Tail loads due to abrupt longitudinal manoeuvres

Proposed Modification of the Specifications on Manoeuvring Loads in the OSTIV Airworthiness Reqs. for Sailplanes

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1. The actual OSTIV Specifications

The actual OSTIV specifications on the loads arising from an abrupt elevator deflection (par. 3.54 of the 1966 edition) state the following:

3.54. *Manoeuvring Loads.* Manoeuvring loads due to control surface deflection shall be calculated from the following assumptions.

3.541. At speed V_M, the full movement of the ailerons, elevator and rudder is assumed to take place separately for each control.

3.542. At speed V_D, ⅓ of the full movement of the ailerons elevator and rudder is assumed to take place separately for each control.

3.543. 75% of the loads obtained in sub-para 3.541 for the elevator and rudder are assumed to be acting simultaneously.

Notes: (i) Such rough handling shall be assumed that the sailplane does not change its attitude before full control movements are achieved. The loads applied shall be assumed to be balanced by inertia forces.

(ii) For the calculation of manoeuvring loads on the horizontal tail surfaces, the assumptions prescribed in sub-paragraphs 3.541 and 3.542 may be replaced by a rational investigation of a pitching motion in which the manoeuvring load factor corresponding with the speed under consideration is just reached. The method used shall be acceptable to the National Authority.

First of all, it should be remarked that the OSTIV specifications are not clearly stated. If η_{trim} is the elevator deflection for the equilibrium of the sailplane at steady airspeed V_M or V_D, at $n = 1$ and η_{max} is the maximum deflection (positive or negative, measured with respect to the elevator neutral position) as limited by elevator stops, two or three different interpretations seem to be possible for the value of the incremental elevator deflection specified by OSTIV at V_M or V_D, respectively:

at airspeed V_M:

1) $\Delta\eta = \eta_{max} - \eta_{trim}$ (elevator deflected to the stops)

$\eta = \eta_{trim} + \Delta\eta = \eta_{max}$

2) $\Delta\eta = \eta_{max}$

(in this case, if $\eta_{trim} \neq 0$, as in general, it will be

$\eta = \eta_{trim} + \Delta\eta < \eta_{max}$ for deflection upwards and

$\eta = \eta_{trim} + \Delta\eta > \eta_{max}$ for deflection downwards

or viceversa)

at airspeed V_D:

1) $\Delta\eta = \frac{1}{3}(\eta_{max} - \eta_{trim})$

$\eta = \eta_{trim} + \Delta\eta = \frac{1}{3}\eta_{max} + \frac{2}{3}\eta_{trim}$

2) $\Delta\eta = \frac{1}{3}\eta_{max}$

$\eta = \eta_{trim} + \eta_{trim}/3$

3) $\Delta\eta = \frac{\eta_{max}}{3} - \eta_{trim}$

$\eta = \eta_{max}/3$

For a better understanding, let us take, as an example, a sailplane having:

$\eta_{trim} = +3°$ at V_M, $\eta_{trim} = +5°$ at V_D, $\eta_{max\,up} = -24°$

$\eta_{max\,down} = +18°$

We would obtain:

at V_M: 1) $\Delta\eta_{up} = \eta_{max\,up} - \eta_{trim} = -24° - 3° = \underline{-27°}$

$\eta = \eta_{trim} + \Delta\eta_{up} = 3° - 27° = -24° = \eta_{max\,up}$

$\Delta\eta_{down} = \eta_{max\,down} - \eta_{trim} = +18° - 3° = \underline{+15°}$

$\eta = 3° + 15° = 18° = \eta_{max\,down}$

2) $\Delta\eta_{up} = \eta_{max} = \underline{-24°}$

$\eta = \eta_{trim} + \Delta\eta_{up} = 3° - 24° = -21°$ ($< \eta_{max\,up}$)

$\Delta\eta_{down} = +18°$

$\eta = 3° + 18° = +21°$ ($> \eta_{max\,down}$)

$\eta = \eta_{max} = +15°$, $\Delta\eta = +15°$ should therefore be taken in this case)

at V_D: 1) $\Delta\eta_{up} = \frac{1}{3}(\eta_{max\,up} - \eta_{trim}) = \frac{1}{3}(-24° - 5°) = \underline{-9.7°}$

$\eta = \eta_{trim} + \Delta\eta = 5° - 9.7° = -4.7°$

$\Delta\eta_{down} = \frac{1}{3}(\eta_{max\,down} - \eta_{trim}) = \frac{1}{3}(+18° - 5°) = \underline{+4.3°}$

$\eta = 5° + 4.3° = 9.3°$

2) $\Delta\eta_{up} = \eta_{max\,up}/3 = -24°/3 = \underline{-8°}$

$\eta = \eta_{trim} + \Delta\eta = 5° - 8° = -3°$

$\Delta\eta_{down} = \eta_{max\,down}/3 = +18°/3 = \underline{+6°}$

$\eta = 5° + 6° = +11°$

3) $\Delta\eta_{up} = \frac{1}{3}\eta_{max\,up} - \eta_{trim} = -\frac{24°}{3} - 5° = \underline{-13°}$

$\eta = \eta_{trim} + \Delta\eta = 5° - 13° = -8°$

$\Delta\eta_{down} = \frac{1}{3}\eta_{max\,down} - \eta_{trim} = \frac{+18°}{3} - 5 = \underline{+1°}$

$\eta = 5° + 1° = 6°$

It can be seen that, different values of $\Delta\eta$ correspond to these different assumptions and, therefore, different values of the tail incremental loads which are directly proportional to $\Delta\eta$ and V^2.

It would be difficult to say which one should be considered as correct, as these specifications have no rational basis, although allowance is made in Note (ii) of par. 3.543 for a rational investigation. In fact, the resulting tail incremental loads are not related to the maximum incremental load factor at the sailplane C. G. as resulting from the manoeuvring n—V envelope. It may thus happen (and usually it does) that the maximum incremental load factor (Δn_{max}) resulting from the OSTIV specifications, largely exceeds the Δn_{max} imposed by the manoeuvring n—V envelope at the corresponding airspeed.

Moreover, if a large horizontal tail (tailplane plus elevator) is designed on a particular sailplane for the sake of ensuring equilibrium and static stability margin (with both fixed and free elevator) at extreme C. G. locations, the manoeuvring tail incremental loads calculated according to the OSTIV Reqs. result unduly large, whereas their magnitude should always be related to the resulting Δn_{max} and not to the size of the tail itself.

In other words, it does not seem reasonable to impose such high manoeuvring loads on the tail (and, consequently, on the fuselage) if the wing is not capable to carry the resulting normal accelerations.

Another criticism to the OSTIV specifications is suggested by considerations on the ratio between incremental loads at V_D and V_M, respectively. If the assumption 2 (at V_M and V_D) is considered valid, the incremental tail loads at V_M and V_D, respectively, give a ratio of 3 to 1. This is absolutely exact only if $\eta_{trim} = 0$ (see comment at point 2, $V = V_M$, above), but it is approximately verified in any practical case.

Now, if the OSTIV minimum values for V_M ($V_M = V_{S1} \sqrt{n_1}$) and V_D ($V_D = 3.25\,w + 150$ km/h) are chosen by the designer, the ratio between these two airspeeds results:

$$\frac{V_M}{V_D} = \sqrt{w}\sqrt{C_{L\,max}}\left(0.0983 + \frac{4.53}{w}\right) \quad \left(\text{being } w = \frac{W}{S}\left[\frac{kg}{m^2}\right]\right)$$

By taking $C_{L\,max} = 1.3$, as an example, the resulting ratio $(V_D/V_M)^2$ is given in the following table as a function of the wing loading:

w	20	25	30	35	40	50
$\left(\frac{V_D}{V_M}\right)^2$	2.75	2.54	2.43	2.36	2.33	2.32

It can be seen that $(V_D/V_M)^2$ is a decreasing function of w in the practical range of used wing loadings. Moreover, its value is always less than three.

In such a situation, tail incremental loads at V_D would always be less than at V_M. This does not necessarily mean that consideration of tail incremental loads at V_D are unnecessary, as the resultant tail load (incremental tail load + balance load corresponding to the steady pre-manoeuvre flight condition) is generally of interest for stressing purposes: balance loads are usually higher at V_D than at V_M.

The modern trend, however, towards fast sailplanes stimulates the choice of V_D higher than $\sqrt{3}$ times V_M (or $\sqrt{3}\sqrt{n_1} = \sim 4$ times V_S, according to OSTIV Reqs. for n_1). In this case, incremental tail loads at V_D become higher than at V_M, and resultant tail loads usually much higher at V_D than V_M. A strong limitation to the choice of high V_D arises, therefore, from the tail loads, this being in evident contrast with the specified manoeuvre load factors which are smaller at V_D than at V_M (+4 and —1.5 at V_D, instead of +5,3 and —2.65 at V_M). V_D limitations, in the author's opinion, should reasonably come from gust cases and flutter prevention criteria, not necessarily from tail loads.

2. The Unchecked Longitudinal Manoeuvre

An attempt is made by the author to correlate in a simple way the maximum tail incremental load (ΔP) to the corresponding maximum incremental manoeuvring load factor ($\Delta n_{max} = n_{lim} - 1$) imposed by the regulations.

Reference is made here to the author's paper 'On the Dynamic Response of Sailplanes to Longitudinal Manoeuvres', 'Aero Revue' for May–June 1967.

In this study, the instantaneous unchecked manoeuvre was investigated by application of the classical dynamic equations to the two typical sailplanes A and B, the data of which are reported on the table at par. 5.

Calculations were carried out for a wide range of C. G. locations. Moreover, the effect of wide variations of the tail volume coefficient and of the sailplane longitudinal moment of inertia was separately investigated.

The calculations were carried out by use of an analogue recording computer.

The analysis of recorded data showed that the load factor response to the unchecked instantaneous manoeuvre is of the aperiodic or quasi-aperiodic type. In other words, Δn_{max} resulted in all cases equal to (or slightly different from) the asymptotic value Δn_∞. This result is due to the ratio between the damping coefficient and the natural damped frequency being always considerably high on sailplanes. A confirmation of this fact may be found in the study referred to, in which the frequency of the 'short period oscillation' on sailplanes was found to be remarkably low and of the same order of magnitude as the 'phugoid oscillation', this resulting from low values of the natural damped frequency.

The reasonable assumption $\Delta n_{max} = \Delta n_\infty$, therefore, made it possible to derive the following simple expression of the maximum tail incremental load:

$$(*) \quad \Delta P = -S_t \frac{W}{S}\frac{1}{\bar{V}}\left[N_{tailless} - x_{CG} + a_t \bar{V} k_t \left(\frac{1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) + \frac{\rho g l_t}{2W/S}\right)\right](n_{lim} - 1)$$

where:

S_t = horizontal tail surface (m^2)
W/S = max. wing loading (kg./m^2)
$\bar{V}$ = $S_t\, l_t/Sc$ = tail volume coefficient
l_t = tail arm (m)
S = wing area (m^2)
c = wing reference chord (m)
x_{CG} = distance of C. G. aft of leading edge of wing reference chord, expressed as a fraction of this chord
$N_{tailless}$ = neutral point of the aircraft less tail (expressed as ratio of its x coordinate from the leading edge of c, to c)
a_t = horizontal tail lift curve slope (per degree)
a = wing lift curve slope (per degree)
$1 - d\varepsilon/d\alpha$ = downwash factor at the tail
n_{lim} = max. specified limit load factor (from n—V manoeuvre envelope)
ρ = air density (kg m^{-4} sec^2)
g = acceleration of gravity (m sec^{-2})
K_t = tail efficiency (dynamic pressure at the tail $= k_t \frac{1}{2}\rho V^2$)

By the introduction of the following conservative values:

$N_{tailless} = 0{,}25$
$K_t = 1$
$\rho = 0{,}125 \text{ kg m}^{-4} \text{ sec}^2$
$g = 9{,}81 \text{ m. sec}^{-2}$

the above expression may be further simplified as follows:

$$(^\circ) \quad \Delta P = -S_t \frac{W}{S} \frac{l}{\bar{V}} \left[0.25 - x_{CG} + a_t \bar{V} \left(\frac{1}{a} \left(1 - \frac{d\varepsilon}{d\alpha}\right) + 0.613 \frac{l_t}{W/S} \right) \right] (n_{um} - 1)$$

The following remarks are evident from this expression:

1) ΔP increases as x_{CG} decreases, i. e. as the C. G. is shifted forwards; ΔP is maximum, therefore, at the max. forward C. G. location.
2) At a given C. G. location, ΔP increases with W.
3) ΔP is independent of the sailplane longitudinal moment of inertia.
4) ΔP is directly proportional to the incremental normal load factor (n—1) and independent of the airspeed. The only dependence on the airspeed derives indirectly from the fact that the regulations may, and usually do specify, different values of the limit load factor at the various design airspeeds.

3. *The Checked Longitudinal Manoeuvres*

The following objection was made to the possible adoption of the expression (^) or (°) in the OSTIV Requirements: does the instantaneous unchecked manoeuvre case cover all possible types of checked manoeuvres likely to occur?

To answer this question, a new set of calculations were carried out for the sailplane B, at airspeed V_M (design manoeuvring airspeed) and C. G. at 0.25 c.

The different types of checked manoeuvres considered are illustrated on fig. 1. It can be seen that also very fast manoeuvres, with $t_1 = 0.15$ sec, have been considered (cases 10 and 11), although they seem unlikely to occur on sailplanes.

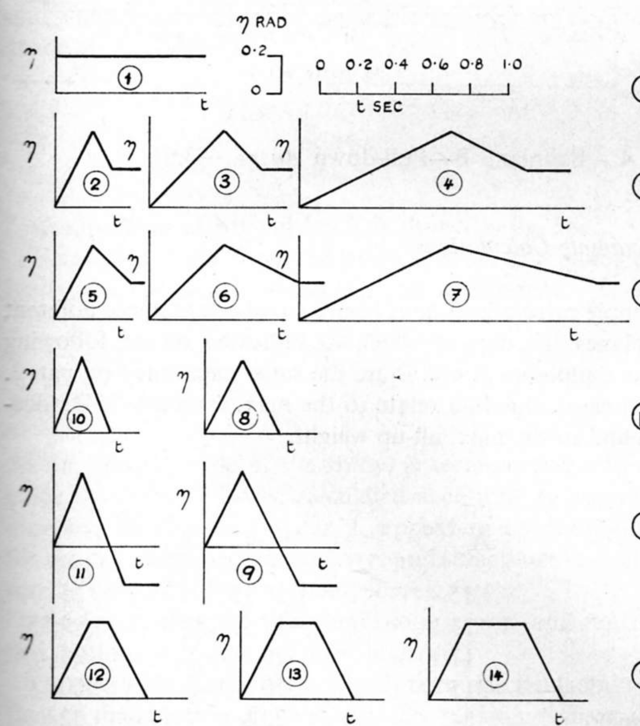

Fig. 1 – Cases of elevator manoeuvres

Note: Cases 8, 12, 13, 14 are specified for military aircraft in the American military regulations MIL-A-8861 (ASG). Specified t_1 are 0,2, 0,3, 0,4 sec.

The following response curves were obtained by use of the same analogue recording computer:

1) incremental load factor at sailplane C. G. ($n—1 = \Delta n$);
2) incremental load factor at the tail ($n_t—1 = \Delta n_t$);
3) incremental aerodynamic tail load (Δ P).

These response curves, in general, show a maximum and a minimum value of Δn_t and Δ P, as typically shown in fig. 2: they are indicated as Δn_{t1} and Δn_{t2}, ΔP_1 and ΔP_2 (down load and up load), respectively.

By imposing to Δn_{max} the limit values of the OSTIV manoeuvring n—V envelope, i. e. $\Delta n = 5{,}3—1 = 4{,}3$ and $\Delta n = —2{,}65—1 = —3{,}65$, the corresponding values of Δn_{t1}, Δn_{t2} and ΔP_1, ΔP_2 were calculated by the simple proportionality rule.

The *net* tail incremental load was then calculated by summing up algebraically $\Delta P + \Delta n_t \times W_t = \Delta P + \Delta P_i = \Delta P_n$, where W_t (= 13 kgs. for the sailplane B under consideration)

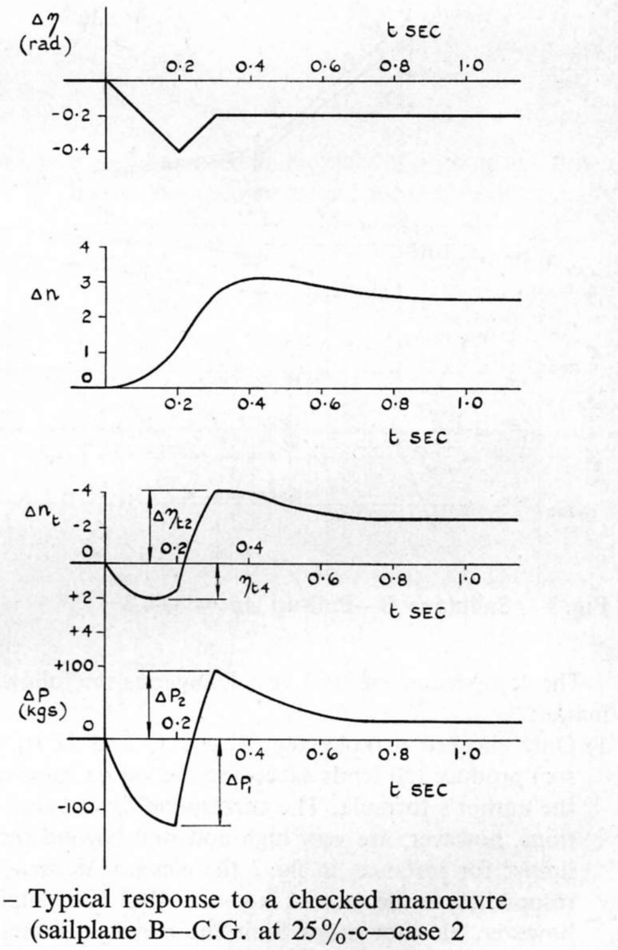

Fig. 2 – Typical response to a checked manœuvre (sailplane B—C.G. at 25%-c—case 2

is the tail weight. ΔP_i is, of course, the alleviating tail inertia load arising from the sailplane pitching acceleration.

The results are shown in fig. 3 for the pull-up manoeuvres ($\Delta n = +4.3$) and in fig. 4 for the pull-down manoeuvres ($\Delta n = —3.65$). Time t_1 for reaching the maximum elevator deflection in the various cases of checked manoeuvre, was chosen as the abscissae.

It should be noted that, owing to the proportional reduction of response curves to the same Δn_{max}, the elevator deflections $\Delta\eta$ also resulted proportionally altered, time t_1 remaining unchanged in all cases. The gradient of elevator deflection $d\eta/dt$, therefore, is different for the various cases of checked manoeuvres.

4. Comparison of Results

In the same figures 3 and 4, different horizontal lines, show the loads calculated according to the authour's formula (°) and the OSTIV loads calculated according to the assumptions 1, 2 ($V = V_M$) and 3, 4, 5 ($V = V_D$).

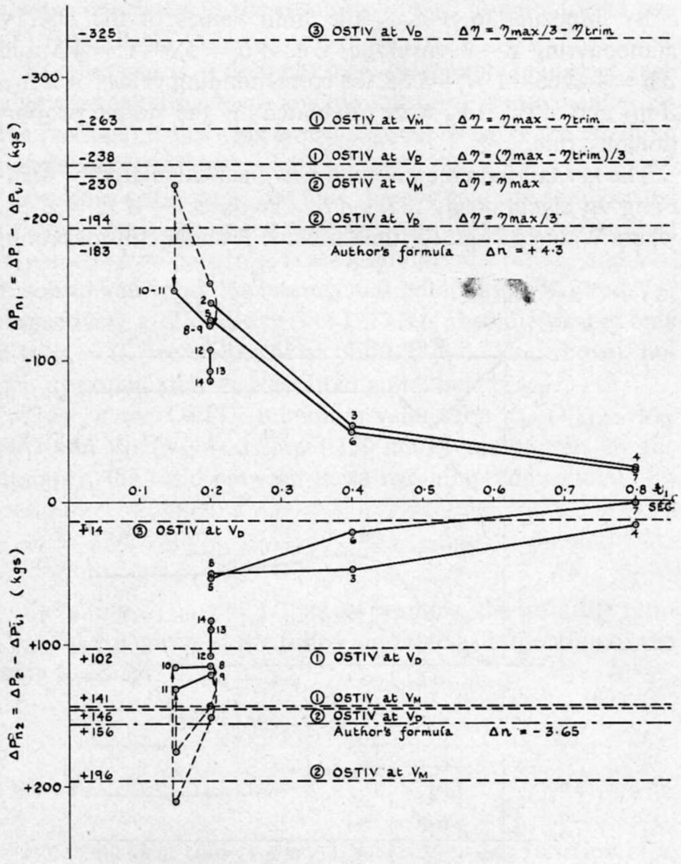

Fig. 3 – Sailplane B—Pull-up $\Delta\eta = +4.3$

The comparison on fig. 3 and 4, suggests the following remarks:

1) Only checked manoeuvres of type 10 and 11 ($t_1 = 0.15$ sec) produce tail loads exceeding the values calculated by the author's formula. The corresponding elevator deflections, however, are very high and well beyond the usual limits: for instance, in fig. 3 the elevator deflection corresponding to the case 11 is $\eta = -41°,1$. On sailplane B, however, elevator stops limit the elevator deflection to $\eta_{max} = -24°$, $+18°$. Being, at V_M, $\eta_{trim} = +3°.3$, $\Delta\eta_{max}$ cannot be greater than $-24 - 3.3 = -27°.3$, instead of $-41°.1$. If this limitation is introduced, the net tail loads are reduced accordingly, as indicated by the arrows on fig. 3 and 4. It can be seen that also cases 10 and 11 are thus reduced within the limits of the autor's formula.
2) Checked manoeuvres with t_1 higher than 0.2 sec are negligible, as far as tail incremental loads are concerned.
3) OSTIV loads appear to be unduly large on the side of ΔP_{n1} (expecially at V_D) and may be too small on the side of ΔP_{n2}. They do not completely cover the tail uploads produced by checked pull-up manoeuvres (as in cases 3, 9, 11).

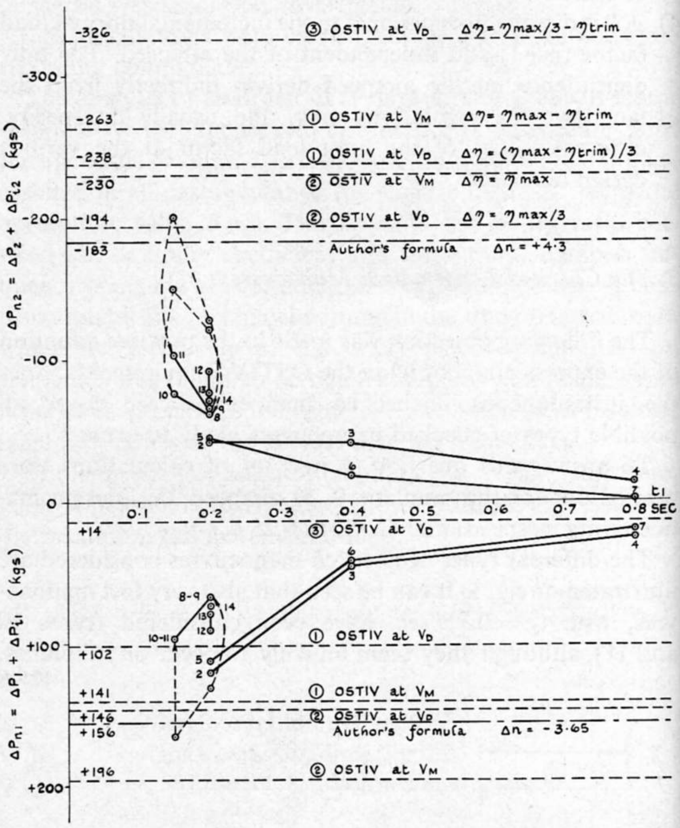

Fig. 4 – Sailplane B—Pull-down $\Delta\eta = -3.65$

5. Example Calculations

Example calculations have been carried out on three different sailplanes, the data of which are indicated on the following table. Sailplanes A and B are the same mentioned on par. 2. In all cases, the data relate to the max. forward C. G. location and to the max. all-up weight.

Sailplane		A	B	C
Wing span	b (m)	15	18.15	15
Wing surface	S (m²)	13.1	17.5	9.15
Wing aspect ratio	A	17.1	19	25
Total weight	W (kgs)	315	570	300
Wing loading	W/S (kgs/m²)	24	32.8	32.8
Wing reference chord	l (m)	0.94	1.06	0.618

Sailplane		A	B	C
Wing lift curve slope	a (per degree)	0.094	0.0945	0.0995
Horiz. tail surface	S_t (m²)	1.6	2.48	0.73
Tail arm	l_t (m)	3.7	4	3.90
Tail volume coefficient	$\overline{V}$	0.485	0.54	0.502
Tail lift curve slope	a_t (per degree)	0.075	0.0715	0.083
Downwash factor	$1-d\varepsilon/d\alpha$	0.75	0.75	0.83
	$\delta a_t/\delta\eta$	0.63	0.59	1.00 (all moving tail)
η_{max} up	(degrees)	—28°	—24°	—17°
η_{max} down	(degrees)	+20°	+18°	+ 4°
η_{trim} at V_M	(degrees)	+ 4°.56	+3°.26	+ 0°.6
η_{trim} at V_D	(degrees)	+ 7°.09	+ 5°.4	+ 2°.18
Horiz. tail weight	W_t (kgs.)	7	13	7
Moment of inertia about y	J_y (kgm/sec²)	16.2	76	34.8
Design manoeuvring speed	V_M (m/sec)	37.1	45	45.3
Design diving speed	V_D (m/sec)	70	71.7	79.2
Limit load factors at V_M	n_1	5.3	5.3	5.3
	n_4	—2.65	—2.65	—2.65
Limit load factors at V_D	n_2	4	4	4
	n_3	—1.5	—1.5	—1.5
Tail balance load, at V_M	P_b (kgs)	—29	—59	—27
Tail balance load, at V_D	P_b (kgs)	—103	—148	—43
C. G. location (max. fwd.)	x_{CG}	0.25	0.25	0.202

OSTIV aerodynamic tail incremental loads are calculated by the following expression:

$$\Delta P = a_t \frac{\partial \alpha_t}{\partial \eta} \Delta\eta \, S_t \tfrac{1}{2} \rho v^2$$

where $\Delta\eta$ is given the different values corresponding to the assumptions 1 and 2 at V_M, 1, 2 and 3 at V_D (see par. 1).

These loads are compared in fig. 5a with those calculated with the author's formula (°) (see page 7), at V_M and V_D.

Net tail incremental loads are also calculated, by adding algebraically the inertia loads P_i due to the sailplane pitching acceleration, and to the acceleration of gravity, to the loads above:

$$P_n = \Delta P + P_i = \Delta P + n_t W_t = \Delta P - \frac{\Delta P \cdot l_t^2}{g \cdot J_y} W_t - W_t$$

$$= \Delta P \left(1 - \frac{W_t l_t^2}{g \, J_y}\right) - W_t$$

Comparison of net tail loads is shown in fig. 5b.

Finally, in fig. 5c total tail loads, i. e. net tail incremental loads plus tail balance loads (P_b), are compared:

$$P = P_n + P_b$$

6. Conclusions

At the present stage of the study, it seems possible to conclude that OSTIV loads, calculated according to any of the different assumptions of par. 1, appear to be unduly large for the case of pull-up manoeuvres and sometimes inadequate for the case of pull-down manoeuvres.

Moreover, they may well impose a strong, and not justified, limitation to the choice of high V_D.

On the other hand, the author's formula yields values of the tail loads rationally related to the maximum manoeuvre load factors as imposed by the n–V manoeuvring envelope, and therefore, well balanced on the sides of both up and down loads. The checked manoeuvre cases appear to be practically

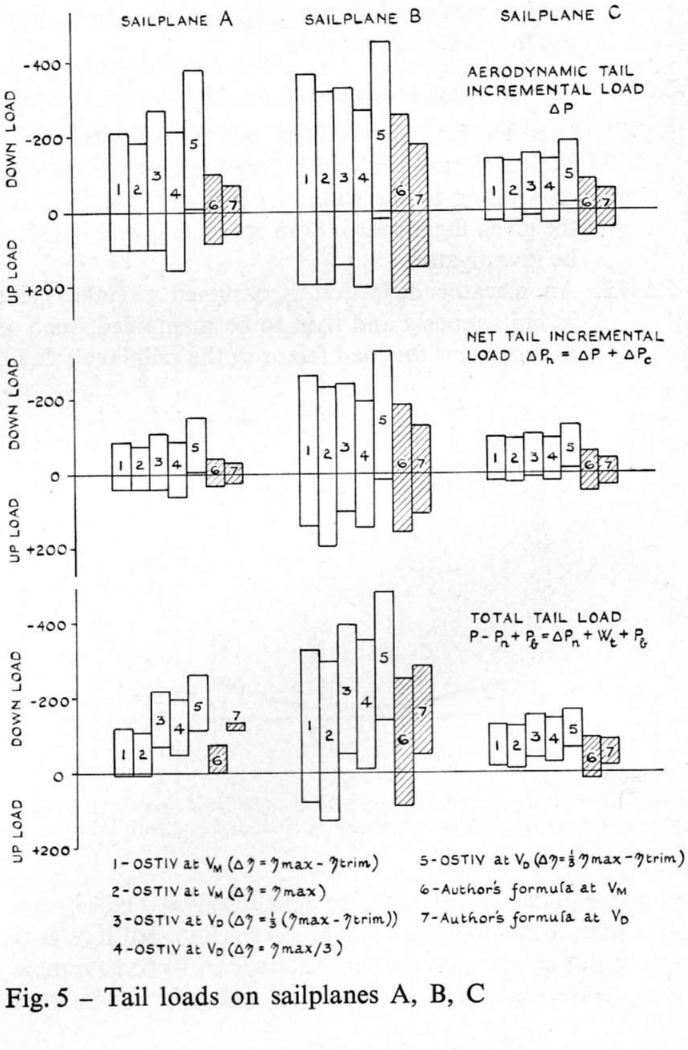

Fig. 5 – Tail loads on sailplanes A, B, C

covered, even in the case of very sharp manoeuvres, unlikely to occur in practice.

A considerable margin is certainly ensured by the following conservative assumptions on which calculations have been based:

1) infinite stiffness of the control transmission, whereas, owing to the stretching produced by aerodynamic and mass forces, the elevator deflections follow with delay and smaller peak values the displacement of the control column.
2) the aerodynamic lag has been neglected. Its existent effect is of delaying and lowering the peak values of the tail load. If the OSTIV specifications, however, are to be mantained, one of the different possible assumptions for the calculation of the incremental elevator deflections (see par. 1) should be chosen and clearly defined.
The author, however, strongly recommends the rationalisation of the OSTIV specifications as discussed in the present report. If this point of view is accepted, the new OSTIV specification might be modified as outlined in the following paragraph.
In any case, it may be useful that the new criteria are submitted to sailplane designers and national authorities for trial calculations on existent sailplanes, asking at the same time for comparison and comments.

7. *Proposed Modification of OSTIV Specifications*

3.54. *Manoeuvring Loads:* Manoeuvring loads due to control surface deflection shall be calculated from the following assumptions.

3.541. *Manoeuvring Loads due to the Elevator:*

3.5411. It is assumed that a balance load P_b acts on the horizontal tail surfaces before the manoeuvre, corresponding to the state of equilibrium (n = 1) for the given flight speed. Both speeds V_M and V_D shall be investigated.

3.5412. An elevator deflection is assumed to take place instantaneously and then to be mantained, such as to increment the load factor at the sailplane's C. G. to the corresponding limit load factor (n_{lim}) resulting from the n–V manoeuvre envelope.
The corresponding aerodynamic incremental tail load can be calculated by the following expression:

$$\Delta P = -S_t \frac{W}{S} \frac{1}{\bar{V}} \left[0.25 - x_{CG} - a_t \bar{V} \left(\frac{1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) + 0.613 \frac{l_t}{W/S}\right)\right](n_{lim} - 1)$$

where:

S_t	=	horiz. tail surface (m^2)
W/S	=	max. wing loading (kg/m^2)
$\bar{V}$	=	$S_t l_t / Sc$ = tail volume coefficient
x_{CG}	=	distance of C. G. aft of leading edge of wing reference chord, expressed as a fraction of this chord (max. fwd.).
a_t	=	horiz. tail lift curve slope (per radian)
a	=	wing lift curve slope (per radian)
$1 - \frac{d\varepsilon}{d\alpha}$	=	downwash factor at the tail
l_t	=	tail arm (m)
n_{lim}	=	limit load factor, as resulting from the V–n manoeuvre envelope at the appropiate airspeed.

3.5413. It shall be assumed that the sailplane does not change its attitude before full elevator movement is achieved. The loads applied shall be assumed to be balanced by inertia forces.

3.5414. The resultant tail load (P) shall be be calculated by summing up algebraically ΔP (par. 3.5412) to the alleviating tail inertia load P_i (3.5413) and to the balance load P_b (par 3.5411):

$$P = P_b + \Delta P + P_i$$

3.542. *Manoeuvring loads due to Ailerons and Rudder:*

3.5421. At speed V_M, the full movement of the ailerons and rudder, is assumed to take place separately for each control.

3.5422. At speed V_D, ⅓ of the full movement of the ailerons and rudder is assumed to take place separately for each control.

3.5423. It shall be assumed that the sailplane does not change its attitude before full control movements are achieved. The loads applied shall be assumed to be balanced by inertia forces.