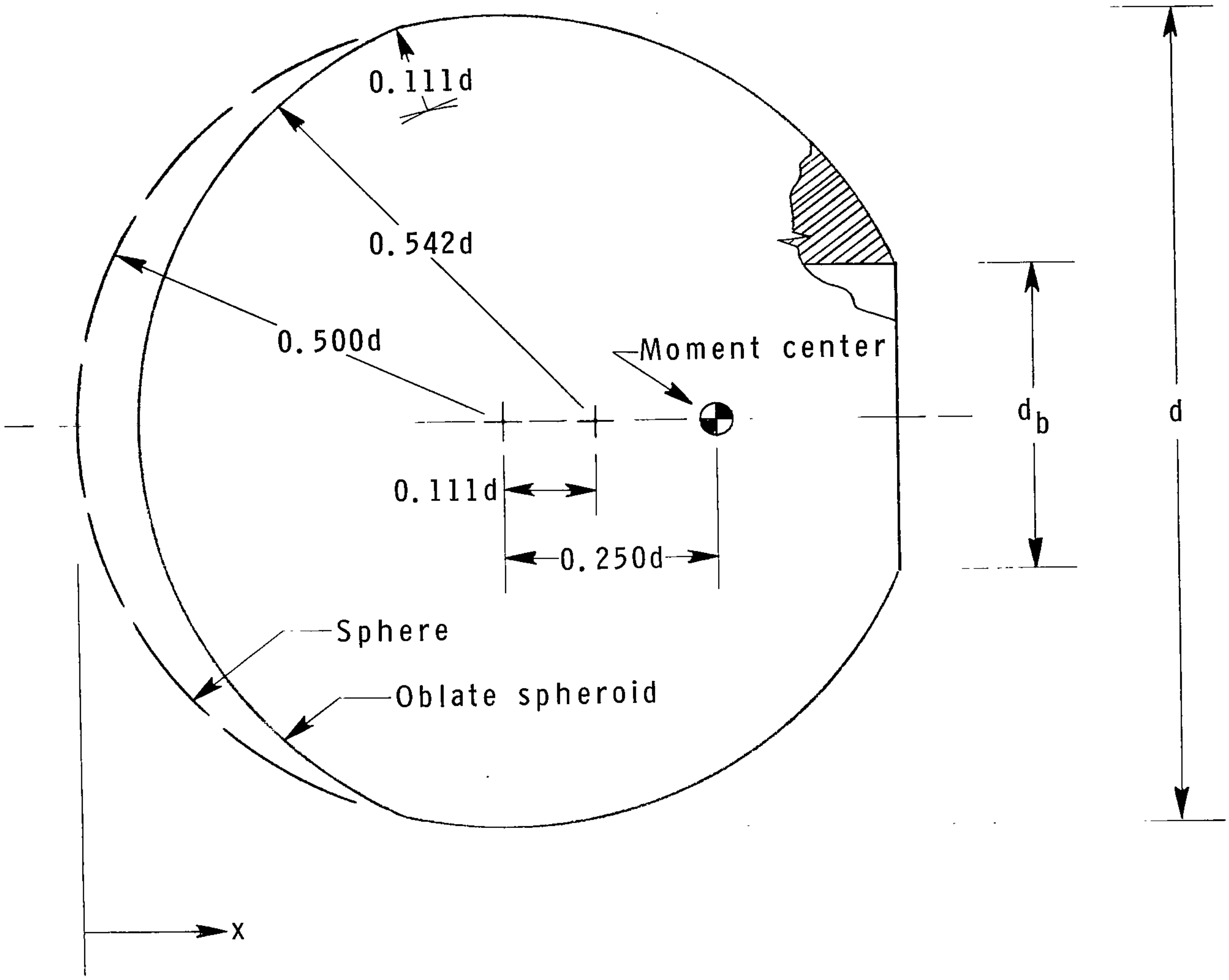

Model	d, in. (cm)	d_b/d
Oblate spheroid	9.00 (22.86)	0.417
Oblate spheroid	5.75 (14.61)	.228
Sphere	6.00 (15.24)	.278
Sphere	5.75 (14.61)	.228

Figure 1.- Model drawing.

M = 1.70 M = 2.96 M = 4.63

Oblate spheroid

M = 1.90 M = 2.86 M = 4.63

Sphere

Figure 2.- Schlieren photographs.

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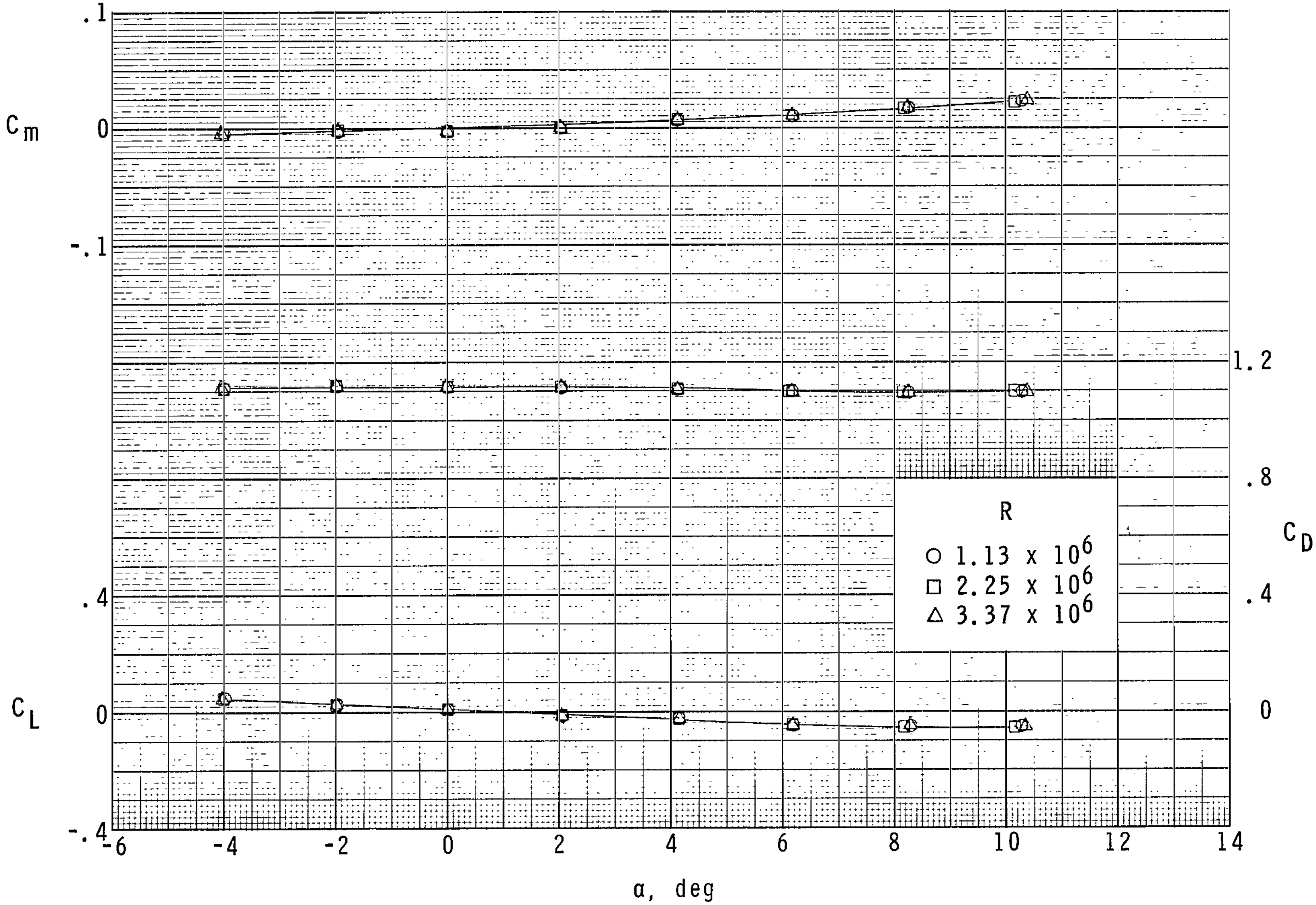
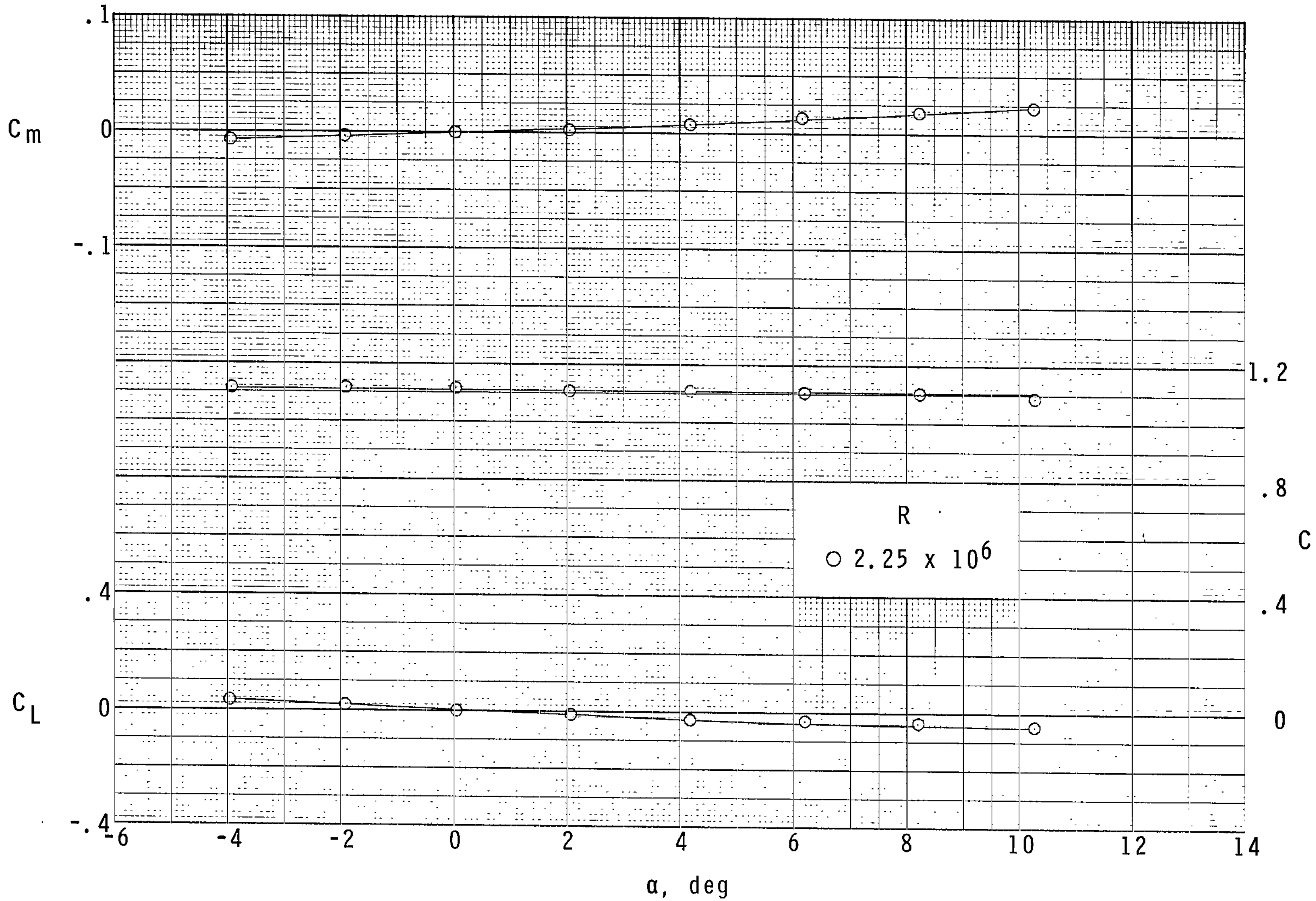


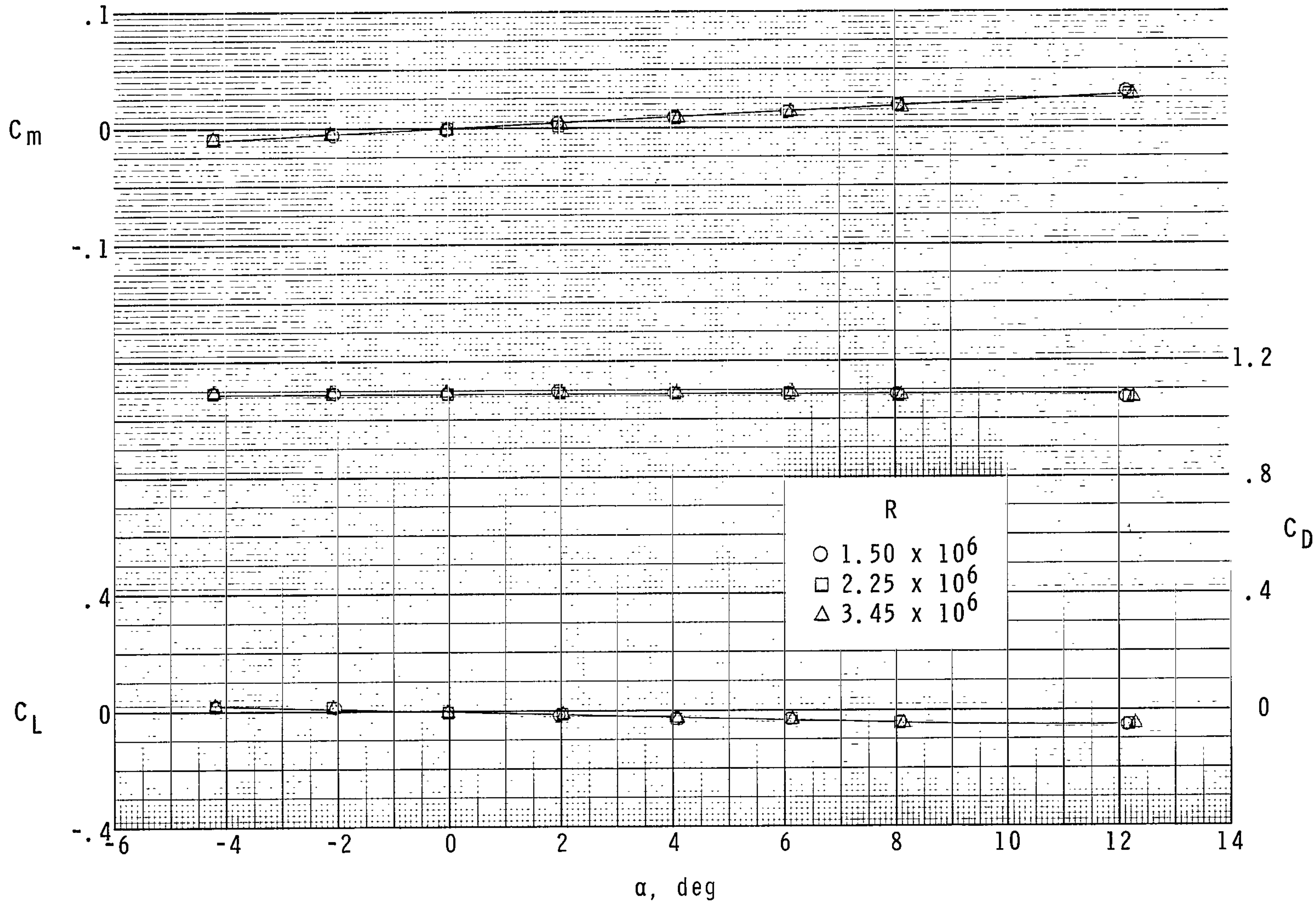
(a) M = 1.70.

Figure 3.- Basic aerodynamic characteristics of oblate-spheroid model.



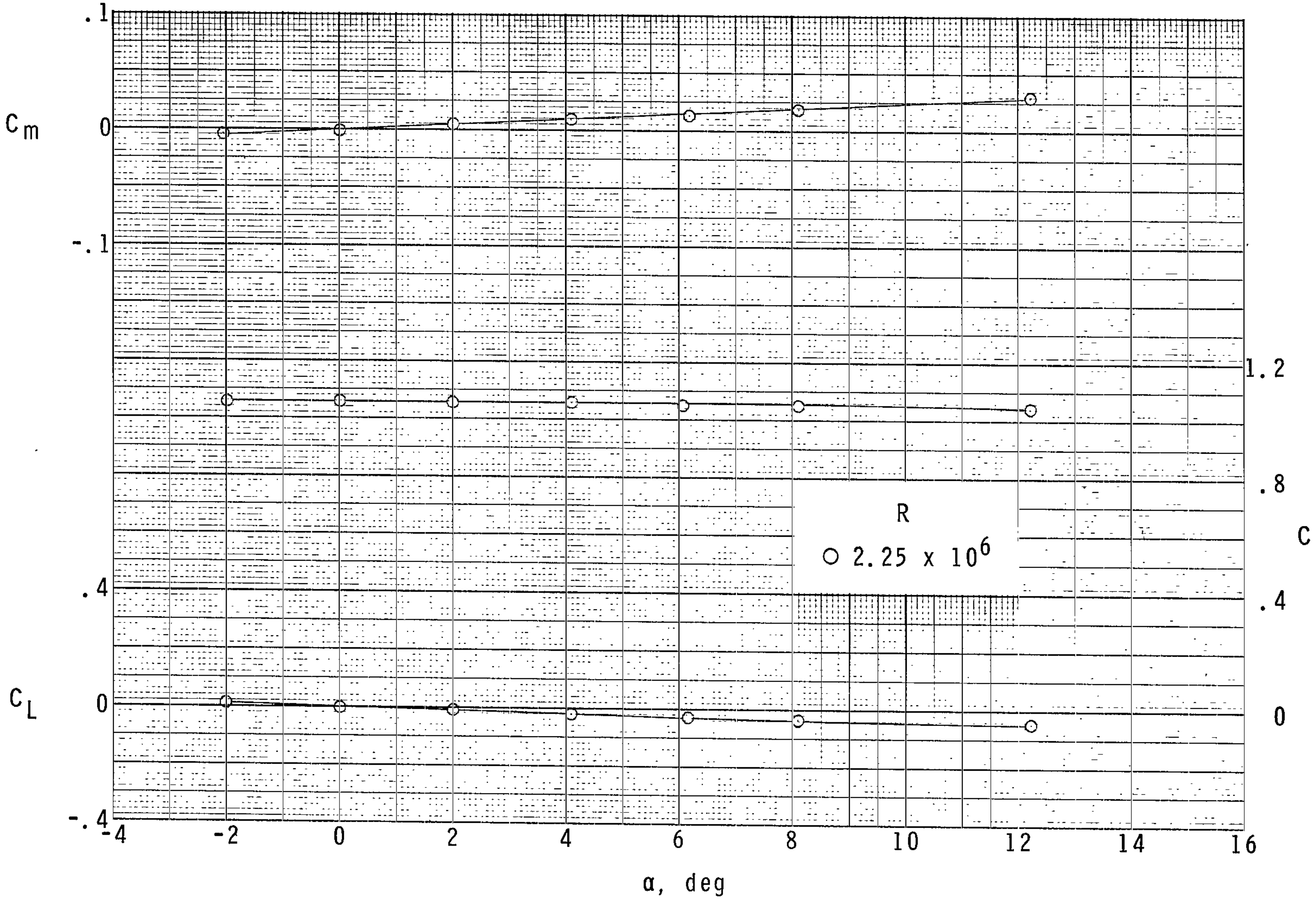
(b) $M = 1.90$.

Figure 3.- Continued.



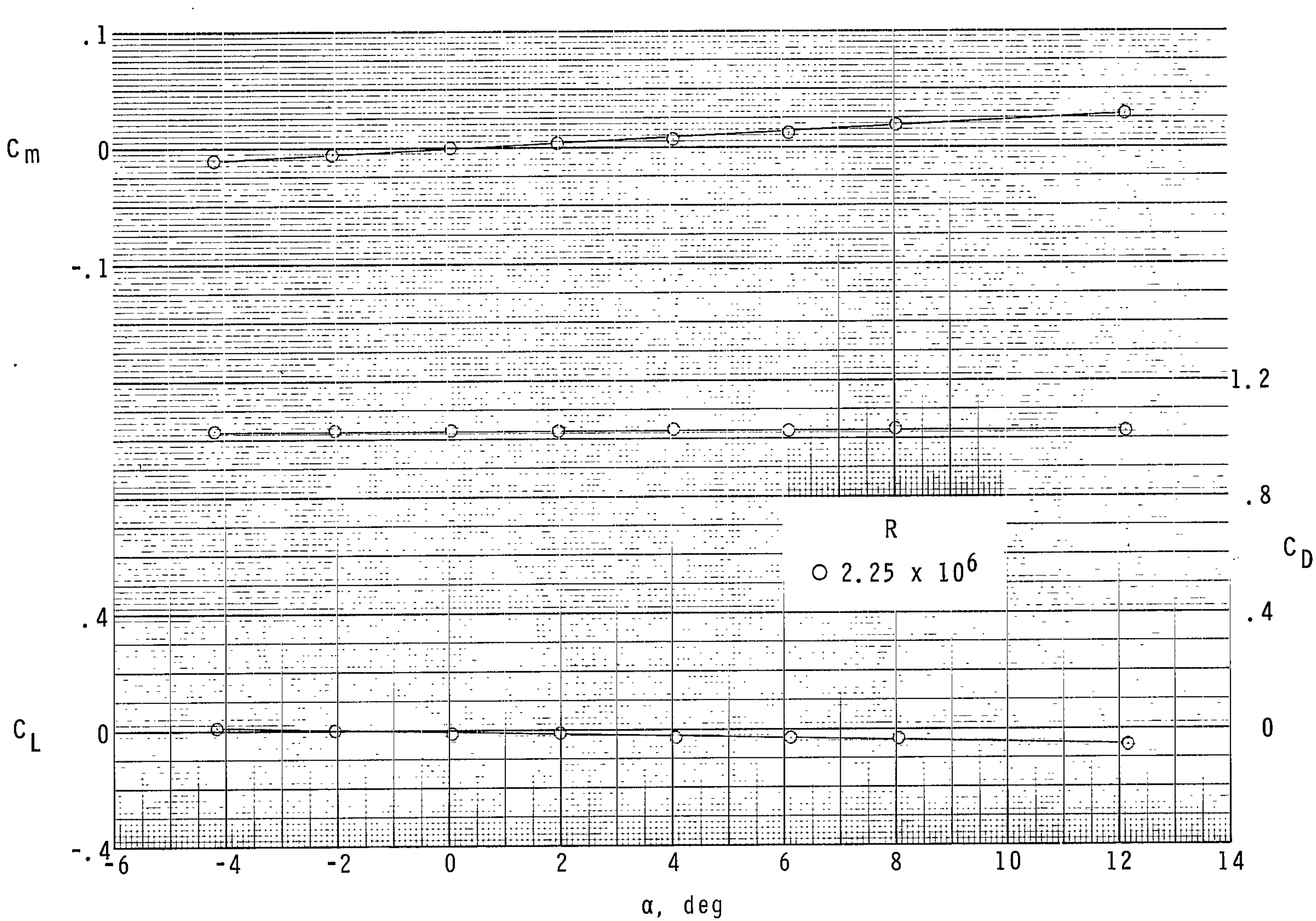
(c) M = 2.30.

Figure 3.- Continued.



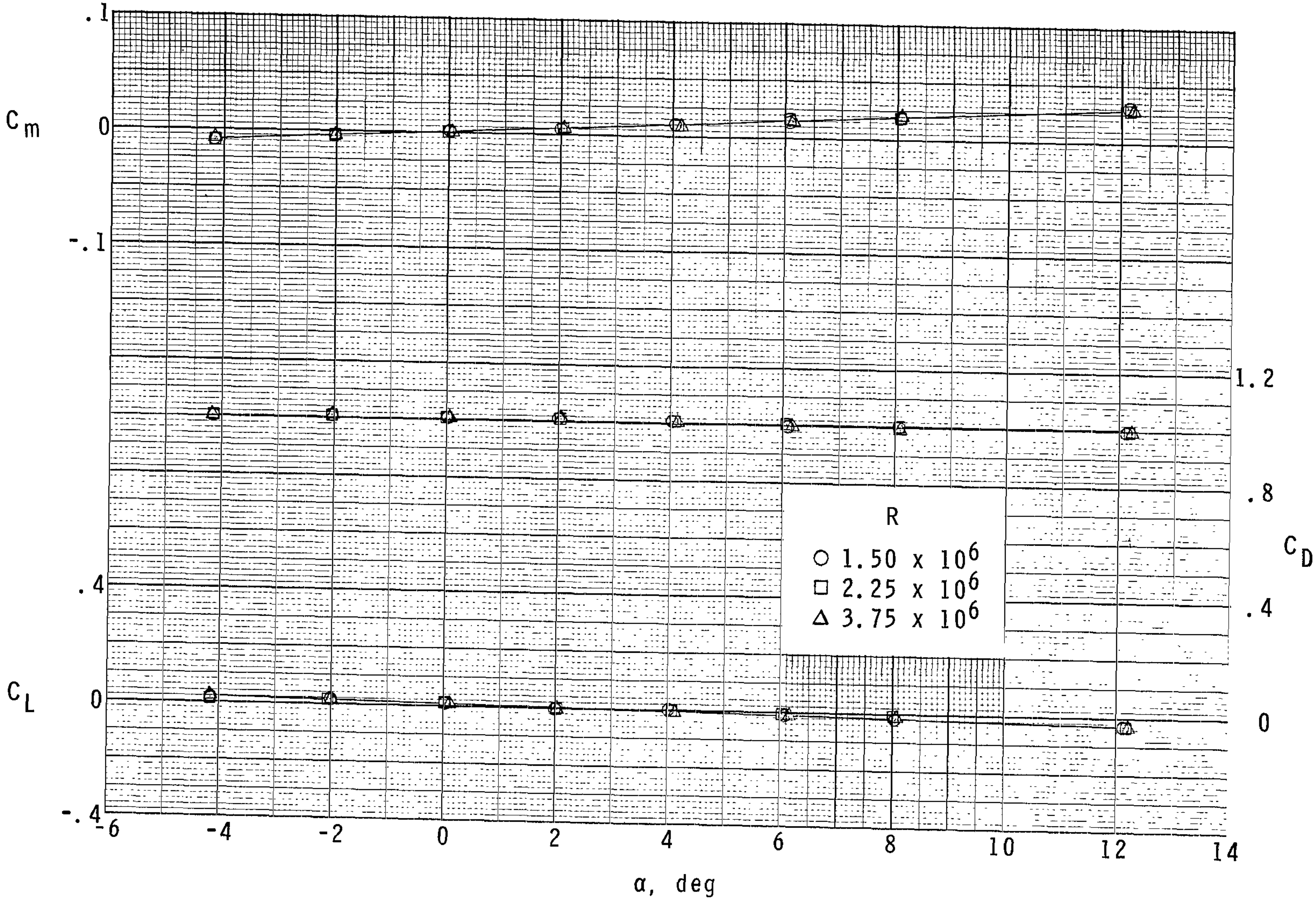
(d) M = 2.96.

Figure 4.- Continued.



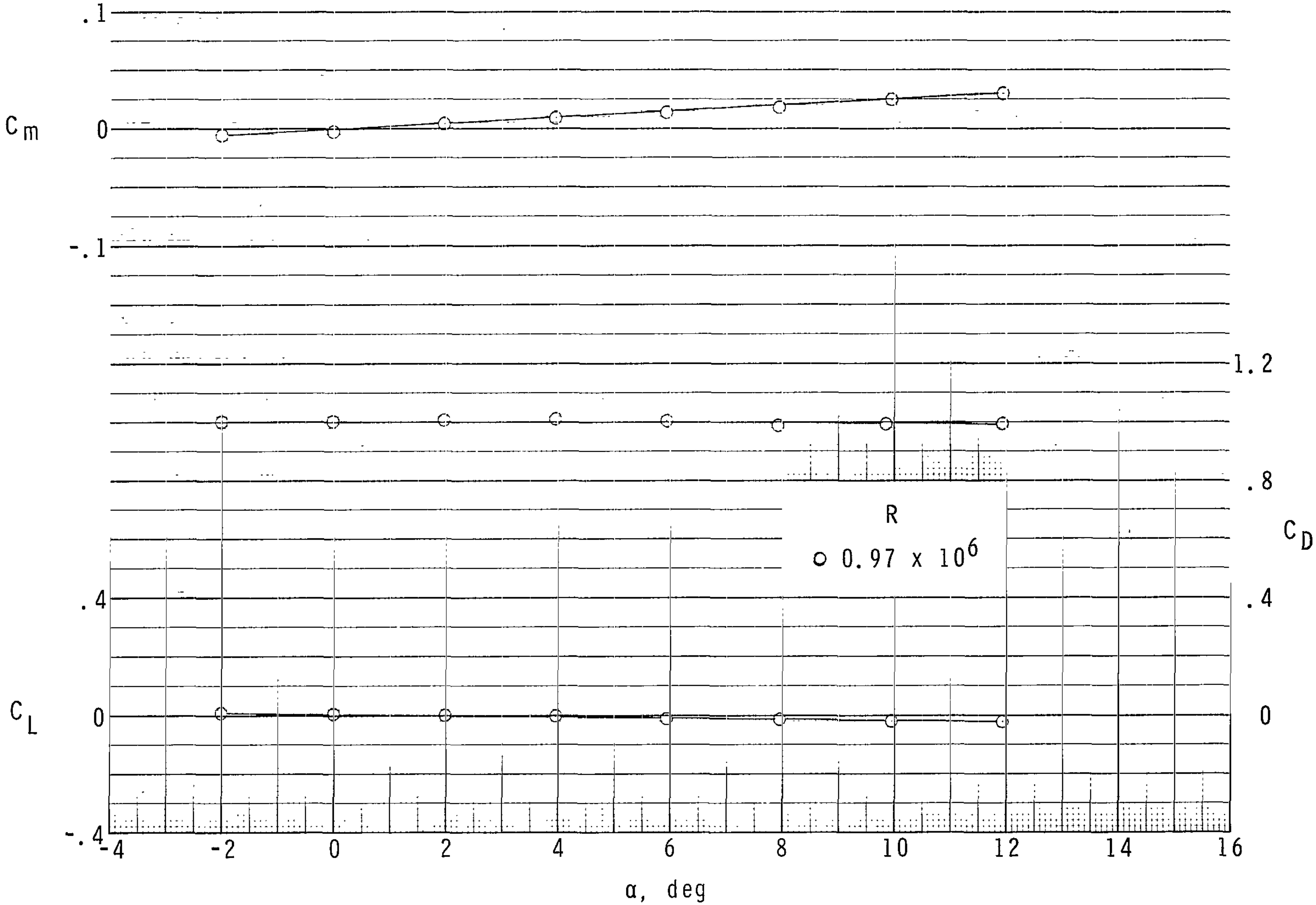
(e) M = 3.96.

Figure 3.- Continued.



(f) M = 4.63.

Figure 3.- Continued.



(g) M = 10.49.

Figure 3.- Concluded.

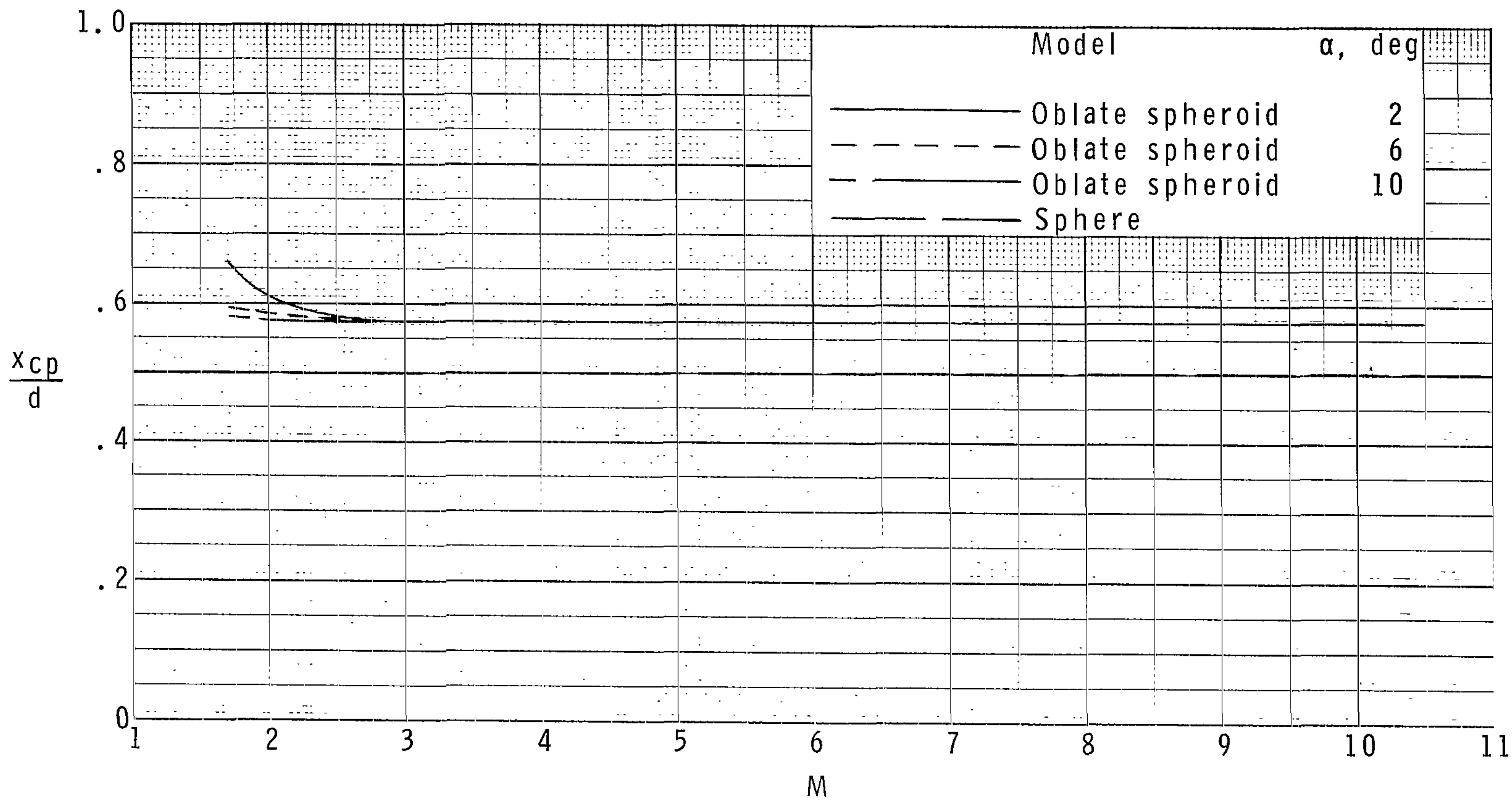


Figure 4.- Center-of-pressure location for oblate spheroid.

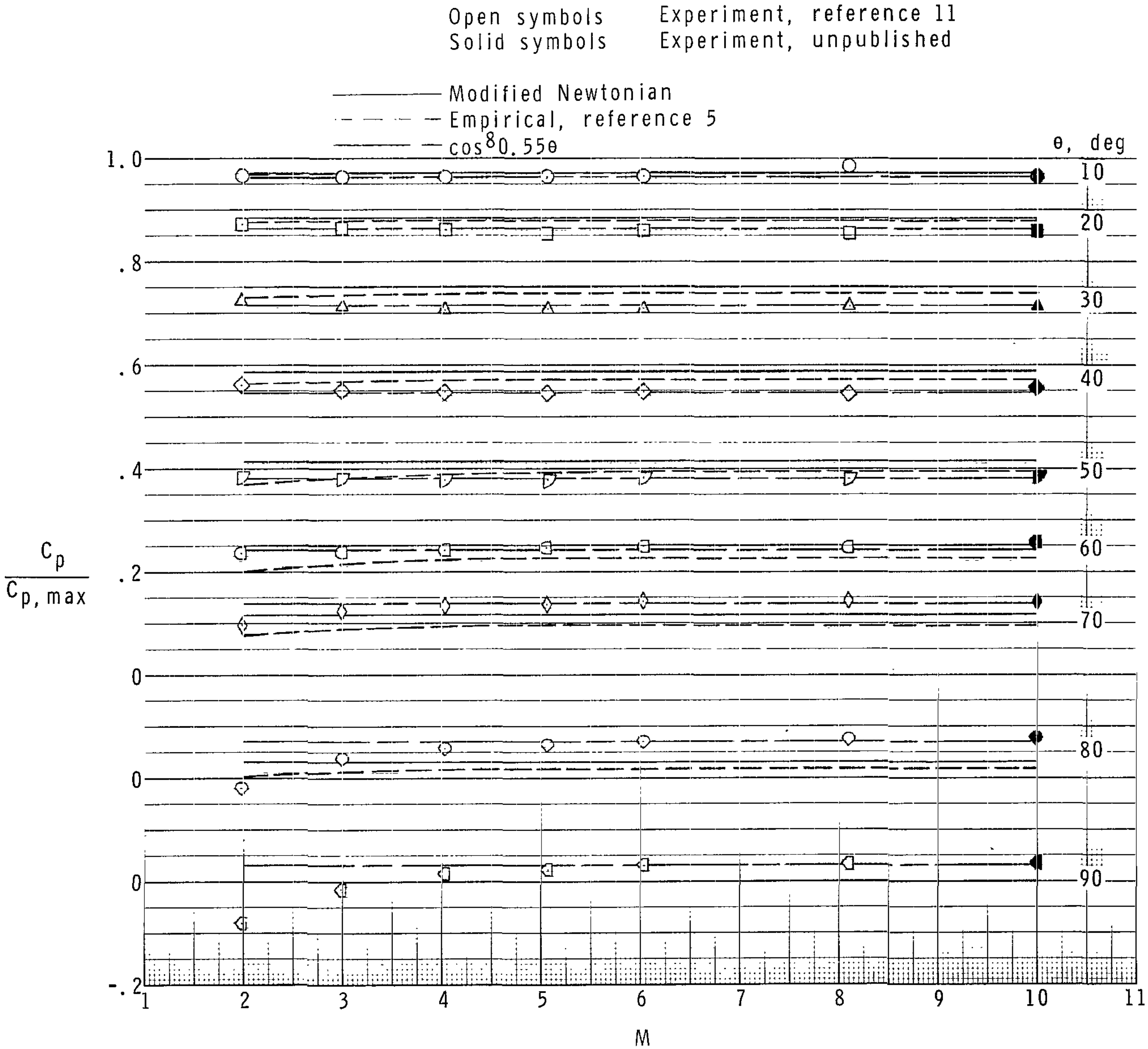


Figure 5.- Pressure distribution over hemispherical forebody.

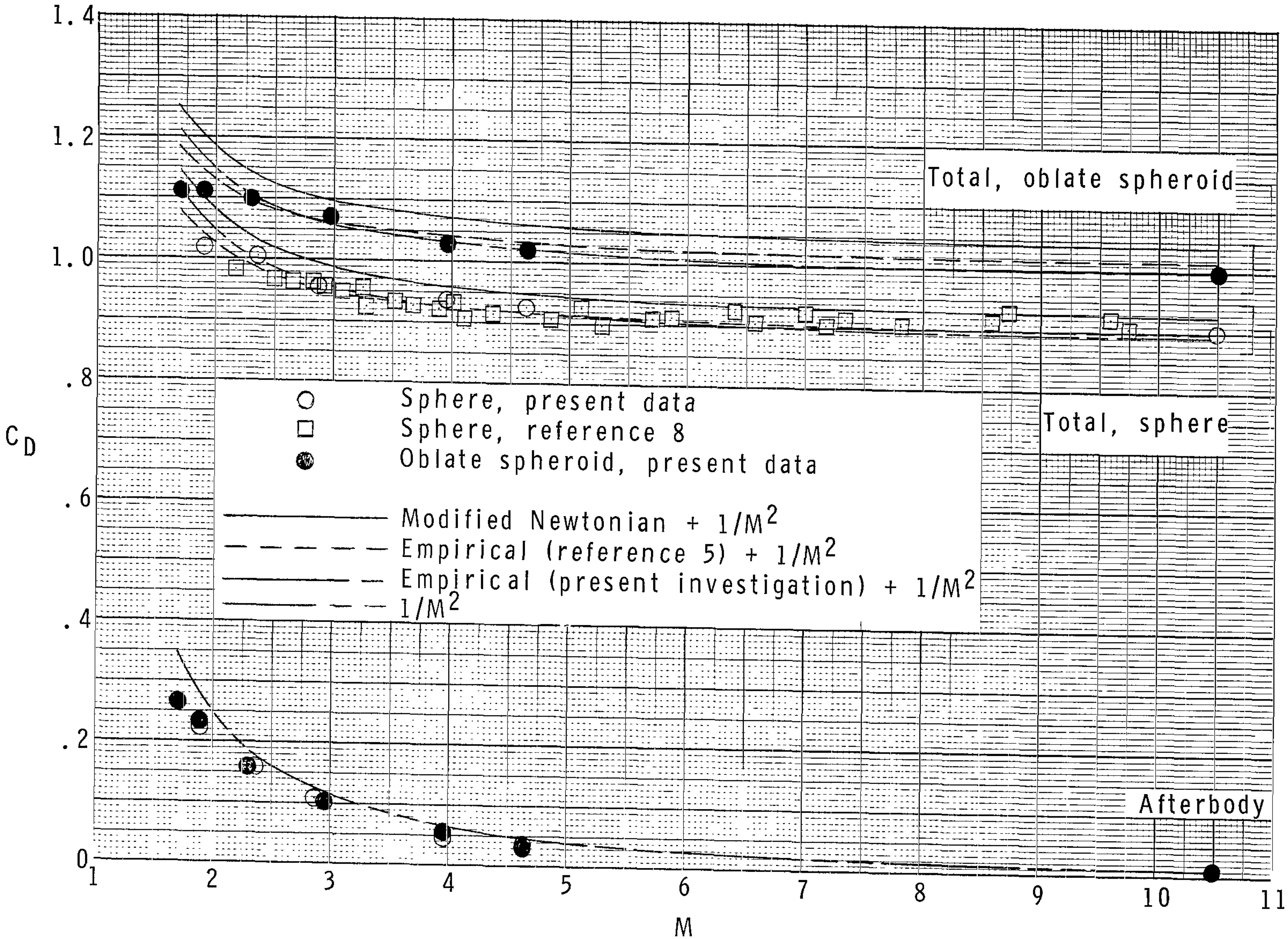


Figure 6.- Variation of drag coefficient with Mach number.

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