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Effects of Thrust Line Offset on Neutral Point Determination in Flight Testing

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On aircraft with high or low thrust lines, conventional stability flight test methods result in shifted neutral points, which do not correspond to the actual pitch stability neutral points of the aircraft. Specifically, e.g., an "elevator-position neutral point" extrapolated from flight test data of an aircraft with a high thrust line, may be significantly behind the actual "stick-fixed neutral point," causing a potential hazard. This implies that "stable" slopes of elevator position and stick force vs velocity diagrams do not necessarily mean that the aircraft is stable in pitch.

Nomenclature

C_L = lift coefficient
C_{L_α} = lift curve slope
$C_{L\delta}$ = derivative of lift coefficient with respect to elevator (or stabilator) deflection
C_m = pitching moment coefficient
C_{m_α} = pitch stability derivative
$C_{m\delta}$ = derivative of aircraft pitching moment coefficient with respect to elevator (or stabilator) deflection
$\bar{c}$ = mean aerodynamic chord
F_s = control stick (or yoke) force
h = c.g. position, as a fraction of $\bar{c}$
h_n = stick-fixed n.p. location, fraction of $\bar{c}$
h_n' = stick-free n.p. location, fraction of $\bar{c}$
L = lift force
M = pitching moment about c.g.
n.p. = neutral point
P = power available at the engine shaft
q = freestream dynamic pressure, $(\rho/2)V^2$
S = wing reference area
T = thrust force
V = velocity, true airspeed
W = aircraft weight at test time
Z = vertical coordinate, downward positive
α = aircraft aerodynamic angle of attack
γ = flight path angle with respect to the horizon
Δ = delta, symbol used for differences
δ = stabilator deflection angle, positive for trailing edge down (TED)
∂ = partial, symbol used in partial derivatives
η_p = propulsive efficiency, TV/P
ρ = air density

Introduction

THRUST line offset affects not only aircraft that are configured for high or low thrust lines, such as amphibious aircraft or transports with external engine nacelles, but also those aircraft that are configured for centerline thrust and undergo significant changes of the vertical c.g. position due variation in payload, fuel, stores, etc.

It is of interest to know what extent offset thrust lines affect longitudinal stability flight tests.

Neutral Points

Static longitudinal stability relates to the initial tendency of the aircraft to return to a trim condition after a pitch disturbance. This requires restoring moments. Typically, moments are expressed in nondimensional coefficient form with the c.g. as reference point. With pitch-up moments defined positive, the criterion for stability is

$$C_{m_\alpha} < 0 \tag{1}$$

The neutral point can be seen as that special c.g. location, where the aircraft shows neither a diverging nor a restoring response to a pitch disturbance. This implies that C_{m_α} is zero. Since c.g. locations ahead of the n.p. cause stability, and c.g. locations behind the n.p. cause instability, neutral point determination is essential for the establishment of the c.g. envelope of the aircraft.

A measure for the static longitudinal stability of an aircraft is the static margin $(h_n - h)$. Etkin[1] derived a relationship between the longitudinal stability derivative and the static margin (p. 24)

$$C_{m_\alpha} = -C_{L_\alpha}(h_n - h) \tag{2}$$

For the rigid aircraft with nonmoving elevator, h_n is referred to as stick-fixed neutral point. Similarly, a stick-free neutral point h_n' can be determined with the elevator freely floating.

Flight Test

In flight test, the pitching moments about the c.g. cannot be measured directly and must be obtained by indirect methods. A relationship between the elevator deflection δ_{trim} at steady flight conditions and C_{m_α} was derived in Etkin[1] (p. 27 ff):

$$\frac{\partial \delta_{\text{trim}}}{\partial C_L} = -\frac{C_{m_\alpha}}{C_{m_\delta}C_{L_\alpha} - C_{m_\alpha}C_{L_\delta}} \tag{3}$$

Therefore, $\partial\delta_{\text{trim}}/\partial C_L$ is zero when C_{m_α} is zero or when $h = h_n$, see Eq. (2). This is the basis of flight test techniques,[2] where δ_{trim} and C_L data are taken at steady flight conditions, and the slopes $\partial\delta_{\text{trim}}/\partial C_L$ are determined for a range of c.g. positions. A plot of these slopes vs c.g. positions then permits finding h_n, by extrapolating the curve to zero.

Similar considerations lead to a correlation between the stick-force slopes $\partial(F_s/q)/\partial C_L$ and h_n'.

Etkin points out that this method is only valid if the coefficients occurring in Eq. (3) do not change during the testing.

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A problem of the conventional flight test method is that it relies on speed changes to obtain different values of the lift coefficient. This is contrary to wind-tunnel tests, where the model can be rotated through a range of lift coefficients at constant tunnel speed. The speed changes in flight testing *do* affect Eq. (3), particularly for aircraft with offset thrust lines. Two examples are discussed in the following.

Offset Thrust Line, Jet Aircraft

At a given power setting, it is reasonable to assume the net thrust of a jet aircraft to remain constant during moderate speed changes. This is reflecting the characteristic of a typical turbojet, which counters increased ram drag with increased gross thrust. This is not true for turbofans or propellers, which change thrust with speed.

A sample aircraft is considered to be in a steady flight condition (trimmed), and equipped with a constant thrust device (turbojet), mounted above the c.g. such that the inlet normal force has no arm (Fig. 1). The only contribution of the thrust device to aircraft pitching moments is then the direct thrust moment

$$M_{TH} = TZ_{TH} \tag{4}$$

or in nondimensional coefficient form

$$C_{m_{TH}} = \frac{T}{qS}\frac{Z_{TH}}{\bar{c}} \tag{5}$$

with Z_{TH} being the thrust arm, i.e., the distance between the c.g. and the thrust force, perpendicular to the thrust line of action. For a thrust line parallel to the flight path, Z_{TH} becomes identical to the Z coordinate of the thrust line in a stability axes system, with $Z_{TH} > 0$ for a low thrust line, and $Z_{TH} < 0$ for a high thrust line.

Since neither the magnitude nor the arm of the thrust force change significantly during pitch disturbances at constant speed, $C_{m_{TH}}$ does not change with α (Fig. 2, curve *a*). This means that the thrust term has no stability contribution:

$$C_{m_{\alpha TH}} = 0 \tag{6}$$

If data are obtained in free flight with equilibrium at different speeds, we must impose the condition

$$L = W\cos\gamma \tag{7}$$

or

$$C_L = \frac{W\cos\gamma}{qS} \tag{8}$$

Using

$$C_L = C_{L_\alpha}\alpha \tag{9}$$

the moment contribution of the thrust becomes

$$C_{m_{TH}} = \frac{T}{W\cos\gamma}\frac{Z_{TH}}{\bar{c}}C_{L_\alpha}\alpha \tag{10}$$

or

$$C_{m_{TH}} = (\text{const})\alpha$$

This is shown as curve *b* in Fig. 2. Curves *d* and *e* show the corresponding graphs for an aircraft with a low thrust line.

The slopes of curves *b* and *e* have been interpreted as actual stability contributions in some text,[3-5] however, it must be

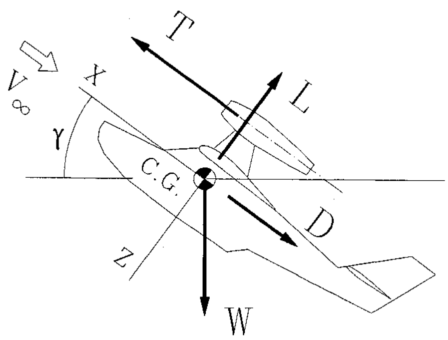

Fig. 1 Constant thrust aircraft (turbojet) with high thrust line.

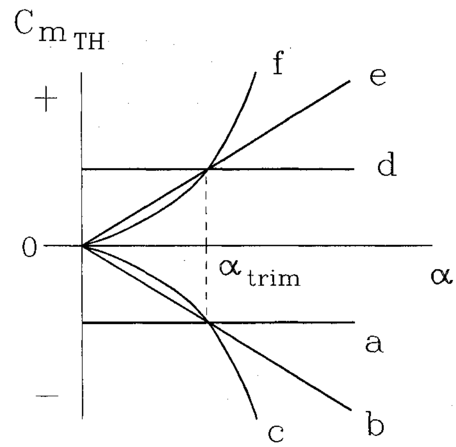

Fig. 2 Thrust moment coefficient vs angle of attack.

pointed out that they are *not*. The slopes of these curves are generated by a change of the dynamic pressure which affects the moment coefficients, but not the moments themselves. Therefore, at constant thrust, a high thrust line does not stabilize the aircraft, nor does a low thrust line destabilize the vehicle in pitch, as is claimed in these texts.

Neutral Point Shift, Jet Aircraft

The speed effects discussed above result in an apparent neutral point shift, which does not reflect changes in pitch stability. If we denote the apparent stability contribution of the high or low thrust line as ΔC_{m_α} (Fig. 2, curves *b* and *e*), then we can modify Eq. (2):

$$C_{m_\alpha} + \Delta C_{m_\alpha} = -C_{L_\alpha}(h_n + \Delta h_n - h) \tag{11}$$

Subtracting Eq. (2) yields

$$\Delta C_{m_\alpha} = -C_{L_\alpha}\Delta h_n \tag{12}$$

The term ΔC_{m_α} is the derivative of Eq. (10) with respect to alpha:

$$\Delta C_{m_\alpha} = \frac{T}{W\cos\gamma}\frac{Z_{TH}}{\bar{c}}C_{L_\alpha} \tag{13}$$

With Eq. (12) we finally get

$$\Delta h_n = -\frac{T}{W\cos\gamma}\frac{Z_{TH}}{\bar{c}} \tag{14}$$

This is the desired expression, relating the apparent neutral point shift obtained in flight test Δh_n, to thrust line offset Z_{TH}.

Conventional stability flight tests of an aircraft with a high thrust line ($Z_{TH} < 0$) will therefore result in an elevator-position neutral point behind the stick-fixed neutral point ($\Delta h_n > 0$, point *B* vs point *A* in Fig. 3, respectively), and a stick-force neutral point behind the stick-free neutral point ($\Delta h_n' >$

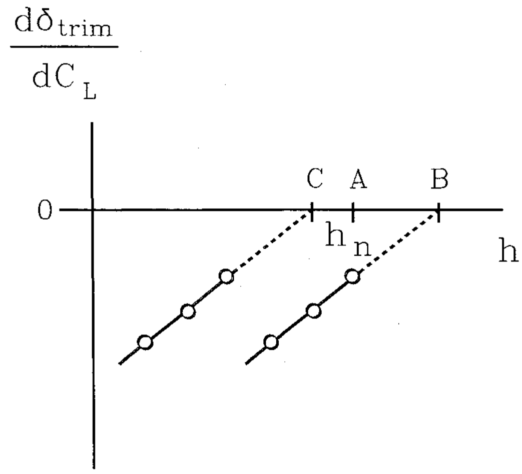

Fig. 3 Neutral points determined from flight test data (B = high thrust line, C = low thrust line) vs pitch stability neutral point (A).

0). Similarly, for low thrust lines ($Z_{TH} > 0$), the flight test neutral points are ahead of the pitch stability neutral points ($\Delta h_n < 0$, point C vs point A in Fig. 3).

A potential hazard exists when, e.g., a flight is attempted with an aircraft loaded such that the c.g. is ahead of the elevator-position neutral point, but behind its stick-fixed neutral point. In this case the pilot and test team are led to believe that the aircraft has a positive static stability margin, while in fact the aircraft is unstable in pitch.

Offset Thrust Line, Propeller Aircraft

At constant power settings, the thrust of a propeller aircraft is inversely proportional to speed:

$$T = (\eta_p P/V) \tag{15}$$

Therefore, as speed decreases, thrust increases. This effect is somewhat diminished by a reduction of propulsive efficiency at lower speed, but still there is a thrust increase that has a pitch-down effect for high thrust lines, and pitch-up for low thrust lines.

This thrust variation with speed has no direct impact on the pitch stability of the aircraft at constant speed, but it influences stability indirectly, since in free flight angle-of-attack changes are followed by speed changes, caused mainly by changes in lift induced drag.

With regard to neutral point determination, these effects tend to increase the apparent neutral point shift beyond the one found for jet aircraft. This can be estimated as follows.

Again, if data are taken at steady flight conditions, the velocity in Eq. (15) can be written as

$$V = \sqrt{\frac{W \cos\gamma}{S} \frac{2}{\rho} \frac{1}{C_{L_\alpha}\alpha}} \tag{16}$$

and the thrust becomes

$$T = \eta_p P \sqrt{\frac{S}{W \cos\gamma} \frac{\rho}{2} C_{L_\alpha}\alpha} \tag{17}$$

Here, the propulsive efficiency and the climb angle are subject to variation with speed, and therefore, angle of attack, too. However, for a first approximation in the analysis of a stability flight test with constant power setting and only moderate speed variation about a trim condition, they may be assumed constant.

Inserting Eq. (17) into Eq. (10) yields

$$C_{m_{TH}} = \eta_p P \left(\frac{C_{L_\alpha}}{W \cos\gamma}\right)^{3/2} \sqrt{\frac{\rho}{2} S}\, \frac{Z_{TH}}{\bar{c}}\, \alpha^{3/2} \tag{18}$$

or

$$C_{m_{TH}} = (\text{const})\alpha^{1.5}$$

This result is shown as curve c in Fig. 2 for a propeller aircraft with a high thrust line, and as curve f for a low thrust line prop.

Neutral Point Shift, Propeller Aircraft

As before, the change of the aircraft C_m vs α curve slope due to thrust is equal to the derivative of the direct thrust moment coefficient $C_{m_{TH}}$, Eq. (18), with respect to α

$$\Delta C_{m_\alpha} = \frac{\partial C_{m_{TH}}}{\partial \alpha} = \frac{3}{2} \eta_p P \left(\frac{C_{L_\alpha}}{W \cos\gamma}\right)^{3/2} \sqrt{\frac{\rho}{2} S}\, \frac{Z_{TH}}{\bar{c}}\, \alpha^{1/2} \tag{19}$$

with Eq. (12), the apparent neutral point shift becomes

$$\Delta h_n = -\frac{3}{2} \eta_p P \left(\frac{1}{W \cos\gamma}\right)^{3/2} \sqrt{\frac{\rho}{2} S C_{L_\alpha}\alpha}\, \frac{Z_{TH}}{\bar{c}} \tag{20}$$

Numerical Examples

For simulated flight tests, a sample aircraft was modeled in a computer program. The model assumed a parabolic drag polar and considered steady flight conditions. Trim drag was ignored. With respect to moments about the c.g., the program considered the contributions of wing lift, wing zero lift pitching moment, thrust, and horizontal tail.

Pitching moment contributions from the fuselage, propeller or inlet normal force, prop wash, drag terms, or others, were assumed to be zero since the main focus of this investigation was on the effect of thrust line offset. Wing downwash at the tail location was estimated (Ref. 1, appendix D). Key parameters could be read into the program as variables. Reference 6 contains more details.

For a given set of simulated flight test conditions, the program determined the load of the horizontal tail from the required equilibrium of pitching moments, and the corresponding elevator deflection and hinge moment. These were considered "flight test data" and were used for subsequent neutral point calculations.

Selected examples for the simulated flight test data are shown in Figs. 4–7. Comparing Fig. 6 with Fig. 4 and Fig. 7 with Fig. 5, reveals that the effect of the high thrust line on the required elevator deflection and stick-force for trim is similar to a forward shift of the c.g. This makes sense since the requirement of balanced pitching moments in steady flight leads to a large tail download to balance either the thrust moment or the pitch-down moment of a forward c.g.

This does not mean, however, that the effect of a high thrust line on pitch stability is similar to a forward shift of the c.g., as was shown before. Figures 6 and 7 also imply, that for a high thrust line aircraft, stable slopes of the elevator position and stick force vs velocity diagrams do not necessarily mean that the aircraft is stable in pitch.

Figures 8 and 9 show examples for data reduction plots resulting in elevator-position neutral points and stick-force neutral points. Figure 8 shows the elevator-position neutral point for centerline thrust on both propeller and jet aircraft to be 50.1% $\bar{c}$, and Fig. 9 shows the stick-force neutral point to be at 57.9% $\bar{c}$ (square symbols). These points are identical with the stick-fixed neutral point and the stick-free neutral point of the aircraft, respectively. The fact that the stick-free n.p. is 0.078$\bar{c}$ behind the stick-fixed n.p. means that the aircraft shows more stability with the stabilator freely floating than with it held in a fixed position. In general, a freely floating elevator reduces the tail power and its contribution to stability; in this case, however, the special tail geometry and tab gearing[6] cause the tail angle of attack to increase a limited amount, thereby adding pitch stability.

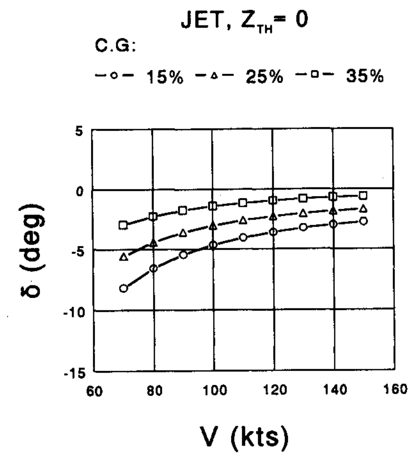

Fig. 4 Elevator deflection vs airspeed for different c.g. locations.

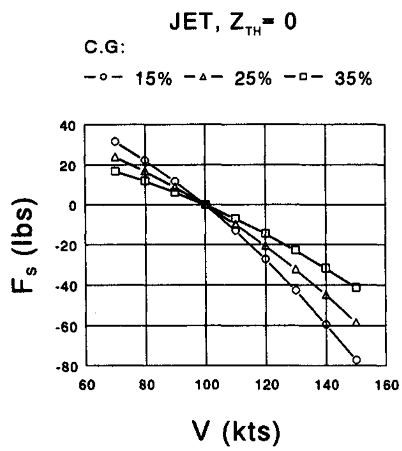

Fig. 5 Stick force vs airspeed for different c.g. locations.

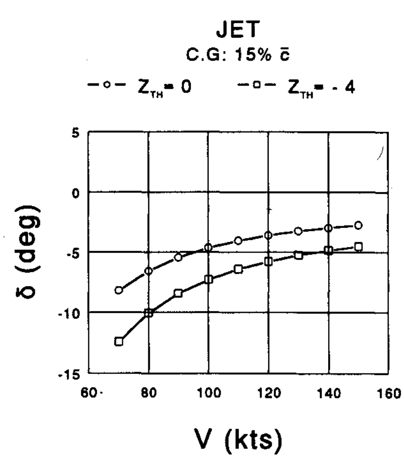

Fig. 6 Elevator deflection vs airspeed for centerline thrust and high thrust line.

Moving the jet thrust line to a position 4 ft above the c.g. causes an apparent rearward shift of 16.3% $\bar{c}$ for both the elevator-position neutral point and the stick-force neutral point (triangular symbols). This is in excellent agreement with Eq. (14), $\Delta h_n = 0.163$.

For the propeller aircraft with a 4-ft-high thrust line, the elevator-position and stick-force neutral point are shifted rearward by 22.9% $\bar{c}$, or 6.6% $\bar{c}$ further aft than for the jet aircraft (circular symbols).

Equation (20) predicts the apparent n.p. shift for the propeller aircraft to be $\Delta h_n = 0.244$. This is 1.5% $\bar{c}$ more than the n.p. shift derived from flight test data. The difference can be explained by the fact that Eq. (20) assumes constant propulsive efficiency and climb angle, which vary somewhat during flight test.

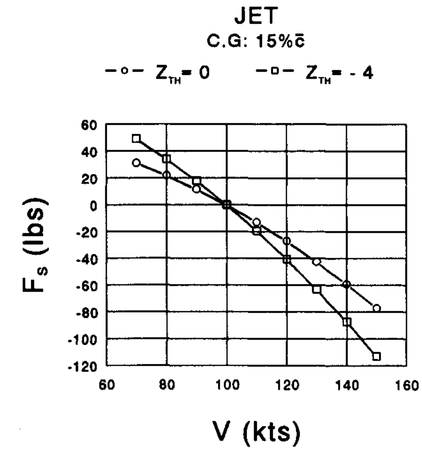

Fig. 7 Stick force vs airspeed for centerline thrust and high thrust line.

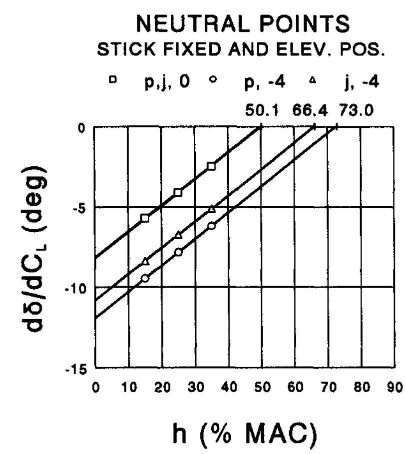

Fig. 8 Data reduction diagram for stick-fixed and elevator-position neutral points (p = prop; j = jet; 0, -4 = Z_{TH} in feet).

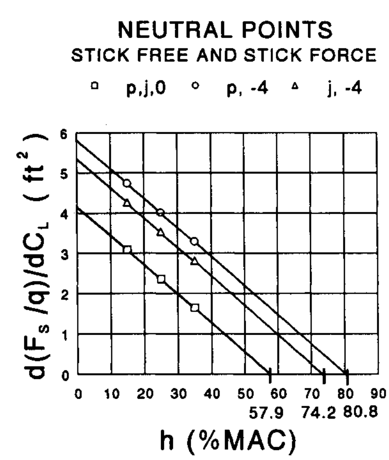

Fig. 9 Data reduction diagram for stick-free and stick-force neutral points (p = prop; j = jet; 0, -4 = Z_{TH} in feet).

Conclusions

It has been shown from theoretical considerations and from computer simulated flight tests that conventional flight test methods on aircraft with offset thrust lines lead to neutral points that differ significantly from actual pitch stability neutral points, obtained from wind-tunnel tests or unconventional flight tests that avoid the effects of speed variation.

For high thrust line aircraft, the elevator-position neutral points and the stick-force neutral points obtained from conventional flight tests, are *behind* the corresponding stick-fixed and stick-free neutral points. This poses a potential hazard, e.g., when a flight is attempted with an aircraft loaded such that the c.g. is ahead of the elevator-position neutral point, but behind its stick-fixed neutral point. In this case the pilot and test team are led to believe that the aircraft has a positive static stability margin, while in fact the aircraft is unstable in pitch.

For low thrust line aircraft, the elevator-position and stick-force neutral points obtained from conventional flight tests, are *ahead* of the stick-fixed and stick-free neutral points, respectively. If the flight test neutral points are used to establish aft c.g. limits, then these limits are unnecessarily restrictive, prohibiting flight at loadings for a range of aft c.g. positions, where the aircraft is actually stable in pitch.

The scope of this article is limited to the effects of offset thrust lines on flight test neutral points and their relation to pitch stability. This is of major importance for the establishment of c.g. limits, e.g., during developmental test flights of prototype aircraft. It is not the intention of the author to question the general validity of certification flight testing. Flight tests at different speeds, c.g. positions, configurations, and power settings are important for assuring not only static stability, but also acceptable dynamic flight characteristics and adequate handling qualities.

Elevator position and stick-force neutral points relate directly to positions and forces of control sticks or yokes vs velocity in steady flight. Stable slopes of these curves are desirable characteristics, and are in part required by regulations. It has been shown here, however, that for aircraft with significant thrust line offset, stable "trim curve slopes" are neither a necessary nor a sufficient condition for pitch stability.

Recommendations

To substantiate these findings, the author recommends actual flight tests to be conducted, that isolate and measure the effects of offset thrust lines.

In addition, the possibility of conducting flight tests that permit the prediction of pitch stability at aft c.g. positions without the adverse effects of speed variation, seems worth investigating.

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