Sailplane With High Performance

Aeroelastic Problems of a Swept-Back Tailless

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Sailplanes have achieved a very high technological level during the last 20 years, mainly due to fibre composite structures and improved aerodynamics. Further improvement can only be expected from small detail modifications or expensive projects like variable wing geometry. For this reason the "Akademische Fliegergruppe Braunschweig" launched a tailless sailplane project for the 15-meter standard class in 1983. The SB 13 (Figure 1) shows a performance improvement up to 10% compared to existing competitors [1]. *Table 1* gives some main design parameters.

Although tailless aircraft have been studied since the beginning of aviation they have never experienced the success one might expect. Many carefully designed tailless gliders had to be modified or redesigned completely after first flight tests because of strange instabilities, which were often misinterpreted or not understood.

To study stability and handling qualities of the SB 13, a remotely piloted ⅓ scale model was built and flown. The handling qualities showed no problems, but an unexpected instability in the longitudinal motion occured at very low speeds. To investigate the flutter behaviour more thoroughly, a ground resonance test was performed at the DFVLR, Institute for Aeroelasticity, in Göttingen.

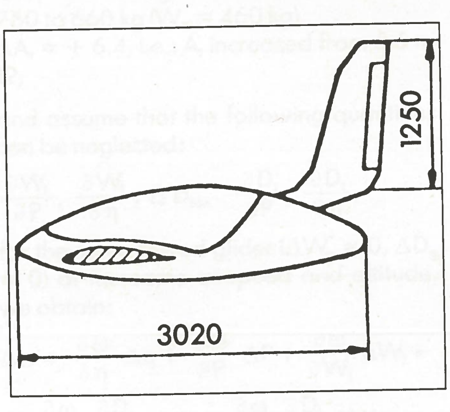


Figure 1: View of the tailless sailplane project SB 13

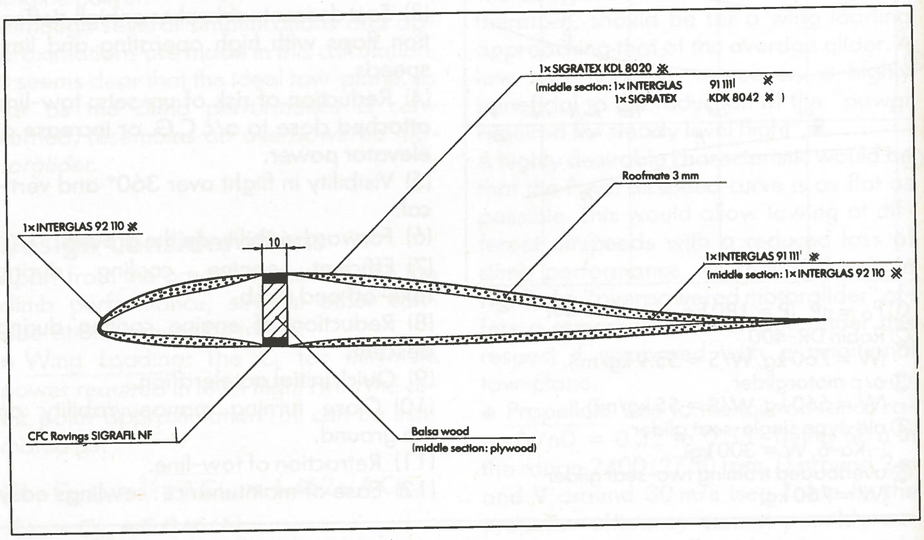


Figure 2: Wing section of the SB 13 model

Table 1 Technical data for the sailplane SB 13

Wing	
Span	15 m
Wing area	11.6 m²
Aspect ratio	19.4
Dihedral	+4°
Twist	−1.5° outboard
Airfoil sections	HQ 34 N/14.83 inboard HQ 36 N/15.12 outboard
Winglets	
Length	1.25 m
Area	0.675 m²
Aspect ratio	2.31
Airfoil	FX-71-L 150/30
Fuselage	
Length	3.02 m
Width	0.66 m
Height	0.84 m
Landing gear	2 retractable wheels, spring suspend
Weights	
Empty weight	2240 N
Payload	700–1100 N
Water ballast	max. 1330 N
Gross weight	2940–4270 N
Wing loading	248–360 N/m²
Performance	
V_{min}	70 km/h
V_{max}	210 km/h
min. sinking speed	0.53 m/s
max. L/D-ratio	43.5:1

Experimental Investigation of the Flutter Behaviour for the ⅓ Scale Model

The model is designed like a modern sailplane (Figure 2). There is one main spar with the flange fabricated from unidirectional CFC rovings. The torsional forces are carried by ±45° plies in a sandwich shell construction.

To perform a flutter analysis we need the structural mode shapes, natural frequencies and the corresponding generalized masses of the model. *Table 2* contains these data determined by a ground resonance test. (Figure 3) gives an isometric view of the first bending mode.

Several flutter calculations were made using these data. With rigid body modes ignored, the first structural mode showed divergence at 100 km/h.

Symmetric modes

Type	Frequency [Hz]	gen. mass [kgcm²]
S1	2.82	2.755
S2	11.21	0.788
ST	19.96	0.029

Antisymmetric modes

Type	Frequency [Hz]	gen. mass [kgcm²]
A1	7.44	2.075
A2	20.17	0.664
AT	17.64	0.171

Total mass and pitching moment of inertia

m_{tot}	[kg]	12.6
Θ_y	[kgm²]	0.884

Table 2: Ground resonance test results for the SB 13 model

	SB 13 model	SB 13	SB 11–18 m Fowler flaps retracted
m [kg]	12,6	280	465
Θ_y [kgm²]	0,884	113	835
i_y [m]	0,265	0,635	1,340
S [m²]	1,33	11,0	13,32
$\bar{c}$ [m]	0,271	0,735	0,772
$\mu_{\bar{c}}$	57,07	56,54	73,83
$c_{L\alpha}$	5,72	5,72	5,71
c_{Mq}	-2,749	-2,749	-20,49
$c_{M\dot{\alpha}}$	0,194	0,194	0,649
$\frac{\partial c_M}{\partial c_L}$	-0,10	-0,10	-0,10

Table 3: Longitudinal motion parameters for the model, the SB 13, and the SB 11

		Glass fiber	HT-CFC	HM-CFC
Fiber volume ratio		0.39	0.55	0.54
E_{11}	[N/mm²]	31985.0	131835.0	202538.0
E_{22}	[N/mm²]	8000.0	7669.0	6430.0
G	[N/mm²]	2600.0	3220.0	2989.0
ν_{12}		0.310	0.312	0.269
ν_{21}		0.075	0.016	0.009
ε_{11}		0.0128	0.0046	0.0012
ε_{22}		0.0028	0.0022	0.0027
ρ	[g/cm³]	1.73	1.51	1.53

Table 4: Material properties

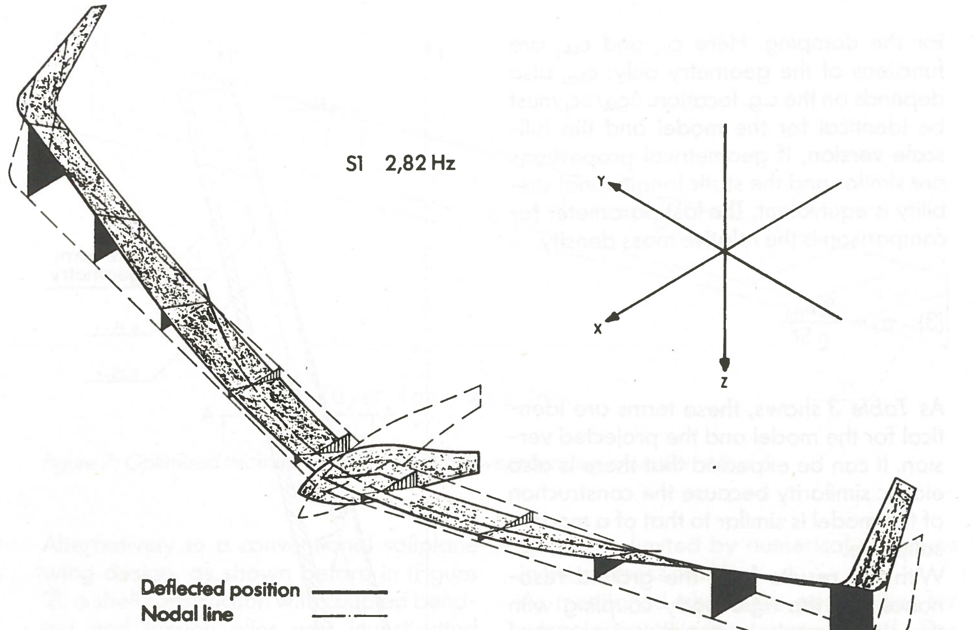


Figure 3: Isometric view of mode S1

Introducing the short period mode divergence occured at 44 km/h; the reason for instability is the coupling between this mode and the first symmetric structural mode (Figure 4).

In (Figure 5) the eigenvalues of the short period are plotted vs. airspeed for the full-scale SB 13 and the conventional SB 11. The frequency of the SB 13 is almost three times that of the SB 11, while the damping is less due to the small pitching moment of inertia of the SB 13. *Table 3* gives a comparison of the important parameters for the longitudinal motion of the model, the SB 13 and the SB 11.

The equations for the short period mode are

(1)
$$\omega_{o\alpha} = \sqrt{-\left(\frac{V}{i_y}\right)^2 \cdot \frac{c_{L\alpha}}{\mu_{\bar{c}}} \cdot \left(\frac{\partial c_M}{\partial c_L} + \frac{c_{Mq}}{\mu \bar{c}}\right)}$$

for the frequency and

(2)
$$\sigma_\alpha = -\frac{V}{2\mu_{\bar{c}}\bar{c}} \cdot \left[c_{L\alpha} - \left(\frac{\bar{c}}{i_y}\right)^2 \cdot \left(c_{Mq} + c_{M\alpha}\right)\right]$$

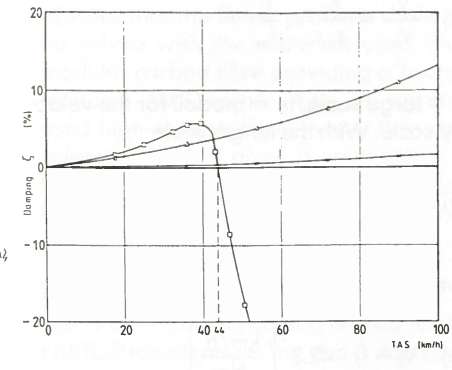


Figure 4: Flutter calculation with rigid body degrees of freedom

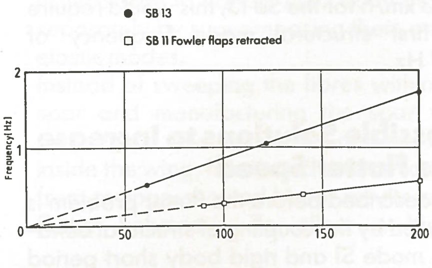


Figure 5: Comparison of rigid body short period modes for the SB 13 and SB 11

Material: spar flange	Material: torsion shell	(φ_s) φ_d=15,1°	V_{div} [km/h]	V_F [km/h]	κ	$-\left(\frac{\partial \zeta}{\partial v}\right)_{V_F}$ [%/(km/h)]	Remarks
HT-CFC	HT-CFC	15,1°	190	123	1,000	1,24	old design
HM-CFC	HT-CFC	15,1°	346	235	1,911	0,79	
HM-CFC	HT-CFC	12,1°	> 400	272	2,211	0,52	redesigned SB 13-wing
HM-CFC	Glass fiber	12,1°	368	262	2,130	0,62	

Table 5: FASTOP calculations for the SB 13

for the damping. Here $c_{L\alpha}$ and c_{Mq} are functions of the geometry only, $c_{M\alpha}$ also depends on the c.g. location. $\partial c_M/\partial c_L$ must be identical for the model and the full-scale version, if geometrical proportions are similar and the static longitudinal stability is equivalent. The last parameter for comparison is the relative mass density

$$(3) \quad \mu_{\bar{c}} = \frac{2m_{tot}}{\varrho S \bar{c}}$$

As *Table 3* shows, these terms are identical for the model and the projected version. It can be expected that there is also elastic similarity because the construction of the model is similar to that of a modern sailplane.

With the results from the ground resonance test the rigid body coupling with the elastic mode is at a flutter speed of 44 km/h (Figure 6). If we assume linearity between flutter speed and first elastic mode frequency, we get

$$(4) \quad \frac{V_l}{V_m} = \frac{\bar{c}_l}{\bar{c}_m} \cdot \frac{f_l}{f_m}$$

(l = large scale, m = model) for the velocity scale. With the length scale

$$(5) \quad \lambda = \frac{\bar{c}_l}{\bar{c}_m} = 2.71$$

we get

$$(6) \quad V_F = f_f \cdot 42.3 \left[\frac{km/h}{Hz}\right]$$

for the SB 13. If we demand a flutter speed equal to the diving speed of V_D = 283 km/h for the SB 13, this would require a first structural mode frequency of 6.7 Hz.

Possible Solutions to Increase the Flutter Speed

As described before the flutter problem is caused by the coupling of structural bending mode S1 and rigid body short period mode S01. Obviously a separation of the two frequencies would be favourable.

- To reduce the mode S01 frequency the pitching moment of inertia must be considerably increased, which is not possible with a tailless configuration. A study at Cranfield of the tailless sailplane "Ricochet"[2] showed that this is the only important parameter for the short period mode; static longitudinal stability or wing sweep angle do not improve the rigid body motion sufficiently. For that sailplane in fact the flutter problem could not be solved and the project was finally abandoned. But that study was the first one known to the author that identified the problem correctly.
- Changing the configuration in such a way that the first elastic mode shape S1 frequency shows no reduction with increasing airspeed would require a completely new design. Because a large effort had already been invested in the aerodynamic layout, this solution was not desirable.
- Active Control Technology is a good method to extend the flight envelope. Although tested for several military and commercial aircraft projects successfully, ACT is not a feasible solution for sailplanes. It would require power supply and a complicated sensor, control and actuation system.
- To change the aeroelastic behaviour using mass balance by addition of lumped masses does not improve the situation with feasible arrangements.
- The only practible solution is a combination of a structural redesign (with small modifications in the wing root geometry), using high elastic modulus carbon fibres to increase the first elastic frequency and tailor the wing for a different elastic behaviour (exploiting the anisotropic material properties to change the mode shapes). This procedure—finally selected—is described in the next section.

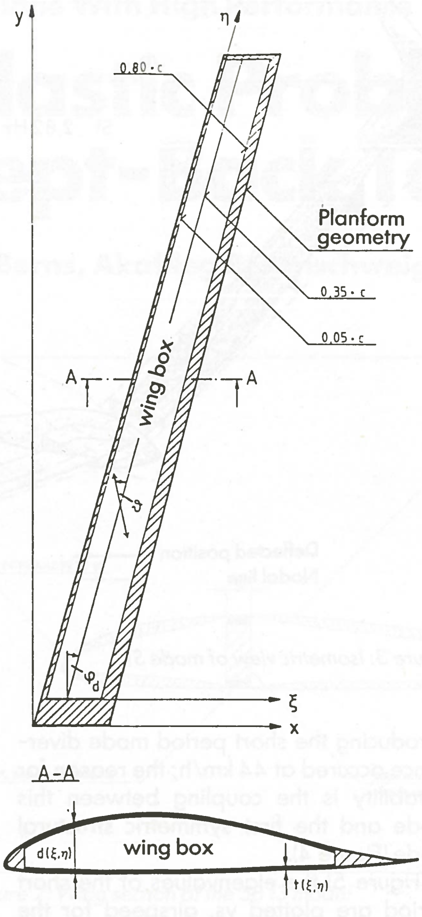


Figure 6: Wing idealization for the TSO program

APPENDIX

Coordinate-Systems

x, y, z	[m]	global coordinate-system
ξ, η		wing box coordinate-system

Symbols

E	[N/mm²]	elastic modulus
G	[N/mm²]	shear modulus
S	[m²]	wing area
V	[m/s]	airspeed
V_D	[km/h]	diving speed
V_F	[km/h]	flutter speed
V_{NE}	[km/h]	maximum allowable speed
V_{div}	[km/h]	divergence speed
$\bar{c}$	[m]	mean aerodynamic chord
$c_{L\alpha}$		lift curve slope
c_{Mq}		pitching moment coefficient due to pitch velocity
$c_{M\alpha}$		pitching moment coefficient due to rate of angle of attack
d	[mm]	airfoil thickness
f	[1/s]	frequency
h	[m]	vertical displacement at the quarter chord line
i_y	[m]	radius of the pitching moment of inertia
m	[kg]	mass
t	[mm]	layer thickness
θ_y	[kgm²]	pitching moment of inertia
α		pitch rotation of the wing
$\partial c_M/\partial c_A$		static longitudinal stability
$-(\partial\zeta/\partial V)_F$	[%/km/h]	gradient of damping at the flutter speed
ε		elongation
ζ		damping
ϑ		layer orientation
κ		flutter speed factor
λ		length scale
$\mu_{\bar{c}}$		relative mass density of the airplane
ν		Poisson ratio
ϱ	[kg/m³]	density
ϱ	[kg/m³]	air density
σ	[1/s]	damping
φ_S		sweep angle of the spar
φ_d		sweep angle of maximum airfoil thickness
ω	[1/s]	radian frequency

Sufficies

l	large-scale version
m	model version
tot	total
w	wing

Abbreviations

CFC	Carbon Fibre reinforced Composite
DFVLR	Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.
FASTOP	Flutter and Strength Optimization Program
HM	High Modulus
HT	High Tension
MBB	Messerschmitt-Bölkow-Blohm GmbH
TAS	True Air Speed
TSO	Aeroelastic Tailoring and Structural Optimization Procedure

Structural Redesign for Increased Flutter Speed

Solving the described problem is a multidisciplinary task. MBB in Munich offered assistance to redesign the wing with the help of modern optimization programs like FASTOP (Flutter And Strength Optimization Program) and TSO (Aeroelastic Tailoring and Structural Optimization Procedure) which permit finding optimum fibre orientations and stiffness distributions for composite structures for aeroelastic and strength requirements.
Only limited potential of aeroelastic tailoring sailplane wings is available, constrained by the extremely high aspect ratio and slenderness of these wings. The main fibre direction can be swept only within small limits. Additionally there is only a small number of ±45° plies which makes it impossible to use them to change the elastic behaviour.

Summary

In 1983 the "Akademische Fliegergruppe Braunschweig" launched a tailless sailplane project which provides a performance gain of 10% over conventional types.
During flight tests with a ⅓ scaled remotely piloted model a severe instability occured at very low speeds. Using data from a ground resonance test, flutter calculations were performed. The results are compared with the flight characteristics of the model and transferred to the projected version.
By applying modern optimization programs to the problem the effect of the fibre orientation and stiffness distribution on the flutter speed was investigated. A probable solution is suggested which supplies an acceptable stability up to the intended maximum allowable speed V_{NE} including a safety margin.

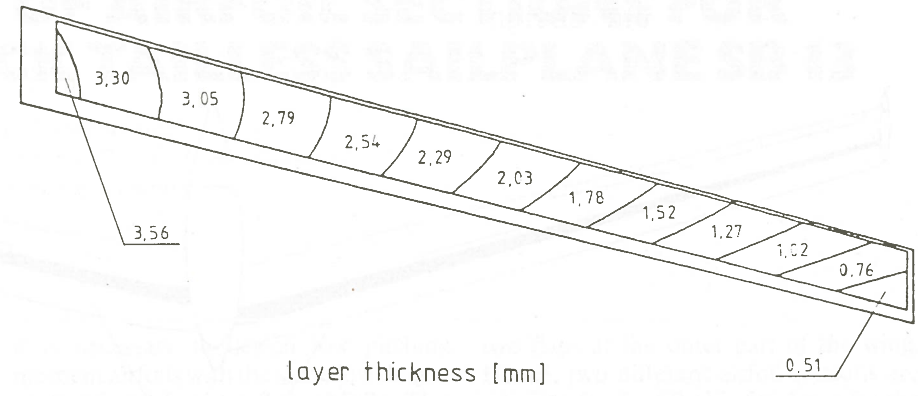


Figure 7: Optimized thickness contour for a +5° swept bending layer (Run 4 and 5)

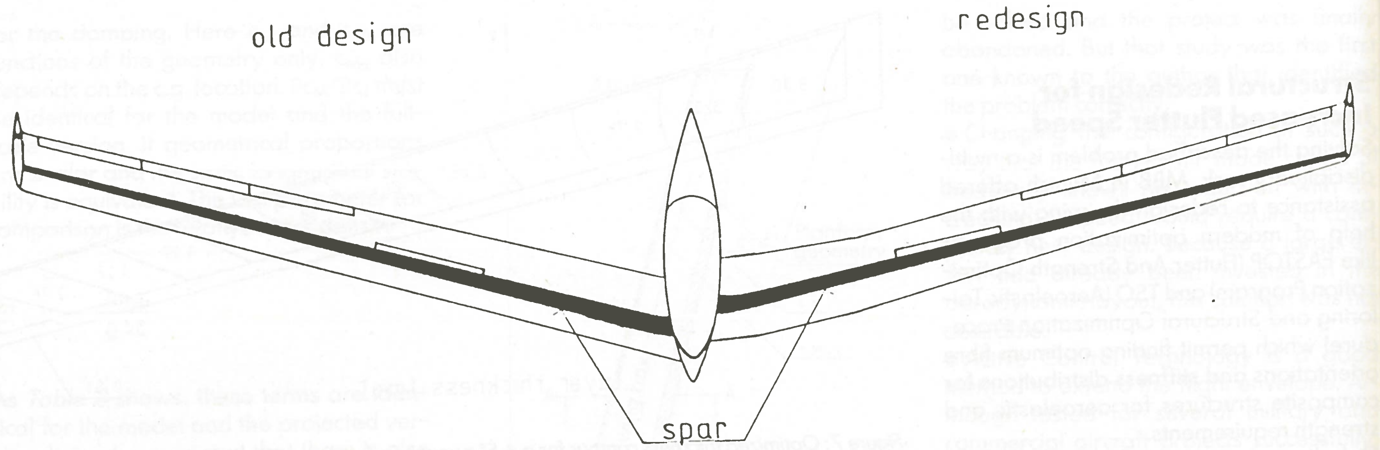
Alternatively to a conventional sailplane wing design, as shown before in (Figure 2), a shell construction with coupled bending and torsion plies was investigated first. This design was given up later, because it did not show improvements, owing to the small number of required plies with a still very small wing chord. It would also be very difficult to fabricate manually.
The final solution is a two web main spar construction (with 0° plies) and an uncoupled torsion shell (±45° plies), described in detail later.

TSO Calculations

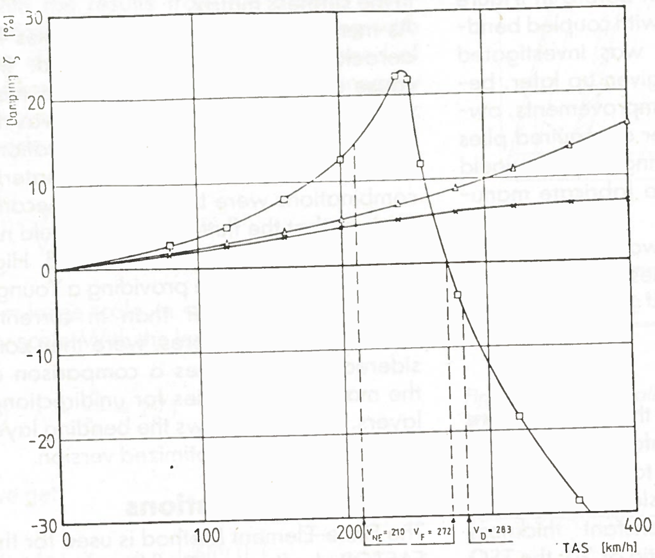
This program describes the wing structure as a plate model. Therefore, check calculations were necessary to see if the plate theory can be used for slender wings. For a constant chord, constant thickness beam with an aspect ratio of 20, the TSO results could be confirmed with analytical beam theory. (Figure 6) shows the idealization of the wing box within the planform geometry.
The first handicap in the application of TSO for "aeroelastic tailoring" the wing was caused by the lack of rigid body modes in this program. Therefore a substitution system had to be chosen to describe the critical flight mechanical mode. This can be achieved by defining soft springs between the structure and an earthed point. The softness of these springs is limited by numerical problems in the stiffness matrix.
As mentioned above the possibilities for aeroelastic tailoring were limited. Because of geometrical constraints, a main fibre sweep angle of 5° forward was the maximum. Owing to these limitations, several different materials and material combinations were tried. Soon it became obvious that the flutter problem could not be solved with the materials used. High modulus carbon fibre providing a Young's modulus 50% higher than in currently used high-tension fibres, were then considered. *Table 4* gives a comparison of the material properties for unidirectional layers. (Figure 7) shows the bending layer distribution for the optimized version.

FASTOP Calculations

The Finite-Element Method is used for the FASTOP idealization. The skin is described by membrane elements whereas the ribs and spars are modelled with shear panels. Although FASTOP can consider free-free conditions in the vibration analysis it is necessary to handle rigid body modes separately by superimposing them on the elastic modes.
Instead of sweeping the fibres within the spar and manufacturing the spar with prepregs, a new model with a swept spar inside the wing, fabricated conventionally from rovings, showed better results in the flutter behaviour. To allow a higher



▲ *Figure 8: Wing geometry modifications for improved flutter behaviour*



◀ *Figure 9: Result of the flutter calculation for the redesigned SB 13 wing*

sweep angle for the spar the wing planform was modified in the inboard section. The sweep angle is reduced with two kinks. The intention was to bring the main spar closer to the pilot's mass without increasing wing area. (Figure 8) shows these modifications.

Using HM instead of HT fibres for the unswept spar increases the flutter speed from 123 km/h to 235 km/h (+91%). Sweeping the spar 3 degrees forward gives 272 km/h (+121%), if HT carbon fibres are used for the torsion layers. Additionally the gradient of damping at the flutter speed has been improved. *Table 5* summarizes these results.

(Figure 9) shows the result of the flutter calculation for the best design. This wing has a weight of 67.7 kg compared to 60.0 kg for the initial design (+12.8%) but the flutter speed is 121% higher! Further calculations were necessary for water ballast. Because the water is positioned very close to the nodal line of mode S1, the first frequency does not drop more than 6% while the short period mode is more than 10% less due to the higher moment of inertia.

Flutter calculations for antisymmetric modes were also performed. Because the first mode is higher than 6 Hz in this case, there is no coupling with low frequency modes. Higher modes are separated without tendency to couple up to 400 km/h.

From these results it can be expected that the flutter speed will be sufficiently high to clear the flight envelope up to the maximum allowable speed of V_{NE} = 210 km/h (including a safety margin).

Conclusions

Tailless sailplanes have the great disadvantage of high frequent short period modes compared with conventional constructions. It could be shown that the reason for aeroelastic instability at very low speeds is the coupling between the rigid body short period mode and the first symmetric structural mode.

To prevent flutter the SB 13 wing had to be redesigned by means of structural optimization programs. By applying these computer codes the flutter speed could be increased to an acceptable level with small modifications of the wing root geometry, a new design of the main spar and by the use of extremely stiff material. The necessary stiffness is provided by new fibres with a very high elastic modulus.

Compared to the initial design the more than 100% increase in flutter speed with only a small weight penalty shows the potential of the new carbon fibres and the use of aeroelastic tailoring.

Manufacturing large-scale spars with these extremely stiff fibres will certainly need several experiments to gather enough experience.

Acknowledgement

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