The Stick-force/Speed Characteristics of Various Types of Tails and Elevator Trimmers

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Introduction

The object of this paper is to indicate, in broad outline, the stickforce/speed characteristics of various combinations of types of horizontal tail and elevator trimmer arrangements. The main consideration is the *shape* of the stick-force/speed curve; numerical values must be determined by detailed calculation. Most of the relevant equations are given without proof, and apply only to a rigid aircraft in incompressible flow. If required, derivations may be found in Ref. 1.

Steady level flight conditions are assumed throughout.

Section I – Aerodynamic Stick Forces

A. Conventional Tail, no tab

$$P_e = \frac{b_2}{a_2}\frac{W}{S}\frac{m_e S_n c_n}{\bar{V}_T} K'_n \left(1 - \frac{V_i^2}{V_{io}^2}\right) \qquad (1)$$

For a given K'_n and V_{io}, the shape of the curve will be as follows:

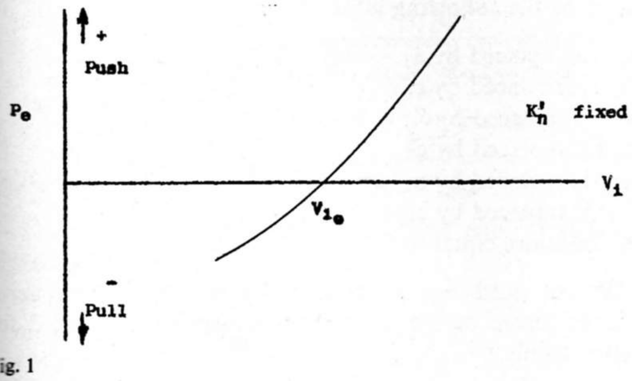

Fig. 1

If C_{Lo} corresponds to V_{io}, i. e.

$$W = L = C_{Lo} \tfrac{1}{2}\rho_o V_{io}^2 S \qquad (2)$$

Then

$$K'_n C_{Lo} = C_{Mo} - \bar{V}_T \bar{a}_1 \eta_T \qquad (3)$$

So, for a given η_T, $K'_n C_{Lo}$ is constant.

The stick-force/speed gradient may be written

$$\frac{dP_e}{dV_i} = -\frac{b_2}{a_2}\frac{m_e S_n c_n}{\bar{V}_T} \rho_o K'_n C_{Lo} V_i \qquad (4)$$

The effect of varying the C. G. position, and hence K'_n, is that C_{Lo} varies so that $K'_n C_{Lo}$ stays constant. At a given V_i, dP_e/dV_i is therefore also constant. The effect of altering the C. G. position is therefore to move the curve shown in Fig. 1 vertically (Fig. 2).

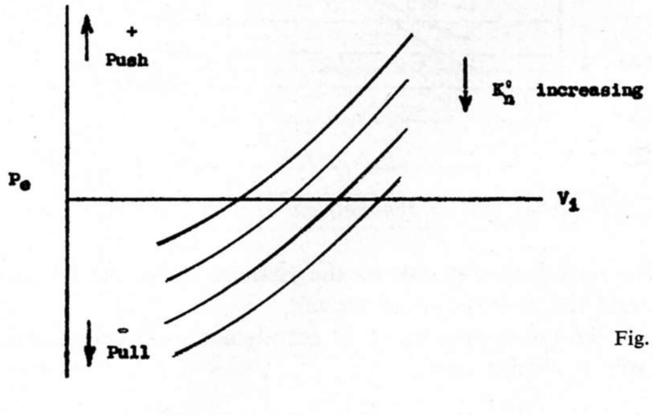

Fig. 2

The slope of each curve is proportional to V_i.

The above curves are shown with a positive (i. e. a 'correct') slope.

The slope will be reversed, for a positive K'_n, if n_T is such that C_{Lo} is negative.

B. Conventional Tail with 'Flettner' elevator tab

The equation for the stick force is (1) above.

The lift coefficient at which the aircraft is in trim with zero stick force varies with tab angle as follows:

$$C_{L_o} = \frac{C_{M_o} - \bar{V}_T (\bar{a}_1 \eta_T + \bar{a}_3 \beta)}{K_n'} \qquad (5)$$

Since $\bar{a}_3$ is negative, more positive (downward) deflections of the tab give increased values of C_{Lo} and hence lower values of V_{io}.

At a given $K_{\dot{n}}$, the only quantity in equn. (1) which varies with β is V_{io}. So, for different tab angles we obtain a series of curves as in Fig. 3.

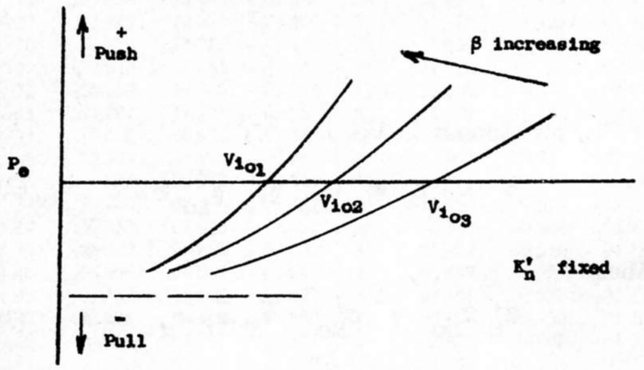

Fig. 3

For any one curve, the slope varies like V_i, but at a series of trimmed speeds (V_{io1}, V_{io2}, ... etc.), the slope varies like $1/V_{io}$.

Other things being equal, the stick force is proportional to $K_{\dot{n}}$, so at different values of $K_{\dot{n}}$, but adjusting the tab setting so that V_{io} is the same in each case, we get Fig. 4:

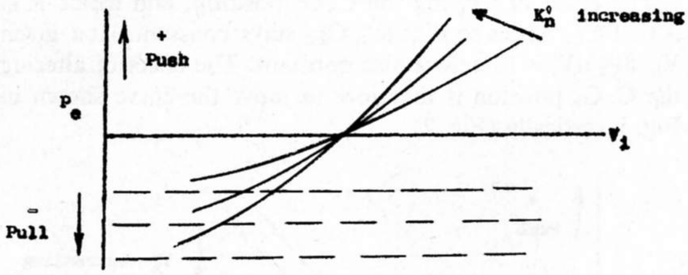

Fig. 4

C. All-moving tail of symmetrical section, no tab

The stick force depends on the moment of the tail lift force about the pivot point of the tail.

If the tail is pivoted at its aerodynamic centre, the stick force is always zero.

If the tail is pivoted at x_T forward of its aerodynamic centre as follows in Fig. 5:

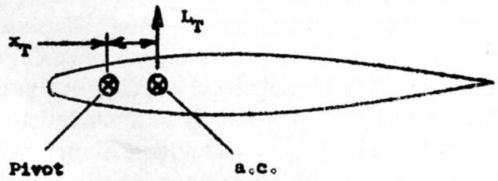

Fig. 5

$$P_e = m_e L_T x_T \qquad (6)$$

and

$$L_T = \frac{C_{M_o} \tfrac{1}{2}\rho_o V_i^2 S\bar{\bar{c}} + (h - h_o)\bar{\bar{c}} W}{l_T'} \qquad (7)$$

With C_{Mo} negative, the gradient dP_e/dV_i will always be negative:

$$\frac{dP_e}{dV_i} = \left(\frac{m_e x_T S_T \rho_o}{\bar{V}'}\right) C_{M_o} V_i \qquad (8)$$

So for various C. G. positions we get Fig. 6:

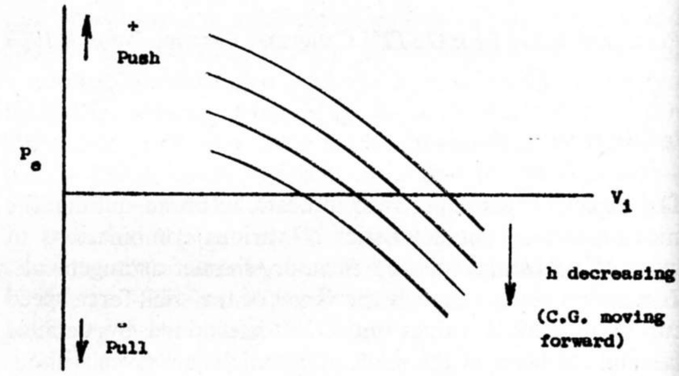

Fig. 6

This arrangement is therefore impracticable. The 'correct' slope would be obtained by making x_T negative but $\partial C_{HT}/\partial n_T$ would then be positive and the tail itself would then be unstable with respect to stick movements.

D. All-moving tail with geared tab

Basic section symmetrical, pivoted at the aerodynamic centre of the basic section

The behaviour is similar to the conventional tail in para B subject to the following adjustments:

a_2 is replaced by $a_1 + ka_3$
b_2 is replaced by $c_3\beta$
s_η is replaced by S_T
c_η is replaced by c_T
$\bar{a}_1$ is replaced by a_1
$\bar{a}_3$ is replaced by a_1/k.
$K_{\dot{n}}$ becomes equal to K_n.

The tail need not necessarily be pivoted at the aerodynamic centre of the basic section. See Refs. 1 and 2 for further details.

E. All-moving tail of cambered section, no tab

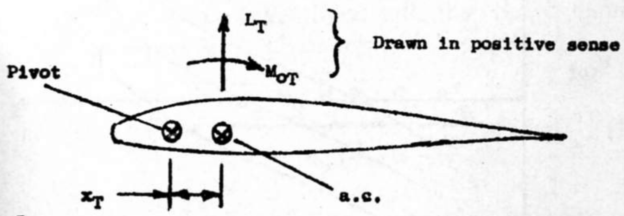

Fig. 7

Instead of equn. (6) we have:

$$P_e = m_e L_T x_T - m_e M_{oT} \tag{9}$$

Whence

$$\frac{dP_e}{dV_i} = m_e \rho_o S_T c_T \left[\frac{C_{Mo}}{\bar{V}'}\frac{x_T}{c_T} - C_{MoT}\right] V_i \tag{10}$$

C_{Mo} will usually be negative, so $\frac{dP_e}{dv_i}$ can be made positive by making C_{MoT} sufficiently negative (i. e. by using positive camber).

i. e.
$$(-C_{MoT}) > \left(-\frac{C_{Mo}}{\bar{V}'}\cdot\frac{x_T}{c_T}\right) \tag{11}$$

Since the gradient is proportional to V_i and is independent of the C. G. position at a given V_i, the characteristics are similar to those described in para A. Fig. 2 will also apply in this case. The necessary tail camber would be reduced by making x_T smaller: in the limit, x_T could be zero, but the effective b_2 of the tail would also then be zero.

Section II – Mechanical Stick Forces provided by springs

Three types are considered: (i) a spring with a positive 'rate' fixed to a lever arm of constant length. The spring attachments can be moved to alter the elevator angle for zero force. (ii) a spring of zero rate (in effect, one of infinite length applying a force independent of elevator deflection) with a variable length of lever arm and (iii) an arrangement similar to (ii) but with a spring of positive rate. Other more complicated arrangements are obviously possible, e. g. by making the effective length of lever arm a function of elevator angle.

F. Spring of positive rate, constant lever arm

See Fig. 8.

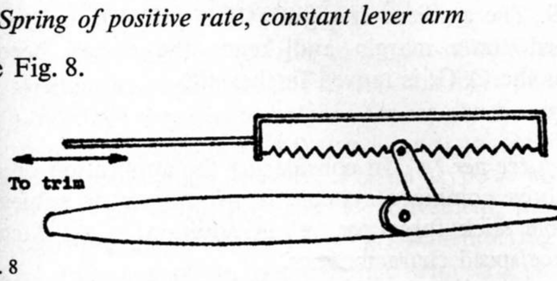

Fig. 8

For any type of tail, the variation of control angle with speed is of the form

$$\eta_{trim} = \eta_o - \frac{K_1}{V_i^2} \tag{12}$$

where K_1 is a positive constant proportional to the stick-fixed static margin.

With the arrangement shown in Fig. 8, the stick force due to the spring will be

$$P_{es} = K_2(\eta_{trim} - \eta_1), \tag{13}$$

where K_2 is a constant proportional to the spring rate and η_1 is a datum setting adjustable by the pilot.

Hence, from (12) and (13):

$$\begin{aligned} P_{es} &= K_2\left(\eta_o - \eta_1 - \frac{K_1}{V_i^2}\right) \\ &= P_o - \frac{K}{V_i^2}, \end{aligned} \tag{14}$$

where P_o is now a datum stick force, adjustable by the pilot.

Equn. (14) therefore corresponds to a series of curves, all of the same shape, displaced vertically by an amount depending on the value of P_o, see Fig. 9.

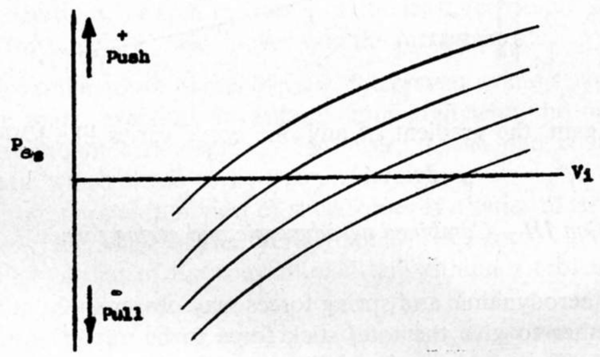

Fig. 9

The gradient of these curves is proportional to $1/V_i^3$.

G. Spring of zero rate, variable lever arm

See Fig. 10.

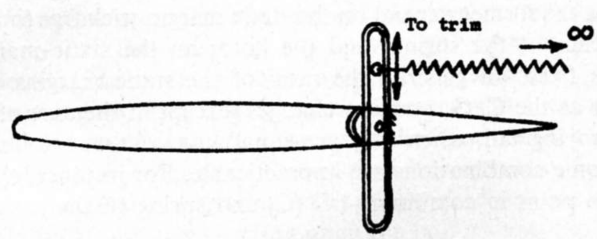

Fig. 10

Since P_{es} will be independent of control deflection, the curves will be simply as follows in Fig. 11:

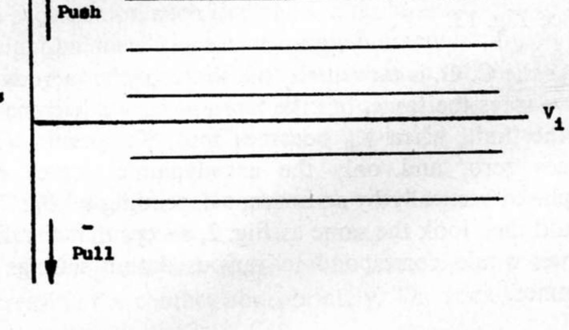

Fig. 11

H. Spring of positive rate, variable lever arm

In effect, the arrangement is as shown in Fig. 10, but with a spring of finite length.

Equation (14) is replaced by

$$P_{es} = P_o \left(1 - \frac{K_3}{V_i^2}\right), \tag{15}$$

and Fig. 12 illustrate the possible characteristics of such a system.

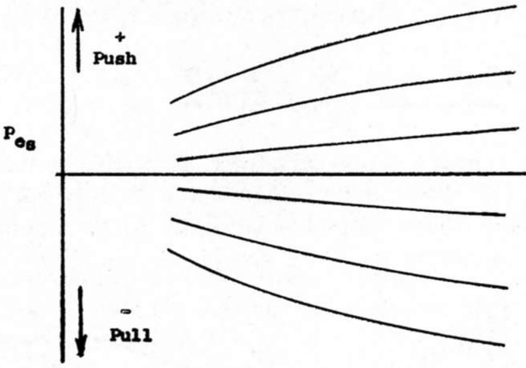

Fig. 12

Again, the gradient of any one curve varies like $1/V_i^3$.

Section III – Combined aerodynamic and spring forces

The aerodynamic and spring forces may obviously be added together to give the total stick force to be applied by the pilot. The number of possible combinations is obviously very large, and only a selection is given here, assuming in all cases that the stick-fixed and stick-free static margins are positive. Again, interest is concentrated on likely shapes of curves: the actual values, and to some extent the shapes, will depend on the relative magnitude of the aerodynamic and spring forces. Moreover, the relative magnitude of the aerodynamic and spring forces may alter with C. G. position, since the former depend on the static margin stick free (in the absence of the spring) and the latter on the static margin stick fixed. In general, the ratio of the static margins will alter as the C. G. position changes (except in the case of an allmoving tail, when they are equal).

Some combinations are impracticable. For instance, there is no point in combining tail (C) and spring (G).

Combination J. Tail (A) or (E) and Spring (F)

Adding Fig. 1 and Fig. 9, the curves of total stick force at a given C. G. position would become:

See Fig. 13.

As the C. G. is moved aft, the shape of the 'aerodynamic' curve stays the same, but the 'spring' curves become flatter. In the limit, when K_n becomes zero, K in equn. (14) becomes zero, and only the aerodynamic curves remain, displaced vertically by an amount depending on P_o. The plot would then look the same as Fig. 2, except that the different curves would correspond to various datum settings of the trimmer.

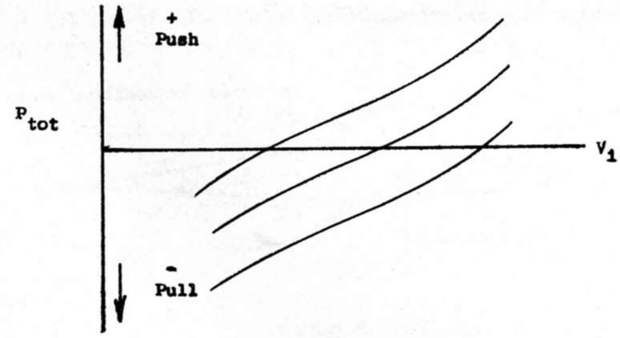

Fig. 13

Combination K. Tail (A) or (E) and Spring (G)

The curve of Fig. 1 is displaced vertically by an amount depending on the spring stick-force. A series of curves are obtained, all of the same shape. See Fig. 14.

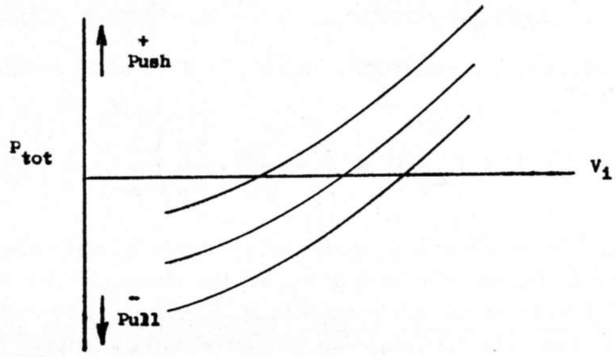

Fig. 14

Since the shape of the aerodynamic curves is independent of C. G. position, the above curves will apply *at all C. G. positions* provided sufficient spring moment is available.

Combination L. Tail (A) or (E) and Spring (H)

The shape of the curves will be in between those of Figs. 13 and 14. The remarks on the effect of C. G. position relating to Combination J also apply in this case.

Combination M. Tail (C) pivoted at its aerodynamic centre and Spring (F)

Since the tail provides no aerodynamic stick force, the stick forces are due solely to the spring and will be as shown in Fig. 9. The gradient at a given V_i is proportional to the stick-fixed static margin and hence the curves become flatter as the C. G. is moved further aft.

Stick-force per 'g'. In considering the application of any of the above combined systems, it is important to achieve a reasonable stick force per 'g' in addition to satisfactory stick-force/speed characteristics.

In general, the stick force arising from a pull-out manoeuvre will be due to:

(i) The aerodynamic elevator hinge moment.

(ii) A mechanical moment arising from the elevator deflection when a positive-rate spring is used.

(iii) An inertia moment due to a bob-weight.

(i) In the case of a conventional tail, the 'aerodynamic' stick-force per 'g' is given by:

$$\frac{P_e}{n-1} = \frac{m_e\, b_2\, W\, S_\eta\, C_\eta\, H'_m}{a_2\, \bar{V}_T\, S}, \tag{16}$$

where H'_m is the stick-free manoeuvre margin calculated without taking into account the effect of any bob-weight in the elevator circuit. An equation of similar form applies to the all-moving tail with geared tabs.

This stick-force is proportional to b_2, other things being equal. It follows that the aerodynamic stick-force per 'g' will always be zero for any tail whose effective b_2 is zero. This will apply to any allmoving tail, not fitted with geared tabs, and pivoted at its aerodynamic centre.

In the case of tail (E)—the all-moving tail of cambered section—there will be an effective b_2 if it is pivoted forwards of its aerodynamic centre. In fact, $b_2\, c_n/a_2$ in Equn. (16) is simply x_T, and S becomes S_T. A suitable aerodynamic stick-force per 'g' can therefore be achieved by the appropriate choice of x_T, subject to providing satisfactory stick-force/speed characteristics.

(ii) The 'spring' stick-force per 'g', given a spring with a positive rate, will depend on the spring rate, the stick-elevator gear ratio and the elevator travel per 'g'. The latter quantity, for a conventional tail, is given by

$$-\frac{V_T\, a_2\, \Delta\eta}{(n-1)\, C_{L_0}} = H_m, \tag{17}$$

Analogous expressions will apply to any other type of tail where C_{LO} is now the lift coefficient in level flight corresponding to the speed at which the manoeuvre is carried out. Whereas the aerodynamic stick-force per 'g' is independent of speed, the spring stick force per 'g' will be inversely proportional to the square of the speed. If, for example, we consider an all-moving tail without a tab, pivoted at its aerodynamic centre, and fitted with a positive rate spring, the only stick-force (in the absence of a bob weight) will be due to the spring. If the stick-force per 'g' is to be reasonable at moderate speeds, it is likely to be considerably too low at high speeds.

This contribution to the stick-force per 'g' will be zero when zero-rate springs are fitted.

(iii) The stick force per 'g' due to an out-of-balance weight moment is simply the same as the stick force under static conditions required to balance the weight moment. It is therefore independent of speed, and no aerodynamic considerations are involved. For any type of tail, a bob weight therefore provides a convenient method of adjusting the stick-force per 'g', remembering that in the presence of an aerodynamic trim tab, a positive weight moment increases the stick-free static margin.

Further considerations. It will be seen that the above considerations enable one to devise an arrangement whose characteristics are independent of the position of the centre of gravity of the aircraft. For example, consider the cambered tail (E), pivoted at its aerodynamic centre.

The aerodynamic stick force will be simply

$$P_e = -m_e\, C_{MOT}\, \tfrac{1}{2}\rho_0\, V_i^2\, S_T\, c_T \tag{18}$$

giving a parabolic curve as shown in Fig. 1, whose datum may be shifted by means of a constant force zero-rate spring acting at a variable moment arm. With this arrangement, stick-force per 'g' can only be provided by means of a bob-weight. If this is done, both the stick-force/speed curve and the stick-force per 'g' are independent of the C. G. position.

Under such circumstances, the conditions governing the permissible range of centre of gravity positions would be:

(a) The forward limit would be determined by stressing considerations or the ability to flare-out after a slow approach, or the occurrence of excessively negative tail lift coefficients at high speeds.

(b) The aft limit would be determined by stressing considerations, or spin recovery, or the least acceptable stick travel per 'g', which-ever was the most critical.

From the above points of view, the system would seem to have many practical advantages compared with the more conventional arrangements. However, it has one characteristic which needs to be examined further.

From the point of view of stick forces at a series of steady speeds, the *shape* of the 'aerodynamic' stick force curve is similar to that of the conventional tail without a tab, as in Fig. 1.

It seems to behave as if b_2 had a value, as in equn. (1). But since C_{MOT} is constant, both b_1 and b_2 are in fact zero for this tail. The variation of stick force arises solely from the V_i^2 term in equn. (18), other quantities being constant, and not from any changes in control angle. Putting it another way (dP_e/da) exists, subject to the condition $L = W$, but $(\delta P_e/\delta a_T)$ at constant V_i does not exist. But to the pilot, flying at a series of steady speeds with $L = W$, the distinction would not be apparent. However, with a zero-rate spring, no change in 'spring' stick force would occur on moving the stick. So, if the effect of any bob-weight is temporarily neglected, and if the machine were in trim with zero stick force at a given speed, small stick movements at that speed would not requires any tick force and the 'feel' would be appropriate to b_2 being zero. There would be inertia stick forces as a consequence of heaving and pitching accelerations (due to the stick movement) acting upon the bob-weight, but it is not clear that such inertia forces would provide satisfactory characteristics. Despite the effective b_2 being zero, nothing very alarming would occur under quasi-steady-state conditions if the stick were released in an out-of-trim condition. The machine would perform a pitching manoeuvre with a normal acceleration such that the inertia moment due to the bob-weight balanced the aerodynamic moment acting on the tail. It is by no means clear that the dynamic stability of the machine, stick-free, would be positive: with b_2 effectively zero, Ref. 3 suggests that it would probably be markedly unstable.

If an effective b_2 is to be provided, there seem to be only three ways of doing so:

(i) By pivoting the tail ahead of its aerodynamic centre, increasing the camber appropriately. The stick force per 'g' is then affected by the C. G. position, although to a lesser extent than for a normal tail.

(ii) By using a normal fixed tail and moving elevator. The stick force per 'g' is again altered by changing the C. G. position.

(iii) By providing some auxiliary surface which always trails at zero lift when the aeroplane is trimmed, but connected by suitable gearing to the elevator circuit. Probably unacceptable in pratice for glider application.

Conclusions

1. In summarizing the main conclusions, comparison should be made with a conventional tail-elevator-tab system, or with an all-moving tail with a geared tab, the tab datum being variable for trimming purposes. In both cases, the aerodynamic stick force is of the form

$$P_e = \text{const.} \times (1 - V_i^2/V_{io}^2)\,, \tag{19}$$

where V_{io} is varied by adjusting the tab and the constant is proportional to the stick-free static margin.

For a given static margin and trimmer setting, the slope of the curve is proportional to V_i. Altering the trimmer setting stretches or contracts the curve along the V_i axis, so that at a series of trimmed speeds, the slopes of the corresponding curves vary like $1/V_{io}$.

2. For a conventional tail without a tab, or for an all-moving cambered tail pivoted ahead of its aerodynamic centre, equn. (19) also applies, but V_{io} now depends on the C. G. position. Altering the C. G. position changes V_{io} and the constant in such a fashion that only the datum of the curves is altered and they are simply moved up or down, remaining the same shape. Using a constant-force spring at a variable moment arm for trimming gives stick-force/speed characteristics which are independent of C. G. position. The stick force per 'g' varies slightly with C. G. position.

If the cambered tail is pivoted at its aerodynamic centre, any stick-force per 'g' will have to be provided by a bob-weight, and will also be independent of C. G. position. However, the tail will have an effectively zero b_2.

3. If an all-moving symmetrical tail is used without a tab, pivoted at its aerodynamic centre, the aerodynamic stick-force will always be zero. Any stick force must be provided by a positive-rate spring, and the stick-force/speed gradient then varies like $1/V_i^3$. The stick-force per 'g' due to the spring will vary like $1/V_i^2$, and will usually have to be supplemented by the provision of a bob-weight.

References

(1) *Irving, F. G.* 'An Introduction to the Longitudinal Static Stability of Low-Speed Aircraft'. Pergamon, 1966.

(2) *Irving, F. G.* 'All-moving Tailplanes'. OSTIV Publication VII. (1963 OSTIV Congress, Argentina).

(3) *Jones, R. T., and Cohen, D.* 'An Analysis of the Stability of an Airplane with Free Controls.' NACA Report Nr. 709, 1941.

List of Symbols

- a lift-curve slope of aircraft-less-tail
- a^1 $\delta c_{LT}/\delta\alpha_T$
- a_2 $\delta C_{LT}/\delta\eta$
- a_3 $dC_{LT}/\delta\beta$
- $\bar{a}_1$ $\delta C_{LT}/\delta\alpha_T$ } With $C_H = O$ (elevator free)
- $\bar{a}_3$ $\delta C_{LT}/\delta\beta$ }
- b_2 $\delta C_H/\delta\eta$
- C_H elevator hinge moment coefficient $H/\frac{1}{2}\rho_o v_i S\eta C\eta$
- C_L lift coefficient of the aircraft
- C_{Lo} lift coefficient corresponding to a trimmed condition (i. e. when $C_{MG} = O$)
- C_{LT} tail lift coefficient $L_T/\frac{1}{2}\rho_o v_i^2 S_T$
- C_{Mo} pitching moment coefficient of the aircraft-less-tail about its aerodynamic centre
- C_{MOT} pitching moment coefficient of the tail about its aerodynamic centre $M_{OT}/\frac{1}{2}\rho_o V_i^2 S_T C_T$
- C_{MG} pitching moment coefficient of the complete aircraft about its centre of gravity
- $\bar{c}$ mean aerodynamic chord of the aircraft-less-tail
- c_T mean aerodynamic chord of the tail
- $c\eta$ elevator mean chord
- c_3 $d\,C_{MOT}/\delta\beta$ for an all-moving tail with tab
- g acceleration due to gravity
- H aerodynamic elevator hinge moment
- H_m manoeuvre margin, stick fixed
- H_m' manoeuvre margin, stick free
- h centre of gravity position (dimensionless) aft of L. E. of $\bar{c}$
- h_o position of aerodynamic centre of aircraft-less-tail (dimensionless) aft of L. E. of $\bar{c}$
- K_n static margin, stick-fixed
- K_n' static margin, stick-free
- k tab/tailplane gear ratio
- L lift on complete aircraft
- L_T tail lift
- l_T distance from aerodynamic centre of aircraft-less-tail to a. c. of tail
- M_{OT} pitching moment of the tail about its aerodynamic centre
- m_e elevator/stick gear ratio, radians/ft
- n load factor, L/W
- P_e stick force applied by the pilot to balance an aerodynamic moment, positive in the push-forward sense.
- P_{es} stick force applied by the pilot to balance a spring moment
- P_{etot} total stick force applied by the pilot
- S gross wing area
- S_T tail area, including control surfaces and tabs
- $S\eta$ elevator area
- V_i equivalent airspeed
- V_{io} equivalent airspeed at which the aircraft is in trim (i. e. when $C_{MG} = O$)
- $\bar{V}'$ tail volume coefficient $l_T S_T/\bar{c}S$
- V_T effective tail vol. coeff., stick fixed, $\bar{V}'/(1 + F)$, where $F = \dfrac{S_T}{S}\dfrac{a_1}{a}(1 - d\varepsilon/d\alpha)$
- $\bar{V}_T$ effective tail vol. coeff., stick free, $\bar{V}'/(1 + \bar{F})$, where $\bar{F} = F\bar{a}_1/a_1$
- W all-up weight of aircraft
- x_T distance of tail pivot point forward of tail aerodynamic centre
- α aircraft incidence (relative to zero-lift line of aircraft-less-tail)
- α_T tail incidence
- β tab angle

ε downwash angle at the tail
η elevator angle
η_T tail setting angle
ρ_o sea-level air density

Summary of the Properties of various Tail Configurations

	Effect of Speed dP_e/dV_i varies like	$(dP_e/dV_i)_o$ varies like	Effect of C.G. position on $(dP_e/dV_i)_o$	Stick force per 'g' (no bob weight)	Other effects
1. Conventional tail/ elevator/tab	V_i	$1/V_{io}$	Proportional to K'_n	Proportional to H'_m	
2. All-moving symmetrical tail with geared tab, pivoted at 0.25 c. Variable tab datum for trimming	V_i	$1/V_{io}$	Proportional to K'_n, and $K'_n = K_n$	Proportional to H'_m	Tab angle always zero at V_{io}
3. Conventional tail and elevator, no tab. Trimming by positive rate spring	$AV_i + B/V_i^3$ (A and B consts)	$AV_{io} + B/V_{io}^3$	Constant A unaffected. B proportional to K_n	Depends on H_m and H'_m	
4. Conventional tail and elevator, no tab. Trimming by zero-rate spring with variable arm	V_i	V_{io}	Unaffected	Depends on H'_m	
5. All-moving symmetrical tail, no tab. Trimming by positive rate spring	$1/V_i^3$	$1/V_{io}^3$	Proportional to K_n	Depends on H_m	Effective b_2 entirely due to spring rate
6. All-moving symmetrical tail. Pivot at 0.25 c. Geared tab with fixed datum. Trimming by zero-rate spring with variable arm	V_i	V_{io}	Unaffected	Depends on H'_m	
7. All-moving cambered tail, no tab. Pivot at 0.25 c. Trimming by zero-rate spring with variable arm	V_i	V_{io}	Unaffected	Zero	Effective $b_2 = 0$
8. As above, but pivot ahead of 0.25 c.	V_i	V_{io}	Unaffected	Depends on H_m	Effective b_2 exists

For brevity, '0.25 c.' is used to mean 'the aerodynamic centre of the basic section'.
Suffix 'o' implies a trimmed condition.

Zusammenfassung

Der Bericht gibt einen Überblick über Gleichungen und Kurvenformen der Höhensteuerhandkraft als Funktion der Geschwindigkeit für verschiedene Anordnungen des Höhenleitwerkes und der Trimmung (anwendbar auf eine starre Zelle in inkompressibler Strömung).

1. Aerodynamische Kraft

A. Übliches Leitwerk, keine Trimmklappe, Gleichung 1, Figuren 1 und 2.
B. Übliches Leitwerk, mit «Flettner»-Klappe, Figuren 3 und 4.
C. Pendelruder mit symmetrischem Profil ohne Trimmklappe, Figuren 5 und 6.
D. Pendelruder mit symmetrischem Profil mit angetriebener Klappe, Ruderdrehachse in der Druckmittellinie. Diese verhält sich ähnlich B, obgleich verschiedene Parameter in den entsprechenden Gleichungen erscheinen.
E. Pendelruder mit gewölbtem Profil, keine Trimmklappe, Gleichung 9, Figur 7.

2. Mechanische Kraft, durch Federn aufgebracht

F. Feder mit positivem «Anteil», mit konstantem Hebelarm, Gleichung 14, Figuren 8 und 9.
G. Feder mit Null-«Anteil», mit veränderlichem Hebelarm, Figuren 10 und 11.
H. Feder mit positivem «Anteil», mit veränderlichem Hebelarm. Gleichung 15, Figur 12.

3. Zusammengesetzte aerodynamische und Federkräfte

I. Leitwerk A oder E mit Feder F, Figur 13.

K. Leitwerk A oder E mit Feder G, Figur 14.

L. Leitwerk A oder E mit Feder H; die Kurven liegen für diesen Fall zwischen denen von Figur 13 und 14.

M. Leitwerk C mit Ruderdrehachse in der Druckmittellinie mit Feder F. Hier gibt es keine aerodynamische Kraft, deshalb sind die Kurven wie in Figur 9.

Die Handkraft «g» hängt auch von dem Typ des verwendeten Systems ab. Sie wird aus drei Komponenten zusammengesetzt:

1. Aerodynamisches Scharniermoment.
2. Mechanisches Moment, herrührend vom Höhenruderausschlag, wenn eine Feder mit positivem «Anteil» vorhanden ist.
3. Trägheitsmoment, vom Trimmklappengewicht kommend.

Die Komponente 1. ist in Gleichung 16 für ein übliches Leitwerk gegeben. Sie verschwindet für ein Pendelruder (im Druckmittelpunkt aufgehängt), wenn nicht belastende Trimmruder angebracht sind. Sie ist vorhanden bei gewölbten Profilen, wenn diese vor dem Druckmittelpunkt gelagert sind. Die Komponente 2. ist nur bei Federn mit positivem «Anteil» vorhanden. Sie hängt von der Federkennlinie, dem Auftrieb und dem Ruderwinkel per «g» ab. Für ein übliches Leitwerk gilt Gleichung 17. Die Komponente 3. ist unabhängig von der Geschwindigkeit.

Es ist möglich, eine Anordnung zu ersinnen, die die gleichen Eigenschaften für alle Schwerpunktlagen ergibt. Eine solche wäre Leitwerk E, im Druckmittelpunkt gelagert, mit einer Null-«Anteil»-Feder konstanter Kraft an einem veränderlichen Hebelarm. Überausgleich oder Klappengewicht wären notwendig, um Handkräfte über «g» zu erzeugen. Diese Eigenschaften wären wünschenswert. Jedoch ist es nicht klar, dass die dynamische Stabilität positiv sein würde (Ref. 3 deutet an, dass sie merklich negativ sein kann). Die Instabilität könnte aber auch durch andere Massnahmen vermieden werden.

Zacher

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