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SOME NOTES ON THE DETERMINATION OF THE STICK-FREE NEUTRAL POINT FROM WIND-TUNNEL DATA

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RESTRICTED BULLETIN

SOME NOTES ON THE DETERMINATION OF THE STICK-FREE NEUTRAL POINT FROM WIND-TUNNEL DATA

By Marvin Schuldenfrei

SUMMARY

The effect on static longitudinal stability of freeing the elevator is shown to be similar to the effect of altering the slope of the tail lift curve by a factor that depends upon the aerodynamic characteristics of the horizontal tail surfaces. The stick-free neutral point may then be determined from stick-fixed data by taking account of the reduction of tail effectiveness.

Two graphical methods for determining the stick-free neutral point, which are extensions of the methods commonly used to determine the stick-fixed neutral point, are presented. A mathematical formula for computing the stick-free neutral point is also given. These methods may be applied to determine approximately the increase in tail size necessary to shift the neutral point (with stick free or fixed) to any desired location on an airplane having inadequate longitudinal stability.

INTRODUCTION

The stick-fixed neutral point was defined in reference 1 as the center-of-gravity location at which the stability, as measured by the slope of the curve of pitching-moment coefficient C_m plotted against lift coefficient C_L, is neutral with the airplane trimmed. The conditions are stated mathematically as $dC_m/dC_L = 0$, $C_m = 0$. This center-of-gravity location is the limiting (most rearward) location at which variation of trim speed with elevator deflection δ_e is conventional (that is, up deflection of the elevator decreases trim speed and down deflection of the elevator increases trim speed). The condition thus defined is $d\delta_e/dC_L = 0$.

Elevator deflection alone, however, does not necessarily determine the variation in stick force that will be felt by the pilot. The stick forces required to change speed are made up of two components: that due to direct elevator deflection, and that due to the change in angle of attack at the tail when the attitude of the airplane changes in response to the control deflection. The stick-force variation with respect to speed, consequently, depends upon both $\partial C_h/\partial \alpha_t$ and $\partial C_h/\partial \delta_e$ of the tail, where $\partial C_h/\partial \alpha_t$ is the rate of change of elevator hinge-moment coefficient with tail angle of attack and $\partial C_h/\partial \delta_e$ is the rate of change of elevator hinge-moment coefficient with elevator deflection.

The neutral point with the stick free (elevator free to float) is related to that with the stick fixed, for the conditions to be met with the stick free are, mathematically: $dC_m/dC_L = 0$, $C_m = 0$, $C_h = 0$. The condition thus defined is $d\delta_T/dC_L = 0$, where δ_T is the trim-tab deflection. The present paper shows how the third condition $C_h = 0$ may be taken into account as an extension to the methods of determining the stick-fixed neutral point of reference 1.

For the purposes of this report it is assumed that $\partial C_h/\partial \delta_e$ and $\partial C_h/\partial \alpha_t$ are constant at any particular lift coefficient being investigated regardless of the angle of attack at the tail or the elevator deflection, that tab deflection has negligible effect on tail lift, and that the elevator is statically balanced. The other qualifications in the use of the methods are given in reference 1. The symbols used in this paper are defined as they occur in the text and are summarized in the appendix.

TAIL EFFECTIVENESS WITH FREE ELEVATOR

The pitching moment contributed by the tail and the increment of stability contributed by the tail are seen to be directly proportional to the slope of the tail lift curve $\partial C_{L_t}/\partial \alpha_t$ from equations (17) and (18), appendix A of reference 1.

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The relation between the slope of the tail lift curve with elevator fixed and the slope of the tail lift curve with elevator free may be found as follows: In general, with the elevator fixed, and at any dynamic pressure,

$$C_{L_t} = \frac{\partial C_{L_t}}{\partial \alpha_t}\alpha_t + \frac{\partial C_{L_t}}{\partial \delta_e}\delta_e \tag{1}$$

and the associated hinge-moment coefficient with elevator statically balanced is

$$C_h = \frac{\partial C_h}{\partial \alpha_t}\alpha_t + \frac{\partial C_h}{\partial \delta_e}\delta_e + \frac{\partial C_h}{\partial \delta_T}\delta_T \tag{2}$$

If the elevator is allowed to float, with a fixed trim-tab setting, the left-hand member of equation (2) may be equated to zero, whence

$$\delta_e = -\left(\frac{\frac{\partial C_h}{\partial \alpha_t}\alpha_t}{\frac{\partial C_h}{\partial \delta_e}} + \frac{\frac{\partial C_h}{\partial \delta_T}\delta_T}{\frac{\partial C_h}{\partial \delta_e}}\right) \tag{3}$$

Combining equations (1) and (3) yields

$$C_{L_{t_f}} = \frac{\partial C_{L_t}}{\partial \alpha_t}\alpha_t - \frac{\partial C_{L_t}}{\partial \delta_e}\left(\frac{\frac{\partial C_h}{\partial \alpha_t}\alpha_t}{\frac{\partial C_h}{\partial \delta_e}} + \frac{\frac{\partial C_h}{\partial \delta_T}\delta_T}{\frac{\partial C_h}{\partial \delta_e}}\right) \tag{4}$$

If equation (4) is differentiated with respect to α_t,

$$\left(\frac{\partial C_{L_t}}{\partial \alpha_t}\right)_f = \frac{\partial C_{L_t}}{\partial \alpha_t} - \frac{\frac{\partial C_{L_t}}{\partial \delta_e}\frac{\partial C_h}{\partial \alpha_t}}{\frac{\partial C_h}{\partial \delta_e}} \tag{5}$$

The ratio of $(dC_{L_t}/d\alpha_t)_f$ to $dC_{L_t}/d\alpha_t$ is then

$$\frac{\left(\dfrac{\partial C_{L_t}}{\partial \alpha_t}\right)_f}{\dfrac{\partial C_{L_t}}{\partial \alpha_t}} = 1 - \frac{\dfrac{\partial C_{L_t}}{\partial \delta_e}\dfrac{\partial C_h}{\partial \alpha_t}}{\dfrac{\partial C_{L_t}}{\partial \alpha_t}\dfrac{\partial C_h}{\partial \delta_e}} \tag{6a}$$

which may be written as

$$k = 1 - R \tag{6b}$$

where

C_{L_t} lift coefficient of horizontal tail with elevator fixed

$C_{L_{t_f}}$ lift coefficient of horizontal tail with elevator free to float

C_h elevator hinge-moment coefficient

α_t angle of attack of tail with respect to relative wind at tail

δ_e elevator deflection with respect to stabilizer chord line

δ_T tab deflection with respect to elevator chord line

$\dfrac{\partial C_{L_t}}{\partial \alpha_t}$ rate of change of tail lift coefficient with tail angle of attack, elevator fixed

$\left(\dfrac{\partial C_{L_t}}{\partial \alpha_t}\right)_f$ rate of change of tail lift coefficient with tail angle of attack, elevator free

$\dfrac{\partial C_{L_t}}{\partial \delta_e}$ rate of change of tail lift coefficient with elevator deflection, α_t fixed

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$\frac{\partial C_h}{\partial \alpha_t}$ rate of change of elevator hinge-moment coefficient with tail angle of attack, elevator and tab fixed

$\frac{\partial C_h}{\partial \delta_e}$ rate of change of elevator hinge-moment coefficient with elevator deflection, angle of attack and tab fixed

$\frac{\partial C_h}{\partial \delta_T}$ rate of change of elevator hinge-moment coefficient with tab deflection, angle of attack and elevator deflection fixed

k elevator-free effectiveness factor $\left[\left(\frac{\partial C_{L_t}}{\partial \alpha_t}\right)_f \Big/ \frac{\partial C_{L_t}}{\partial \alpha_t}\right]$

$$R = \frac{\partial C_{L_t}/\partial \delta_e}{\partial C_{L_t}/\partial \alpha_t} \frac{\partial C_h/\partial \alpha_t}{\partial C_h/\partial \delta_e}$$

It may be seen from equations (6) that the effectiveness of the tail with elevator free in producing lift (and hence stability and pitching moment) is related to the effectiveness of the tail with elevator fixed by a factor k dependent upon the aerodynamic characteristics of the horizontal tail and elevator. Further, it may be seen that this factor is independent of the trim-tab setting, stabilizer setting, and dynamic pressure at the tail, if the dynamic-pressure ratio is fairly uniform over the tail.

The neutral point with the stick free may then be determined by rectifying data from conventional tests with elevator fixed according to the factor given in equations (6).

DETERMINATION OF STICK-FREE NEUTRAL POINT

Method I

Assume that conventional pitching-moment curves of the form shown in figure 1 have been obtained for a model with elevator fixed. (These curves are for a fictitious airplane.)

It has been shown in reference 1 that, if $\left(dC_m/dC_L\right)_x$ is plotted against C_m/C_L for two elevator (or stabilizer) settings at a given C_L (fig. 2), the location of the center of gravity for neutral stability is the point where $\left(dC_m/dC_L\right)_x$ is equal to C_m/C_L; that is, the neutral point is the point of intersection between a straight line connecting these two plotted points and a line having the equation $\left(dC_m/dC_L\right)_x = C_m/C_L$. In figure 2, the neutral point is given in chords forward or rearward of the center of gravity about which the data are given, depending upon whether C_m/C_L is positive or negative at the point of intersection. The value of dC_m/dC_L and C_m/C_L for the tail-off curve is now plotted in figure 2; the values are taken at the same C_L as for the two elevator settings. For this example, C_L is selected as 1.2.

From figure 2, it is apparent that the contribution of the tail to stability is the difference in ordinates between the tail-off and tail-on points plotted, whereas the contribution of the tail to pitching moment (plotted as C_m/C_L) is the difference in abscissas. If, then, the action of freeing the elevator is represented by a decrease in tail effectiveness as has been shown, these values of the differences in ordinates and abscissas may be multiplied by the effectiveness factor k. The result obtained is the equivalent of multiplying by k the length of the dashed lines a of figure 2.

As an example in the use of this method, assume that the following aerodynamic characteristics have been determined for the tail of the airplane of figure 1 (the methods for obtaining these characteristics will be discussed later):

$$\partial C_h/\partial \alpha_t = -0.0012 \qquad \partial C_{L_t}/\partial \alpha_t = 0.0680$$

$$\partial C_h/\partial \delta_e = -0.0030 \qquad \partial C_{L_t}/\partial \delta_e = 0.0340$$

Then, from equations (6),

$$\begin{aligned} k &= 1 - \frac{-0.0012}{-0.0030}\,\frac{0.034}{0.068} \\ &= 0.80 \end{aligned}$$

and

$$R = 0.20$$

which indicates that the slope of the tail lift curve with the elevator free is 80 percent of that with the elevator fixed. If this factor is applied to the dashed lines of figure 2, a new line is obtained; the intersection of this line with the line

$$\left(\frac{dC_m}{dC_L}\right)_x = \frac{C_m}{C_L}$$

determines the stick-free neutral point. From figure 2, it may be seen that the stick-free neutral point is forward of the stick-fixed neutral point about 0.054 (or 5.4 percent) of the mean aerodynamic chord for this example.

Method II

It has been shown in reference 1 that, if the tangents to two or more elevator (or stabilizer) curves at a given lift coefficient are extended until they meet (fig. 3), the slope of the line drawn from this point of intersection through $(C_m = 0, C_L = 0)$ gives the location of the stick-fixed neutral point in chords forward or rearward of the center-of-gravity location about which the data are computed. The principles involved are the same as those used to obtain neutral points by the method of figure 2.

It can be shown that, if the tangent to the tail-off curve at the C_L under consideration is extended to a point having the same abscissa as the point of intersection of the tangents to the elevator curves, the difference in ordinates of the two points b is proportional to the elevator-free effectiveness factor k (fig. 3). For the fixed-elevator condition, $k = 1.0$. With the elevator free, the value of k determines a new point through which to draw the line through $(C_m = 0, C_L = 0)$ in order to find the neutral point. For the example under consideration (fig. 3), the difference between stick-free and stick-fixed neutral points is again seen to be equal to 5.4 percent of the mean aerodynamic chord.

Method III

A mathematical analysis to determine the shift in the neutral point due to freeing the elevator, which takes into account the variation of dynamic-pressure ratio at the tail, has been made in reference 2. The neutral-point shift has been shown to be

$$\Delta n_p = n_{p_f} - n_p = \frac{\left(\Delta\frac{\partial C_{L_t}}{\partial \alpha_t}\right)\frac{q_t}{q_o}\frac{V}{dC_L/d\alpha}\left(1 - \frac{d\epsilon}{d\alpha}\right)}{1 - \dfrac{d\frac{q_t}{q_o}/dC_L}{\frac{q_t/q_o}{C_L}}} \tag{7}$$

where

n_p neutral-point location, chords behind leading edge of mean aerodynamic chord, stick fixed (x_o in reference 1)

n_{p_f} neutral-point location, chords behind leading edge of mean aerodynamic chord, stick free

Δn_p shift in neutral point due to freeing elevator $\left(n_{p_f} - n_p\right)$

$\Delta\frac{\partial C_{L_t}}{\partial \alpha_t}$ increase in slope of tail lift curve due to freeing elevator $\left(-R\frac{\partial C_{L_t}}{\partial \alpha_t}\right)$

V tail volume $\left(\frac{S_t}{S}\frac{l_t}{\bar{c}}\right)$

S_t horizontal tail area

S wing area

l_t tail arm

$\bar{c}$ mean aerodynamic chord of wing

$\frac{q_t}{q_o}$ average dynamic pressure at tail compared with free-stream dynamic pressure

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$\dfrac{d\frac{q_t}{q_o}}{dC_L}$ rate of change of q_t/q_o with airplane C_L

$\dfrac{dC_L}{d\alpha}$ slope of lift curve for complete airplane

$\dfrac{d\epsilon}{d\alpha}$ rate of change of average downwash angle at tail with airplane angle of attack

If q_t/q_o has the constant value 1 (as for windmilling conditions), equation (7) reduces to

$$\Delta n_p = \Delta\frac{\partial C_{L_t}}{\partial \alpha_t} \frac{V}{dC_L/d\alpha} \left(1 - \frac{d\epsilon}{d\alpha}\right) \tag{8}$$

Inasmuch as

$$\left(\Delta\frac{\partial C_{L_t}}{\partial \alpha_t}\right) \frac{q_t}{q_o} V = -\frac{dC_m}{di_t} R \tag{9}$$

and

$$\frac{1 - \frac{d\epsilon}{d\alpha}}{dC_L/d\alpha} = \frac{d\alpha_t}{dC_L}$$

then equation (7) becomes

$$\Delta n_p = -\frac{R \frac{dC_m}{di_t} \frac{d\alpha_t}{dC_L}}{1 - \frac{d\frac{q_t}{q_o}\Big/dC_L}{\frac{q_t/q_o}{C_L}}} \tag{10}$$

where

$\dfrac{dC_m}{di_t}$ rate of change of pitching-moment coefficient with stabilizer angle, at any particular airplane C_L, elevator fixed

$\frac{d\alpha_t}{dC_L}$ rate of change of tail angle of attack with airplane lift coefficient $\left(\frac{1 - \frac{d\epsilon}{d\alpha}}{dC_L/d\alpha}\right)$

METHODS FOR DETERMINING TAIL CHARACTERISTICS AND FACTOR R

Aerodynamic characteristics, such as $\partial C_h/\partial \alpha_t$ and $\partial C_h/\partial \delta_e$, mentioned in the present paper (except for dC_m/di_t in equations (9) and (10)) were based on actual dynamic pressure at the tail. Thus these would be the values found in tests of an isolated tail surface. In tests of a complete model, however, the dynamic pressure at the tail will influence the hinge moment and lift produced per degree of elevator or stabilizer variation; and the dynamic pressure will vary, in general, with airplane attitude. It is then necessary to determine the value of the tail characteristics and R under conditions where q_t/q_o at the tail varies, as it would on the actual airplane.

The value of the factor R has been shown to be $\frac{\partial C_h/\partial \alpha_t}{\partial C_h/\partial \delta_e} \frac{\partial C_{L_t}/\partial \delta_e}{\partial C_{L_t}/\partial \alpha_t}$. The ratio $\frac{\partial C_h/\partial \alpha_t}{\partial C_h/\partial \delta_e}$ is independent of the dynamic-pressure ratio. The value of $\frac{\partial C_h/\partial \alpha_t}{\partial C_h/\partial \delta_e}$ may be determined from elevator and stabilizer tests by taking the ratio at any lift coefficient or finding the average at several lift coefficients of the airplane, if the hinge-moment-coefficient variation is linear. By the same reasoning $\frac{\partial C_{L_t}/\partial \delta_e}{\partial C_{L_t}/\partial \alpha_t}$ is independent of q_t/q_o at the tail if it is assumed that q_t/q_o is fairly uniform over the tail span and, further, $\partial C_{L_t}/\partial \delta_e$ is directly proportional to dC_m/di_t. Thus

$$\frac{\partial C_{L_t}/\partial \delta_e}{\partial C_{L_t}/\partial \alpha_t} = \frac{dC_m/d\delta_e}{dC_m/di_t}$$

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and the ratio $\frac{dC_m/d\delta_e}{dC_m/di_t}$ is constant at any value of airplane lift coefficient.

If the actual values of $dC_h/d\alpha_t$ and $dC_h/d\delta_e$ (with respect to the actual value of the dynamic pressure at the tail) are desired from wind-tunnel data obtained from tests of complete models, they may be found from the relationship

$$\frac{\partial C_h}{\partial \delta_e} = \frac{\left(\partial C_h/\partial \delta_e\right)_{exp}}{q_t/q_o}$$

and, similarly,

$$\frac{\partial C_h}{\partial \alpha_t} = \frac{\left(\partial C_h/\partial i_t\right)_{exp}}{q_t/q_o}$$

If the values for $dC_{L_t}/d\delta_e$ and $dC_{L_t}/d\alpha_t$ are desired from wind-tunnel data, the following relations apply:

$$\frac{\partial C_{L_t}}{\partial \alpha_t} = -\frac{dC_m/di_t}{\frac{q_t}{q_o}V}$$

and, similarly,

$$\frac{\partial C_{L_t}}{\partial \delta_e} = -\frac{dC_m/d\delta_e}{\frac{q_t}{q_o}V}$$

DISCUSSION OF METHODS

It may be advantageous at this point to indicate the physical significance of the operations performed by these methods for finding the stick-free neutral point.

Basically, it is desired to obtain two or more curves of C_m plotted against C_L for the model with the elevator free to float. Because, with the controls free, an airplane must fly with zero elevator hinge moment, flight speed or attitude can be changed only by varying either center-of-gravity location, trim-tab setting, or stabilizer incidence, for any particular airplane configuration. Control-free flight may be reproduced in the wind tunnel by obtaining two or more pitching-moment curves with the elevator free with different trim-tab settings (or stabilizer incidences), and the neutral points with the stick free may be found directly by the methods of reference 1.

This procedure may also be used in flight to determine neutral points with elevator free. The airplane may be flown with several center-of-gravity locations and the trim-tab settings required for trim may be determined throughout the speed range. Because an airplane can fly steadily only with $C_m = 0$, the out-of-trim pitching-moment curves as obtained from wind-tunnel tests need not be determined. The neutral points may be determined directly as the center-of-gravity locations at which the variation of tab angle required for trim does not change with speed $(d\delta_T/dC_L = 0)$. Similar tests can be made with a wind-tunnel model if the elevator is statically balanced and allowed to float freely with the tab at various settings. The pitching-moment curves obtained might then be handled in the manner described in reference 1 for the determination of stick-fixed neutral points. This method has been avoided, in general, because of the necessity for increasing the length of the test program but may be the only satisfactory method to follow for models having nonlinear hinge-moment characteristics.

By applying the methods previously described it is possible to determine the stick-free characteristics graphically or mathematically from the stick-fixed characteristics, provided that the hinge moments of the elevator have been determined during the elevator-fixed tests made with various stabilizer and elevator settings.

Although the lift characteristics of the tail of wind-tunnel models have been found to represent fairly closely those of the tail of the actual airplane, the hinge moments have been found to be critically dependent

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upon the accurate representation of the tail-surface dimensions, with respect to such details as gap, thickness, and trailing-edge angle. Further, the effect of scale may distort the model hinge-moment characteristics even if the tail configuration is reproduced with the maximum of accuracy. It has, consequently, been found desirable at times to test isolated tail surfaces of relatively large scale and to apply these data in conjunction with small-scale complete-model data to estimations of flying qualities of the airplane. It is apparent that the aerodynamic characteristics of the large-scale tail surface with respect to stick-free stability may be represented to a fair degree of accuracy by determining the value of the constant k. The effect of the free-floating elevator on the location of the neutral point may then be found by the methods described if the tail-fuselage interference effects are approximated. The effects of tail-fuselage interference have not been subjected to rational analysis. Some approach to the interference effect may be made by testing the large-scale tail surface in the presence of a stub fuselage, for conventional airplanes, or in the presence of stub booms, for twin-boom airplanes. If such tests are not possible, the effect must be estimated.

The effectiveness of a tail surface as measured by the slope of the tail lift curve with elevator fixed may prove to be different in the tests of a large-scale tail model from that obtained from tests of a small-scale complete model. In this case the effects may be taken into account and the wind-tunnel results corrected graphically by considering that the difference is due to an increase in the factor k, or mathematically by the use of equation (7) where $\Delta\frac{\partial C_{L_t}}{\partial \alpha_t}$ is the increase or decrease in $\partial C_{L_t}/\partial \alpha_t$ obtained from tests of the large-scale surface over that obtained from tests of the small-scale complete model. Also the size of the tail surface needed to shift the stick-fixed neutral point to any desired location may be determined approximately by considering a larger surface as having an increased effectiveness and solving graphically or by equation (7) again.

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APPENDIX

SYMBOLS

C_m	pitching-moment coefficient
C_L	lift coefficient
C_{L_t}	lift coefficient of horizontal tail, elevator fixed
$C_{L_{t_f}}$	lift coefficient of horizontal tail, elevator free to float
C_h	elevator hinge-moment coefficient
α_t	angle of attack of tail with respect to relative wind at tail
δ_e	elevator deflection with respect to stabilizer chord line (positive with T.E. down)
δ_T	tab deflection with respect to elevator chord line (positive with T.E. down)
$\frac{\partial C_{L_t}}{\partial \alpha_t}$	rate of change of tail lift coefficient with tail angle of attack, elevator fixed
$\left(\frac{\partial C_{L_t}}{\partial \alpha_t}\right)_f$	rate of change of tail lift coefficient with tail angle of attack, elevator free
$\frac{\partial C_{L_t}}{\partial \delta_e}$	rate of change of tail lift coefficient with elevator deflection, α_t fixed
$\frac{\partial C_h}{\partial \alpha_t}$	rate of change of elevator hinge-moment coefficient with tail angle of attack, elevator and tab fixed
$\frac{\partial C_h}{\partial \delta_e}$	rate of change of elevator hinge-moment coefficient with elevator deflection, angle of attack and tab fixed

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$\frac{\partial C_h}{\partial \delta_T}$	rate of change of elevator hinge-moment coefficient with tab deflection, angle of attack and elevator deflection fixed
k	elevator-free effectiveness factor $(1 - R)$

$$R = \frac{\partial C_{L_t}/\partial \delta_e}{\partial C_{L_t}/\partial \alpha_t} \frac{\partial C_h/\partial \alpha_t}{\partial C_h/\partial \delta_e}$$

x	original center-of-gravity location about which data are given, chords behind leading edge of mean aerodynamic chord
n_p	neutral-point location, chords behind leading edge of mean aerodynamic chord, stick fixed (x_o in reference 1)
n_{p_f}	neutral-point location, chords behind leading edge of mean aerodynamic chord, stick free
Δn_p	shift in neutral point due to freeing elevator $\left(n_{p_f} - n_p\right)$
$\Delta\frac{\partial C_{L_t}}{\partial \alpha_t}$	increase in slope of tail lift curve due to freeing elevator $\left(-R\frac{\partial C_{L_t}}{\partial \alpha_t}\right)$
V	tail volume $\left(\frac{S_t}{S} \frac{l_t}{\bar{c}}\right)$
S_t	horizontal tail area
S	wing area
l_t	tail arm
$\bar{c}$	mean aerodynamic chord of wing
i_t	angle of incidence of stabilizer (stabilizer setting) with respect to horizontal reference line of model (positive with T.E. down)
$\frac{q_t}{q_o}$	average dynamic pressure at tail compared with free-stream dynamic pressure

$\dfrac{d\frac{q_t}{q_o}}{dC_L}$ rate of change of q_t/q_o with airplane C_L

$\dfrac{dC_L}{d\alpha}$ slope of lift curve for complete airplane

$\dfrac{d\epsilon}{d\alpha}$ rate of change of average downwash angle at tail with airplane angle of attack

$\dfrac{dC_m}{di_t}$ rate of change of pitching-moment coefficient with stabilizer angle at any particular airplane C_L, elevator fixed

$\dfrac{dC_m}{d\delta_e}$ rate of change of pitching-moment coefficient with elevator angle at any particular airplane C_L, stabilizer angle fixed

$\dfrac{d\alpha_t}{dC_L}$ rate of change of tail angle of attack with airplane lift coefficient $\left(\dfrac{1 - \frac{d\epsilon}{d\alpha}}{dC_L/d\alpha}\right)$

Subscripts:

1,2 elevator settings

x referred to center of gravity about which data are presented

exp experimental values

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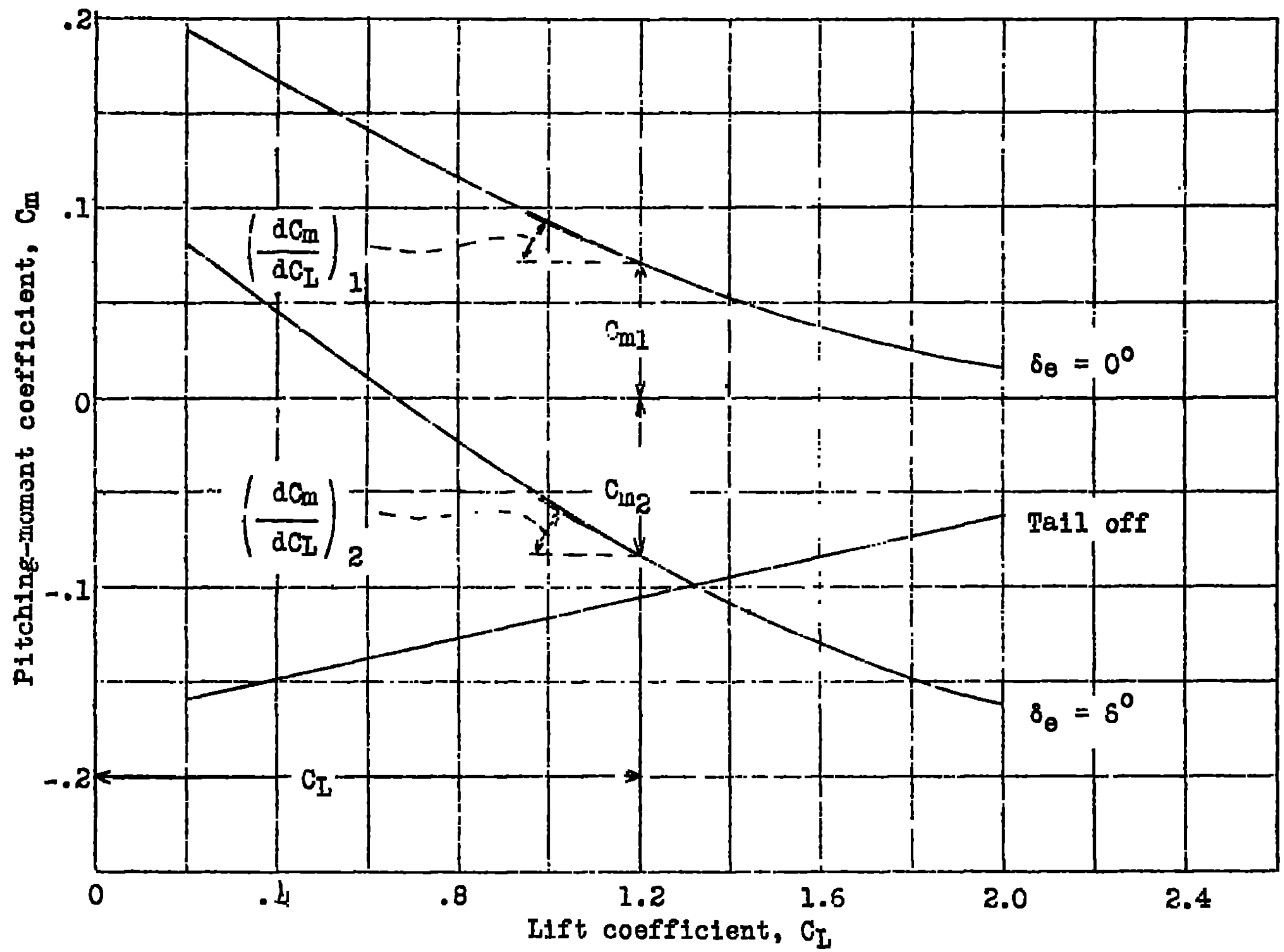

Figure 1.- Typical variation of C_m with C_L obtained in wind tunnel. Center of gravity at 20 percent of mean aerodynamic chord, on thrust line. Power on; flaps down; $i_t = 0^\circ$.

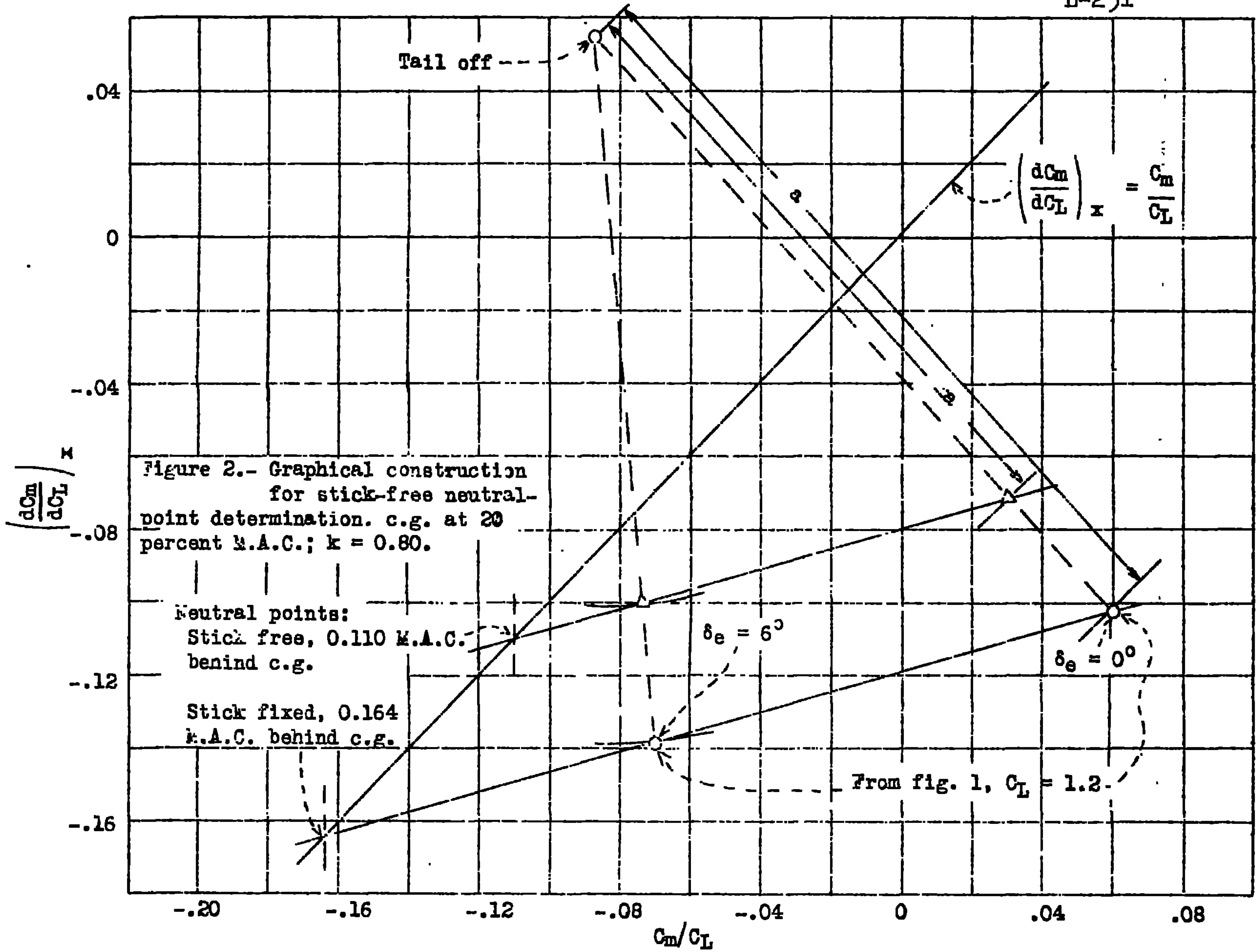

Figure 2.- Graphical construction for stick-free neutral-point determination. c.g. at 20 percent M.A.C.; k = 0.80.

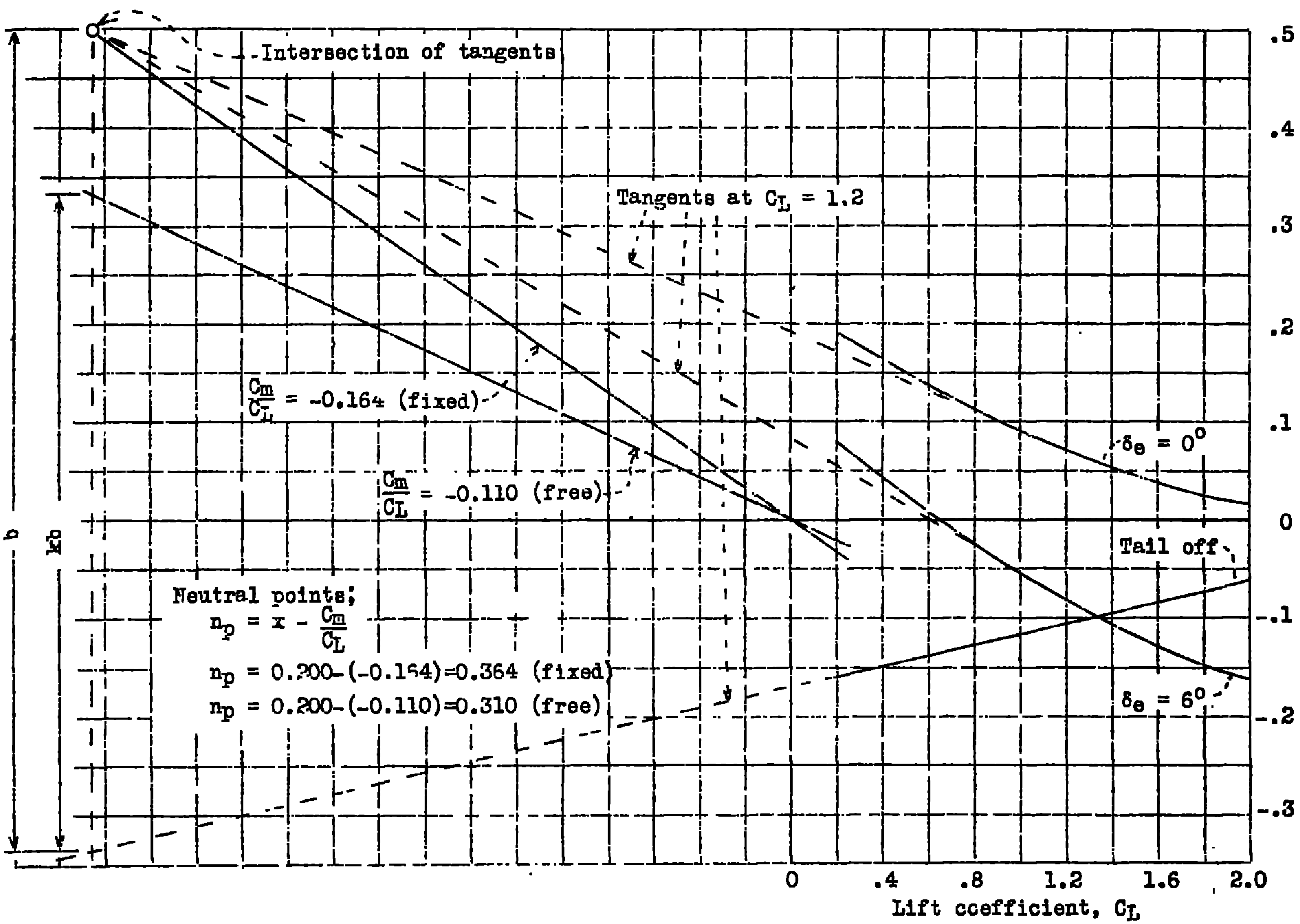

Figure 3.- Graphical determination of stick-free neutral point by intersection method. $i_t = 0°$; $\partial C_h/\partial \alpha_t = -0.0012$, $\partial C_h/\partial \delta_e = -0.0030$, $\partial C_{L_t}/\partial \alpha_t = 0.068$, $\partial C_{L_t}/\partial \delta_e = 0.034$; $k = 0.80$.