Sailplane Stiffness Measurements

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1. Aim of measurements

The tendency to increase the permissible diving speed of sailplanes, especially evident in the post-war period, resulted in the necessity of reckoning in strength calculation with aero-elastic phenomena, particularly flutter.

As in typical aircraft structures the stiffness of individual elements of the sailplane has a decisive influence on the value of the critical flutter speed, stiffness criteria have been established for aeroplanes and are applied for quite a long time in the relevant British rules. The method of stiffness measuring was described in R & M No. 2208. However, analogous data for sailplanes are still unknown.

Hereunder you will find a description of endeavours to determine the values of criteria for individual sailplane elements, based on statistical data obtained while investigating 10 high performance sailplanes of various types specified in Table 1.

List of sailplanes used for research work

Table 1

Sailplane No.	Sailplane type	Number of seats	Weight[1] kg	Span m	Length m	Wing area m²	max. Glide ratio	Design diving speed km/h
1	Sep	1	350	17.50	7.50	17.2	26.5	250
2	Mucha-bis	1	270	15.00	6.80	15.0	25.0	250
3	Gövier-4	2	400	14.69	6.20	19.0	19.2	220
4	Minimoa	1	350	17.00	7.09	19.0	26.0	220
5	Bocian	2	450	18.00	7.50	20.0	26.0	250
6	Zuraw (Kranich)	2	465	18.00	7.70	22.7	23.6	215
7	Mucha 100	1	290	15.04	7.01	15.0	25.5	250
8	Sohaj	1	295	15.00	7.13	14.0	27.0	230
9	Jaskolka	1	340	16.00	7.42	13.6	27.0	250
10	Jastrzab	1	340	12.00	6.00	12.0	20.0	450

[1] Max. weight admissible in flight

2. Test program

The research program consisted of:

(*a*) The measurement of torsional stiffness of wings, stabilizers, controls, ailerons and fuselage;

(*b*) The measurement of flexural stiffness in the vertical plane of wings and fuselage;

(*c*) The measurement of the lateral flexural stiffness of the fuselage;

(*d*) The measurement of stiffness of control circuit systems of the elevator, the rudder, and the ailerons;

(*e*) The stiffness measurement of the aileron inter-connecting circuit.

Additionally the position of the centres of torsion of the measured wing sections was determined, as well as that of the centres of gravity of the sailplane elements.

3. Stiffness measurement method

3. 1. *Stiffness measurement of the wing and aileron*

The stiffness of the structure is understood as the ratio of the load acting at a given section to the value of the deflection at that section in relation to a previously selected section, e. g. the wing root section. As the bending and torsion stiffness of the wing changes along the span, a conventional reference section is selected, for which the calculated potential energy due to torsion is equal to the energy of the twisted wing, strictly determined as follows:

$$\frac{1}{2}\, m\theta\, \Theta^2 = \frac{1}{2}\int_0^l C\,(y) \left(\frac{d\,\Theta}{d\,y}\right)^2 dy$$

where $m\theta$ = stiffness of the reference section in relation to the wing root section,
Θ = angle of twist of that section in relation to the wing root section,
$C\,(y)$ = section torsional stiffness,
l = distance from wing root to tip.

In conventional designs the section determined in such a manner is located between 0.67—0.75 of the distance from the root to the tip of the wing, which corresponds approximately to mid aileron span. It is on this basis that the section located at mid aileron span was chosen as reference section.

To check the stiffness of the outer part of the wing, measurements were performed also at the section located at 0.9 semi-span.

Both the sections in question were in a plane parallel to the plane of symmetry of the sailplane.

3. 1. 1. *Measurements of the wing torsional stiffness*

The torsional stiffness of the wing $m\varphi$ is determined as the ratio of the torque M_s and the angular displacement of the section being investigated with reference to the root section:

$$m_y = \frac{M_s}{\varphi} \;\; (kGm/rad.)$$

The torsional moment was produced by a pair of vertical forces applied to a frame (fig. 1a) fixed at the measuring section.

Measurement of the angle of twist of the reference section and of the root section was made, depending on the magnitude of the deflections, by means of either dial gauges or rulers with a millimeter scale.

The deflections were measured by means of a bar fixed either to the investigated section near the spars (fig. 1c) or to the nose box only (fig. 1b).

The tests were performed on the complete sailplane fixed in a frame anchored to the floor. The fuselage was immobilized laterally by means of a beam at the cabin and also

Table 2 *Summary of wing and aileron stiffnesses*

Sailplane N°	Sailplane type	Wing										Ailerons					
		Torsional stiffness				Bending stiffness				Position of the centre of gravity		Inner			Outer		
		Section at 0.9 semi-span		Section at mid-aileron		Section at 0.9 semi-span		Section at mid-aileron				Torsional stiffness	Position of the centre of gravity		Torsional stiffness	Position of the centre of gravity	
		m_φ	Position of the centre of torsion	m_φ	Position of the centre of torsion	P_f	m_δ	P_f	m_δ			m_φ			m_φ		
		$\frac{KGm}{rad}$	$\%C^*$	$\frac{KGm}{rad}$	$\%C^*$	KG/m	$\frac{KGm}{rad}$	KG/m	$\frac{KGm}{rad}$	a/l	b/C^*	$\frac{KGm}{rad}$	a/l	$\%C$	$\frac{KGm}{rad}$	a/l	$\%C$
1	Sep	280	26.5	1060	23.5	200	11 600	778.0	24 400	0.296	0.480				22.4	0.46	20.0
2	Mucha-bis	370	24.0	750.0	25.5	284	11 000	750.0	22 700	0.339	0.362				17.7	0.45	0
3	Gövier-4	540	27.5	1360	29.0	726	25 200	2120	42 100	0.347	0.441				22.4	0.50	36.0
4	Minimoa	200	11.7	930.0	9.3	318	16 800	810.0	26 000	0.334	0.434				27.4	0.47	41.0
5	Bocian	670	27.5	1650	36.6	368	21 300	1100	41 500	0.316	0.361	68.4	0.47	30.0	44.6	0.47	28.0
6	Zuraw	654	17.9	3070	20.7	517	31 200	1880	63 700	0.305	0.384	25.5	0.50	37.0	26.1	0.53	34.0
7	Mucha 100	412	21.7	1010	20.8	227	9 560	565.0	15 600	0.335	0.314				26.1	0.49	15.0
8	Sohaj	348	10.0	1020	16.2	182	8 330	541.0	14 500	0.367	0.312				23.1	0.45	25.0
9	Jaskolka	401	25.0	1620	35.0	270	14 000	686.0	24 400	0.310	0.392	32.2	47.0	17.0	37.4	0.47	17.0
10	Jastrzab	1060	35.0	3740	35.0	768	22 800	3680	72 900	0.257	0.342	166.0	0.45	0	65.1	0.49	0

C-mean chord of aileron aft of the hinge axis C*-chord

under the tail skid. The wing was fixed by immobilizing the end of the wing not subjected to measurements.

In the first sailplane measurements, only the body was immobilized and the value of the stiffness was measured simultaneously on both wings, and determined using symmetrical and antisymmetrical torques. The results of such measurements justify the chosen test method.

3. 1. 2. *Measurements of the flexural wing stiffness*

The value of the flexural wing stiffness P_f is the ratio of the force P applied at the bending section to the value of deflection of that section relative to the root section

$$P_f = \frac{P}{f} \ (kG/m)$$

For the sake of analogy to the torsional stiffness it is better to determine the flexural stiffness $m\delta$ as the ratio of the bending moment M acting at the root section to the angle of rotation δ of the reference section relative to the root section.

$$m\delta = \frac{M}{\delta} = \frac{P \cdot 1}{\frac{f}{1}} = P_f \cdot 1^2 \ (kGm/rad.)$$

where 1 = distance between the reference section and the root section.

For measurement of the flexural stiffness of the wing the sailplane was fixed as for the measurements of the torsional stiffness. To determine the flexural stiffness it is necessary to know the position of the torsional centres in the investigated sections. That stiffness was not determined directly, but by means of the so-called flexural torsional measurements, which make it possible to determine the position of the torsional centre. For this purpose the frame fixed as for torsional measurements was loaded by a downward force in several points along the wing chord (fig. 1d). Then the twist of the investigated section was calculated for each loading point separately and the torsional centre was determined accordingly. Once the torsional centre found, the flexural stiffness of the wing was calculated using the results obtained during the flexural and torsional measurements.

3. 1. 3. *Aileron stiffness measurements*

On the aileron only torsional stiffness was measured. The reference sections were situated at a distance of 0.1 of the aileron span measured parallel to the hinge axis. Measurements were performed on dismounted ailerons. One reference section was immobilized in a special frame. The load was applied similarly as to the wing.

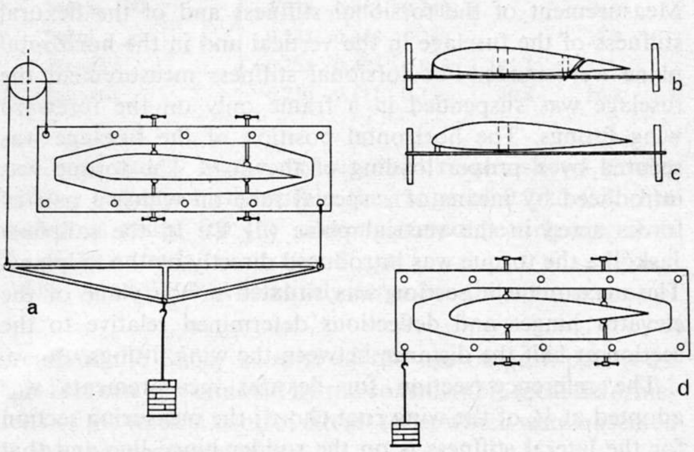


Fig. 1 a, b, c, d

3. 1. 4. *Analysis of test results*

It is noticeable that the absolute value of the results obtained vary within wide limits. For example the torsional stiffness of a section situated at 0.9 of the semi-span varied between 200 and 670 kGm/rad., and in the case of the aerobatic sailplane Jastrzab (Hawk) it amounted to 1060 kGm/rad.

Fig. 2 Measurement of the fuselage torsional stiffness

Similar variations appear also in the mid-aileron section and in the case of the flexural stiffness P_f in the same section there are even larger variations (540—2120 kGm/rad. and 3680 kGm/rad. in the Jastrzab). Only the values of the aileron torsional stiffness are more uniform and for unsplit ailerons they oscillate within the range of 17.7 and 27.4 kGm/rad. Such great variations of stiffness values are easily explained by the variety of design methods, geometrical dimensions, and purposes of the investigated sailplanes.

3. 2. *Fuselage stiffness measurements*

Measurement of the torsional stiffness and of the flexural stiffness of the fuselage in the vertical and in the horizontal plane were made. For torsional stiffness measurement the fuselage was suspended in a frame only on the foreward wing fittings. The horizontal position of the fuselage was secured by a proper loading of the nose. The torque was introduced by means of a special tube on which a pair of forces acted in the vertical plane (fig. 2). In the sailplane Jaskółka the torque was introduced directly by the tailplane. The measurement section was situated in the plane of the elevator hinges and deflections determined relative to the section at half the distance between the wing fittings.

The reference section for flexural measurements was adopted at ¼ of the wing root chord; the measuring section for the lateral stiffness is on the rudder hinge line and that of the vertical stiffness on the elevator hinge line.

Loading in the vertical plane was effected by means of a belt running across the body in the elevator hinge line. The force acting in the horizontal plane was introduced by the bottom hinge, usually reinforced, of the rudder.

Comparison of measurement results shows that the vertical flexural stiffness of standard fuselages is approximately twice as large as the lateral stiffness, showing at the same time, similarly to the wing, large variations of the absolute stiffness value.

In sailplanes which were investigated first, the flexural stiffness of the foreward part of the fuselage was also measured. Very large values ranging in 10^4—10^5 kG/m were obtained. In subsequent research work those measurements were abandoned because of the inaccuracy of the proceedings.

3. 3. *Tailplane stiffness measurements*

In the stabilizers and control surfaces only torsional stiffness was measured. Deflections were determined relatively to the stabilizer root sections and the reference section was on the horizontal stabilizer at the distance of 0.1 of the span from the end, and on the vertical stabilizer on the uppermost rib where load can still be applied. On the rudder the reference sections were situated at a distance of 10 % of the span from the end, and on the elevator at a distance of 5 %.

Stiffness measurement of the fin was performed on the sailplane with the horizontal tailplane fixed. Measurements of all the other parts of the tailplane were performed on a special rig as in the case of aileron measurements.

The horizontal tailplane proved to be the stiffest part. Its stiffness varies between 130 and 1890 kGm/rad. However, the relevant values for the fin were within the same range and sometimes even higher. The most flexible elements are the elevators with a stiffness range 5.5—55 kGm/rad.

3. 4. *Measurements of stiffness of the control circuits*

For the measurement of control circuit stiffness the sailplane was fixed as for wing stiffness measurements. After immobilizing the proper control surface the angular deviation of the stick (pedal) under the load of a reference force was investigated. The force in question acted on that element so as to imitate the pilots action.

The measure of stiffness is the ratio

$$\Delta\,\Theta = \frac{\Theta}{\Theta_{max}}$$

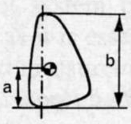
where Θ = stick or pedal deflection under the load of a force of 23 kG or for the pedal under the load of a force p_f 45 kG;

Summary of fuselage stiffnesses

Table 3

Sailplane No.	Sailplane type	Flexural stiffness in the vertical plane P_f KG/m	m_δ KGm/rad	Flexural stiffness in the horizontal plane P_f KG/m	m_δ KGm/rad	Torsional stiffness m_φ KGm/rad	Position of the centre of gravity a/l
1	Sep	6 300	106 000	3220	57 400	5 400	0.363
2	Mucha-bis	8 800	119 000	4100	66 900	2 920	0.354
3	Gövier-4	4 350	74 300	5000	99 700	3 680	0.297
4	Minimoa	5 520	95 000	2370	46 300	4 500	0.358
5	Bocian	5 810	87 700	3100	64 500	2 460	0.419
6	Zuraw	10 100	190 000	2580	55 500	2 640	0.330
7	Mucha 100	9 190	119 000	4530	71 500	2 340	0.363
8	Sohaj	6 700	88 800	2520	40 400	2 860	0.367
9	Jaskolka	2 050	42 500	2220	47 200	1 540	0.325
10	Jastrzab	38 000	302 000	5000	50 000	20 100	0.341

Table 4 *Summary of tailplane stiffnesses*

Sailplane N°	Sailplane type	Tailplane: Torsional stiffness m_φ	Tailplane: Position of the centre of gravity	Fin: Torsional stiffness m_φ	Elevator: Torsional stiffness m_φ	Elevator: Position of the centre of gravity	Rudder: Torsional stiffness m_φ	Rudder: Position of the centre of gravity 	
		$\frac{KGm}{rad}$	$\%C^*$	$\frac{KGm}{rad}$	$\frac{KGm}{rad}$	$\%C$	$\frac{KGm}{rad}$	a/b	$\%C$
1	Sep	330.0	— 46.0	1060	21.9	50.0	170.0	0.42	43.5
2	Mucha-bis	350.0	— 36.0	785	14.4	24.0	88.0	0.45	40.0
3	Gövier-4.	573.0	— 54.0	250	16.4	43.0	70.6	0.46	39.3
4	Minimoa	130.0	— 46.0		30.0	32.0	305.0	0.45	18.0
5	Bocian	882.0	— 41.0	1280	46.1	39.5	215.0	0.41	29.0
6	Zuraw.	253.0	— 54.0	215	31.0	41.0	127.2	0.41	42.5
7	Mucha 100	825.0	— 47.0	720	12.1	21.4	152.0	0.41	38.0
8	Sohaj	470.0	— 50.0	387	5.50	29.8	46.4	0.37	40.5
9	Jaskolka.	476.0	— 45.0	465	23.5	21.0	122.5	0.36	32.0
10	Jastrzab	1890.0	— 53.0	108	55.2	21.0	307.0	0.37	27.0

C-mean chord aft of the hinge line   C*-mean chord before the hinge line

Θ_{max} = the maximum possible angular deflection of the stick (pedal) between extreme positions measured in the plane of force with free control surfaces. If the backward pedal deflection does not depend on the stiffness of the control system, then Θ_{max} was taken as the double of the value of the maximum forward deviation from the neutral.

In cable type control circuits the idle cable was as a rule slackened for measuring.

Within the range of control circuit stiffness measuring, the stiffness of the control circuit interconnecting the ailerons was investigated separately. The stiffness is the ratio of value of the moment M about the hinge axis applied symmetrically to the arithmetic mean of the angle of deflection of the ailerons from neutral position

$$m\xi = \frac{2M}{\xi_1 + \xi_2} \quad (kGm/rad.)$$

where ξ_1 and ξ_2 are the angles of deflection of the left-hand and right-hand aileron under load of moment M.

The value $m\xi$ can be also determined with one aileron being locked. The value of stiffness is then determined by the formula

$$m\xi = \frac{2M}{\xi} \quad (kGm/rad.)$$

where ξ is the angle of deflection of the aileron loaded relatively to the neutral position under the influence of the moment M.

The moment was introduced on the aileron by means of its operating lever. In cases where the sailplane was provided with two aileron operating levers or with individually driven split units, the measurements were made for both control circuits.

Summary of control circuit stiffnesses

Table 5

Sailplane No.	Sailplane type	Control circuit: Elevator θ/θ_{max}	Control circuit: Rudder θ/θ_{max}	Control circuit: Ailerons θ/θ_{max}	Aileron inter-connecting circuit: Inner ailerons $m\xi$ $\frac{KGm}{rad}$	Aileron inter-connecting circuit: Outer ailerons $m\xi$ $\frac{KGm}{rad}$
1	Sep		0.670	0.655		24.9
2	Mucha-bis	0.260	0.330	0.350		39.3
3	Gövier-4	0.187	0.184	0.204		88.4
4	Minimoa	0.280	0.401	0.258		77.6
5	Bocian	0.145	0.177	0.399	78.8	78.6
6	Zuraw	0.203	0.236	0.403	39.2	30.25
7	Mucha 100	0.378	0.469	0.240		39.6
8	Sohaj	0.273	0.385	0.249		32.8
9	Jaskolka	0.254	0.425	0.018	143.5	143
10	Jastrzab	0.230	0.111	0.196	80.8	80.8

A brief survey of the measurement results shows similar stiffness values, chiefly within the range of 0.2 to 0.4. The analogous range for the aileron interconnecting circuit is 25—90 kGm/rad.

The value of $\frac{\Theta}{\Theta_{max}}$ is relatively large for the aileron control circuit of the Sohaj in spite of the use of push-pull rods. This fact can be explained by the considerable local deformations of the torsion control circuit tube, which were observed during the measurements.

To finish this description it should be stated that the measuring error amounted at the average to 5%.

Comparison of measured and calculated stiffnesses relevant to wing torsion for three sailplanes (Bocian, Jaskólka, and Mucha-100) showed that the theoretical results are about 30% smaller than the experimental ones. The same can be said about the flexural stiffness of the wing of the sailplane Mucha-100.

4. Analysis of the stiffness criteria

The above stiffness measurements were directed toward the collection of data for calculation of the stiffness criteria which would serve as a guide to the designers and permit the determination of flutter tendencies. The formula underneath represents a typical criterion:

$$K = \frac{1}{V}\sqrt{\frac{m\theta}{a \cdot b \cdot c}}$$

where K = criterion value (kG $^{1/2}$ sec m^{-2})

V = permissible diving speed of the sailplane (m/sec)

$m\theta$ = stiffness of the considered sailplane element (kGm/rad.)

a, b, c = linear dimensions relevant to the given element *(m)*, for example in the case of the aileron:

a = aileron span measured parallel to the hinge axis,

$b = c$ = part geometrical mean of the aileron part situated beyond the hinge axis.

Criteria of control systems are determined directly by the stiffness of those systems.

A comparison is also given of measured sailplane values with relevant values for aeroplane criteria.

Stiffness criteria for fuselage, tailplanes, and wing torsion in a cross section situated at 0.9 semi-span exceed the minimum values admissible for aeroplanes, however, that surplus is but small and more or less similar in all the sailplanes subjected to investigation. Moreover, as lately, within the period of several years no case of flutter is known resulting from the lack of stiffness of the fuselage and tailplane, we suggest extension of the relevant aeroplane criteria to sailplanes.

The matter of wing, aileron, and control system criteria is quite different.

As shown in the diagram (fig. 3), some of the sailplanes do not fulfill the wing torsional stiffness criterion in the mid-aileron, however, flutter does not appear in every one of those planes. On the other hand, among sailplanes which stand the criterion, is one sailplane in which wing flutter occurred at a given moment several times. This suggests that aeroplane criteria cannot be extended directly to sailplanes. However, there is no certainty that the cases of flutter were a consequence of the small torsional stiffness of the wing, as flexural aileron vibrations could also occur. For this reason it seems that without much more test data results and calculations, any definite suggestion would be rather unfounded.

As a rule, the criterion of the flexural stiffness of the wing is not taken into consideration in English aeroelasticity requirements; this suggests that while establishing those

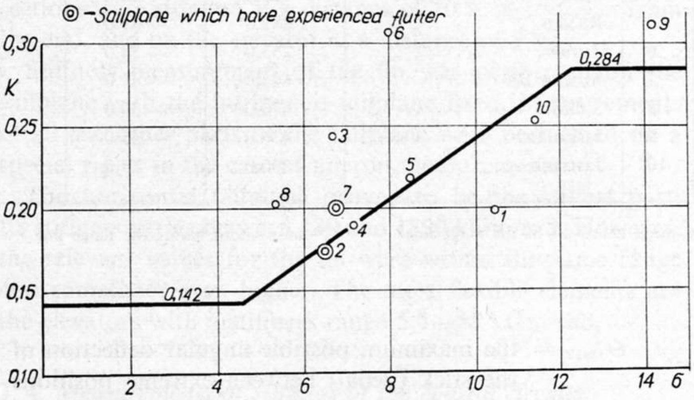


Fig. 3 K = criterion value. $\sigma = \frac{Q}{S\,l}$, where
σ = the effective wing density *(kG/m³)*
S = area of wing outboard of face of fuselage *(m²)*
Q = weight of wing structure, including control surfaces and circuits, and any fabric covering in the area S *(kG)*
l = geometric mean chord of that part of wing defined by S *(m)*. Numbers at individual points mark the subsequent number of the sailplane

rules, only the torsional and flexural wing flutter was taken into consideration—a case when a small flexural stiffness is advantageous.

Values shown in the fig. 4 are taken from R & M No. 1505.

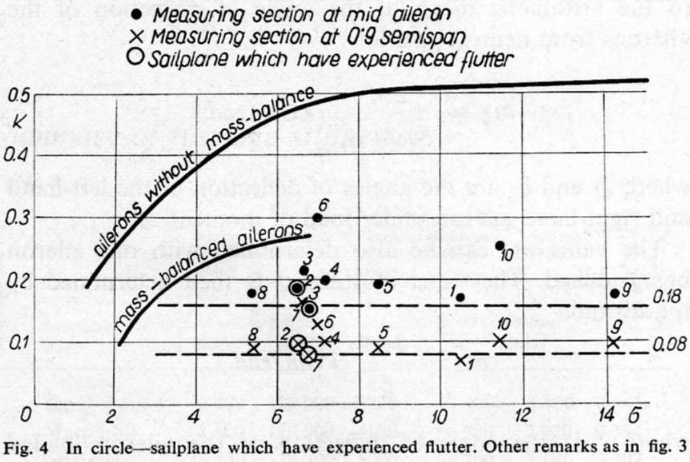


Fig. 4 In circle—sailplane which have experienced flutter. Other remarks as in fig. 3

The diagram shows that differences between sailplanes and aeroplanes are very considerable in that range. Nevertheless the distribution of points gives some assistance to the designers, i. e. that the value of the criterion generally exceeds 0.08 in a section situated at 0.9 wing semi-span and exceeds 0.16 in the section situated at mid-aileron.

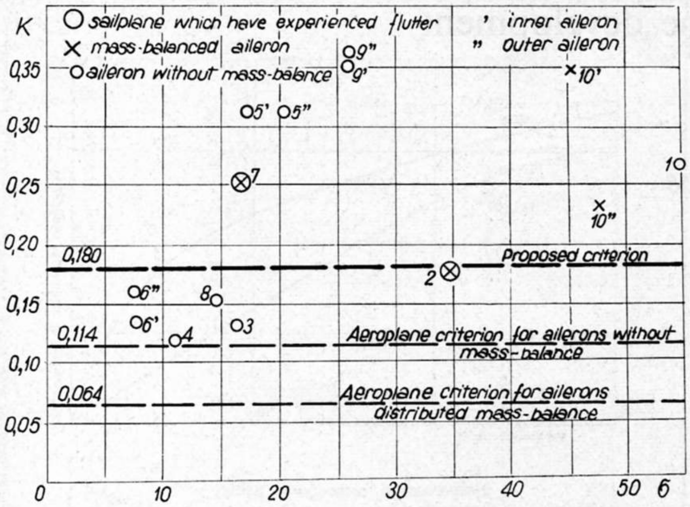


Fig. 5 K = criterion value. $\sigma_1 = \frac{Q_1}{S_1\, l_1}$, where

σ_1 = the effective aileron density (kG/m^3)

S_1 = aileron area aft of the hinge line (m^2)

l_1 = geometric mean chord of that part of aileron defined by S_1 (m)

Q_1 = weight of aileron structure

It is true that all the sailplanes satisfy the torsional aileron criterion as shown in fig. 5; nevertheless on some of them wing-aileron flutter has occurred. Moreover, resonance testing of sailplanes Zuraw, Sohaj, and Goevier show strong aileron torsion even at a relatively low vibration frequency. This means that considering ailerons of those sailplanes as stiff elements is unfounded as far as flutter calculation is concerned. For this reason our suggestion aims at establishing a minimum value of the aileron stiffness at 0.18 independently of the aileron mass balance, the more so that in modern sailplanes much greater values of that criterion were obtained though it was not the stiffness value which determined the design, and the increase of the criterion did not increase the aileron weight.

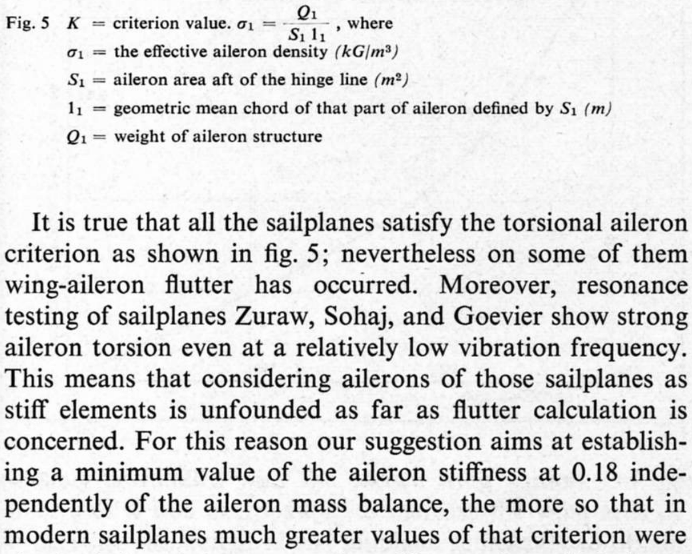


Fig. 6 $\Delta\Theta$ = criterion value

Only the Jaskólka satisfies the criterion of the control circuit stiffness (see fig. 6) and with regard to the aileron control only. On the other hand, there are no records of cases of flutter appearing as the result of the excessive flexibility of the control systems. For this reason taking into account the measured values we should like to suggest for sailplanes a control circuit stiffness criterion one quarter of that of the British aeroplane requirements. This would be representative of the present stage of design. Establishment of a stricter check on the value of control system cable tensions in production also seems advisable, as it is essential for the effective stiffness of those systems, and measurements show that there are great discrepancies in this respect between sailplanes of the same type.

On similar grounds we suggest the introduction of a uniform aileron interconnection control circuits stiffness of 40 kGm/rad. independently of the direction of aileron deflection (fig. 7).

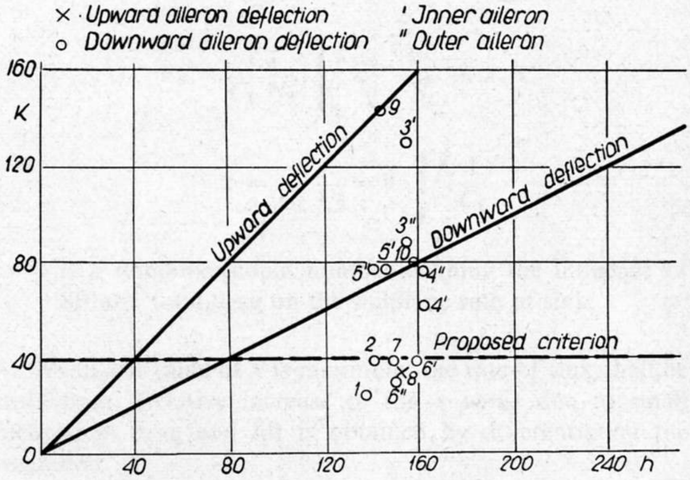


Fig. 7 K = criterion value. $h = 132 + \frac{2}{3}\frac{Q}{S}\, n\, S_1\, l_1$ (kGm), where

Q/S = gross wing loading (kG/m^2)

n = maximum norma lacceleration coefficient

S_1 = aileron area aft of the hinge line (m^2)

l_1 = mean chord of aileron aft of the hinge line (m)

Numbers at individual points mark the subsequent number of the sailplane

5. Further developments

Being quite aware that the results of stiffness measurements performed on ten sailplanes selected rather at random cannot serve as a basis for far-reaching generalizations, in our further research work we will try to obtain a greater number of measurements. However, even now our endeavours are hampered by the lack of types of sailplanes for tests, as the series already investigated comprise in principle all the performance sailplanes either in production or recently withdrawn.

Results of investigation of sailplanes of a lower class, with smaller admissible diving speed, are less interesting, as the existence of flutter is in that case most improbable, and in consequence the stiffness calculations have little importance in the structural strength analysis.

In our further work we propose to obtain some general data concerned with the question of sailplane stiffness, for example the dependence of the stiffness on the quality of the fabric cover, variations of stiffness values among sailplanes of the same type, alterations of stiffness during production and use, etc.

We intend also to use our measurement results for calculation of the critical flutter speed, effected by means of an electronic computer.

(Swiss Aero Review 1959/5 and 6)