MULTI-DISCIPLINARY DESIGN OF A HIGH ASPECT RATIO, GRAVITY CONTROL HANG GLIDER WITH AERO ELASTICALLY ENHANCED MANOUEVRABILITY

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Abstract

In this paper the preliminary design of a new concept hang glider with a rigid wing is presented. This design uses flexibility in the wing structure to comply with manoeuvrability requirements using pilot weight-shift as the single means of control.

The structural flexibility is realised by introducing a separate central wing part with a relatively low torsional stiffness compared to the outer wing parts. The main manoeuvrability requirement consists of a minimum roll speed requirement.

The influence of the torsional stiffness of the centre-section of the wing and the pilot-wing connection on the roll performance is analysed using CFD 3D panelling code (FASD) and basic engineering mechanics. The influence on the aero elastic behaviour of the hang glider is also analysed using Finite Element Aero elastic Analyses (NASTRAN).

Results show that decreasing the torsional stiffness of the centre-section of the wing improves the roll performance. Decreasing the torsional stiffness also decreases the divergence speed. Flutter is not a significant problem within the low speed range of the hang glider. The pilot-wing connection determines the stiffness range for the centre-section of the wing and the roll performance.

1 General Introduction

A study of the development of hang gliders over the last 20 years has shown that they have evolved from a low performance "rogallo wing" into a design, which gives pilots the capability to make long flights, using the same thermalling techniques as sailplanes. During competitions hang gliders are divided into two separate classes; Class 1 gliders use pilot weight shift as the sole means of control, Class 2 gliders have movable aerodynamic surfaces for control around at least two axes.

FIGURE 1 – Class 1 hang glider

FIGURE 2 – Class 2 hang glider

Today hang gliders that are classified as class 1 are the most popular and the most commonly known (see Figure 1). These types of glider have a flexible wing structure composed out of sailcloth supported by an aluminium frame, under which the pilot is suspended and can shift his weight by steering with the control bar, which is rigidly connected to the wing. The wing is supported by steel wires connected to the wing and the control bar. Increasing the aspect ratio of the wing and improving the aerodynamic shape with special profile battens have increased the gliding performance compared to the early designs. High-performance gliders have an L/D-ratio of around 12 and a minimum sink ratio of approximately 1 m/s.

Recently a new generation of rigid wing hang gliders has appeared (see Figure 2). The design bears close resemblance to the conventional hang glider, but have instead of an aluminium frame a composite D-nose spar to carry the air loads, behind which double sail is supported by ribs. The performance compared to the flexible wing gliders is improved due to several reasons. Firstly, the composite D-nose can be made relatively light and yet strong enough to carry all the loads, diminishing the need for support wires, resulting in less drag. Secondly, the composite D-nose structure also makes it possible to build wings with a higher aspect ratio. Finally, the nose can be shaped in any form and the sailcloth that is supported by the ribs forms a closed profile, resulting in a more optimal aerodynamic shape. The pilot is still suspended beneath the wing, but the control bar can swing sideways. With this movement the pilot controls roll and yaw by actuating spoilers that are located on top and on the outside of the wing. This type of glider can have an L/D-ratio of more than 16 and a minimum sink rate of less than 0.8 m/s. Due to the special control system this type of glider has been classified as class 2.

From a marketing perspective the development of a rigid wing hang glider that can compete as a type class 1 is very attractive due to the fact that this would become the glider with the highest performance in the most popular competition class. The design must have pilot weight shift as the sole means of control and no moveable control surfaces. The performance ratings must be equal or preferably better than those of the class 2 rigid wing gliders. Such a glider has also several advantages over the current rigid wing gliders, namely a more reliable control system, without mechanical parts, and secondly, it would give the pilot the same feeling of control as with a conventional glider. Many pilots that have switched to the rigid wing gliders have complained about the fact that the control bar is not rigidly connected to the wing, making it more difficult to fly under turbulent conditions.

This paper describes the development of a design of a class 1 rigid wing hang glider. The contents of this paper will emphasise on the aero elastic analysis of the design due to unconventional nature of the wing structure. Other aspects of the design such as the configuration, structural layout and performance and stability will be discussed in less detail.

2 Design Specifications

The design specifications were based on performance data of present-day rigid wing gliders, classification requirements and experiences of professional hang glider pilots. The main specifications are as follows:

- Classifiable as type class 1
- Maximum glide ratio more than 16
- Minimum glide ratio of 10 at 80 km/h
- Minimum sink speed less than 1m/s
- Minimum landing speed less than 30 km/h
- Minimum roll rate from zero to 45 degrees roll angle less than 3 seconds
- Structural weight (including control bar) less than 40 kg

3 Design Process

A multi-disciplinary design procedure was used to complete the design process from conceptual to preliminary design. The layout of the configuration was based on the layout of existing rigid wing gliders. First the relation between the flexibility of the wing structure of conventional hang gliders and their roll performance was analysed. The results were used for the development of a concept that uses only pilot weight shift for roll control. Different variants were considered, which will be discussed in more detail later. The final concept was further analysed in different areas; stability and performance, roll control and aero elasticity. Stability and performance were analysed with the use of CFD software (FASD). The roll control analysis was used to determine the structural requirements to comply with the specified roll performance. Aero elasticity was analysed with the use of the aero elastic module of the Finite Element program MSC/NASTRAN. This analysis was used to determine the structural requirements to prevent aero elastic problems in the speed range of the design. The findings of the stability and performance, roll control and aero elasticity analyses were integrated to form the final preliminary design.

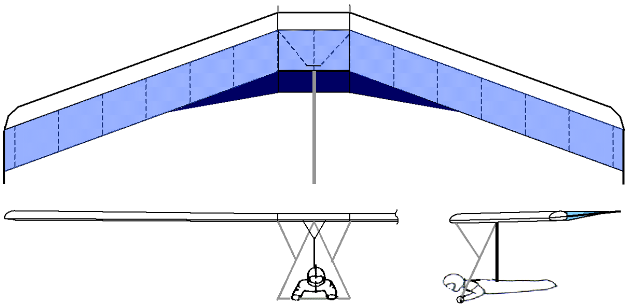

FIGURE 3 – Final configuration

4 Final Configuration

A general view of the design layout is shown in Figure 3. The total wingspan is 12 meters and the total wing area is 15.1 square meters. The aspect ratio is 9.5. The sweep angle of the outer wing parts is 20 degrees. Along the trailing edge of the centre wing part and along the inner half of the outer wing parts, simple landing flaps are attached to provide a greater approach angle and lower approach speed during descent.

The wing has a chord length of 1.15 meters (not including the landing flaps), which is constant to reduce production cost. The first 30% of the wing cord of the outer wing parts is formed by a composite D-nose, composed of a Glass fibre/Epoxy sandwich skin and Carbon fibre/Epoxy spar caps. Behind the D-nose the sail, is supported by lightweight aluminium ribs. These ribs are hinged to the D-spar and can be folded onto the D-spar for transportation. A special wing section is used with good stalling characteristics and which generates most of the lift at the nose of the profile, to make maximum use of the rigid section of the wing.

The wing has a special centre-section, which enables the pilot to control the glider using only weight shift. This will be discussed in more detail further in this paper. The pilot's harness is attached to the centre-section and the control bar consists of a conventional aluminium A-frame. Two aluminium rods support the A-frame. An aluminium keel rod provides support when the glider is standing on the ground.

5 Roll Control

5.1 Conventional Gliders

Experience has learned that the tension of the sail of flexible wing hang gliders is of great influence on the gliding and roll performance. A glider with a high sail tension has an optimum gliding performance but has a very low roll rate. By loosening the sail the roll performance improves and the gliding performance decreases. After analysing the wing structure and its deformation under aerodynamic loading the following explanations were derived:

- Lower sail tension results in more wing twist in such a way that the lift distribution gets more "bell-shaped", thus reducing the gliding performance of the wing.
- Lower sail tension also makes it easier for the wing to deform during a roll manoeuvre in such a way that the twist in the downward wing half increases and the twist in the upward wing half decreases, thus reducing the dampening of the roll manoeuvre.

A second aspect that was investigated was the influence of the pilot connection to the wing. Using simplified models of the wing structure to analyse the deformation of the wing due to pilot weight shift, it was found that pilot weight shift has a small wing warping effect, which increases the roll moment and therefore the roll rate.

From this it was concluded that in order to let the pilot weight shift be the sole means of control, the wing should warp during a roll manoeuvre in such a way that the dampening is reduced. This is a passive way of increasing the roll performance. To further increase the roll performance the pilot weight shift should have a wing warping effect, giving the pilot active roll control. This was incorporated in the conceptual design and different variants were considered.

5.2 Warping Concepts

Two different methods for warping the wing were considered. In the first variant the outer parts of the D-nose of the wing had low torsional stiffness with the torsional axis in front of the centre of pressure on this section of the wing. During a roll manoeuvre part of the down going wing half would twist forward, and part of the up going wing half would twist backward, thus reducing the dampening of the wing. This variant resembles the warping of a flexible wing, but also has similar disadvantages. During straight flight the outer parts will twist upwards, thus reducing the performance of the wing. Also, in this variant it is more difficult to meet the requirements for stability, due to the fact that the outer wing parts of a hang glider wing are used as stabiliser.

The second variant that was considered was incorporating a straight wing-section in the centre with special stiffness characteristics. The load carrying spar of this section has sufficient bending stiffness, but the torsional stiffness when loaded a-symmetrically is much lower than when loaded symmetrically. This can be achieved by using a spar that has a relative short length and an open cross-section. As with the other variant the torsional axis is in front of the centre of pressure of the outer wing parts. During a roll manoeuvre the centre part is a-symmetrically loaded, the down going outer wing warps forward and the up going outer wing warps backward, thus reducing the dampening. With this variant the wing performance and stability compared to a normal rigid wing glider is not compromised during a straight flight when the centre part is loaded symmetrically.

The variant with the flexible centre wing part was chosen over the variant with the flexible outer wing parts. For the chosen variant different concepts were developed for the connection of the pilot to the wing. These concepts were used to investigate different methods actively warping the wing by pilot weight shift

5.3 Centre-section Concepts

Both the torsional stiffness of the spar of the centre-section as the way that the pilot is attached to the spar are of great influence on the roll performance and aero elastic behaviour of the glider. The torsional flexibility of the centre-section determines the decrease of roll damping. The attachment of the pilot and control bar to the centre-section determine the a-symmetric torsion moment that can be achieved by lateral weight displacement, to warp the wing and increase the initial roll moment.

The centre-spar has an open cross-section. The difference in torsional stiffness under symmetric and a-symmetric loading depends on the material properties, the dimensions and the boundary conditions.

Three different ways of connecting the pilot to the spar were analysed. The attachment of the control bar is similar for all three concepts. The design of this part was restricted due to the desire of a conventional set up. A standard A-frame was used. This A-frame is attached to the spar in such a way that when the pilot pushes himself sideways, a small a-symmetrical torsion moment is created acting on the centre-spar.

Figure 4 shows the Finite Element model of the centre-section of Concept 1. In this concept the pilot is attached to the centre-spar via two ribs, which are connected to the ends of the spar. The harness of the pilot is attached to two cables, which are connected to the end of the two ribs. The ends of the two ribs are kept apart by a rod. The control bar is connected to the centre-spar via a central rib. The control bar is furthermore supported by two rods, which are connected to ends of the spar in front of the elastic axis. With this design, lateral pilot weight shift will result in a relative high a-symmetric torsion moment on the centre-spar.

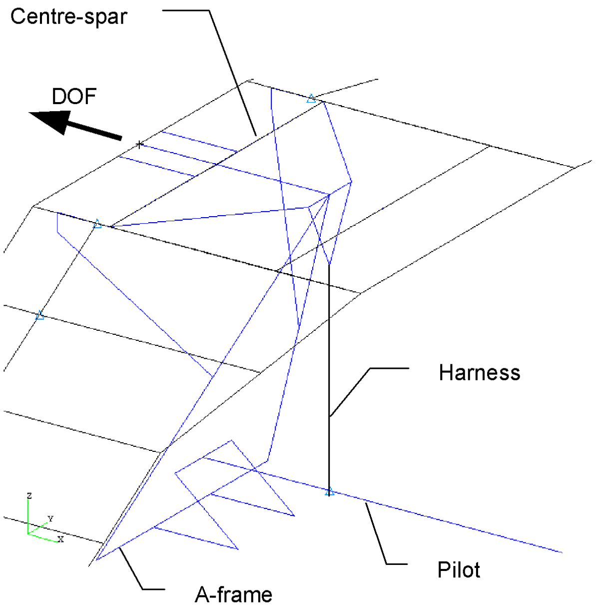

FIGURE 4 – FE-model of Concept 1

Figure 5 shows the Finite Element model of the centre-section of Concept 2.

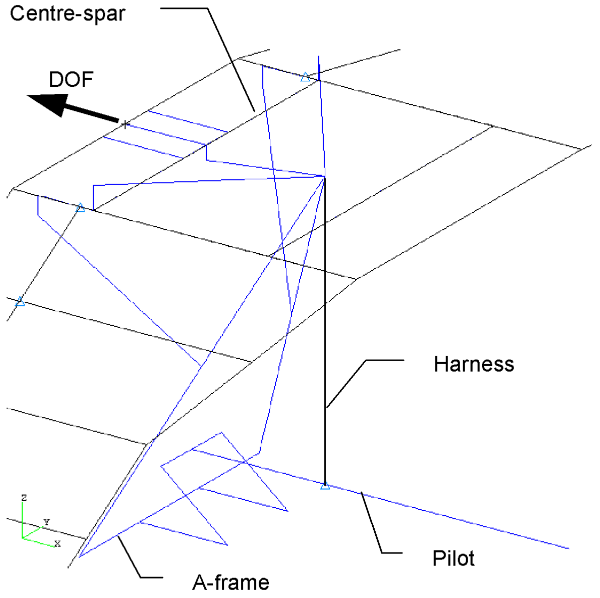

FIGURE 5 – FE-model of Concept 2

In this concept the pilot is attached to the centre-spar via three rods, which form a knot at the hinge point of the attached harness of the pilot. The two outer rods are connected to the upper corners of the centre-spar. The middle rod is connected to the lower middle section of the centre-spar and hinges sideways. The control bar is attached in a similar manner as in Concept 1. This concept is less complex than Concept 1, but lateral pilot weight shift will result in a much smaller a-symmetric torsion moment.

Figure 6 shows the Finite Element model of the centre-section of Concept 3. In this concept the pilot is attached to the centre-spar via a central rib, which is connected to the centre of the centre-spar. The harness is connected to the end of the rib. This concept is the most simple of the three. Lateral pilot weight shift will result in an a-symmetric torsion moment that is almost as large as that of Concept 2.

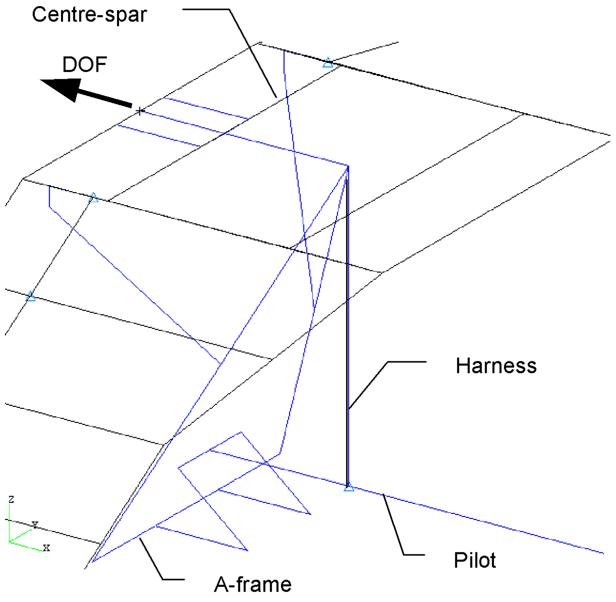

FIGURE 6 – FE-model of Concept 3

The functionality of these concepts is described in more detail in reference [1]. For each of these concepts the effective torsion moment caused by lateral weight shift was determined for different configurations and different torsional stiffness values of the centre-spar.

6 Roll Analysis

The roll performance specification was used as a constraint to numerically determine the minimum required torsion moment acting on the centre-spar produced by a maximum lateral weight shift of the pilot as a function of the torsional stiffness. The roll manoeuvre was modelled as a co-ordinated turn. The results are shown in Figure 7.

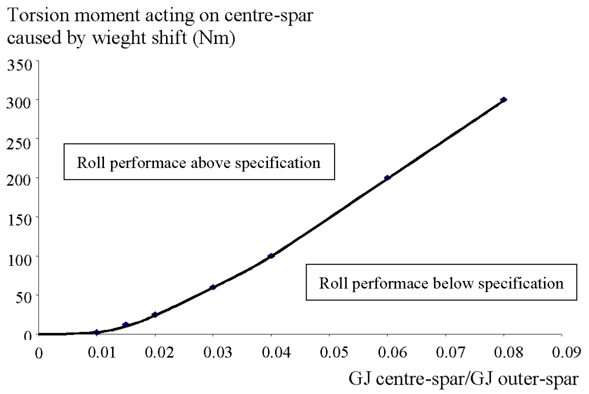

FIGURE 7 – Relation between centre-spar torsion moment and centre-spar torsional stiffness to comply with specified roll performance requirement.

The horizontal axis represents a non-dimensional value of the torsional stiffness of the centre-spar: GJ of the centre-spar as a fraction of GJ of the D-nose spar in the outer wings. The vertical axis represents the torsion moment acting on the centre-spar produced by maximum lateral displacement of the pilot weight.

From these results the following can be noted:

- The relation between the minimum torsion moment required for initial warping of the centre-section and the torsional stiffness of the centre-section is non-linear.
- At very low torsional stiffness, only a few percent of the stiffness of the outer wings, little active warping of the centre-section by the pilot is needed due to the low roll damping.

7 Stability and Performance

As flying wings, do hang gliders use the outer parts of the swept back wing as stabiliser. For stability the weight and drag of the pilot and the A-frame need also be considered, because they are of great influence on the resulting moment around the centre of gravity of the complete system. Two different methods to obtain stability were analysed. In the first variant the outer wings were fitted with a certain amount of negative twist. This is a conventional method for obtaining stability. In the second variant the shape of the wing profile in the outer wings was modified in such a way that the aerodynamic moment and the amount of lift produced by the outer wings is reduced. This was done by turning the outer ribs upward over a certain angle. With this method it becomes unnecessary to twist the D-nose structure, which significantly simplifies production. Due to the advantages in production and trimming during testing, the variant with the turning outer ribs was chosen for stabilising the design.

The stability analyses emphasised on the following aspects:

- Pitch and pitch-control stability of the hang glider design with pilot
- Pitch up moment of the wing
- Stall behaviour of the wing

Yaw and roll stability were not considered due to the limited time frame of the project. The aerodynamic characteristics needed for the stability analyses were obtained with a 3D CFD model of the wing. The CFD model was analysed with FASD, which uses a higher order panel method.

The aerodynamic characteristics that were obtained with the 3D CFD model of the wing, together with drag estimates for the pilot and control bar, were used to predict the glide ratio and the sink rate. A maximum glide ratio of 17 to 1 was estimated at a speed of approximately 50 km/h. The minimum sink rate is estimated at 0,75 m/s at a speed of approximately 45 km/h. At a speed of 80 km/h the glide ratio is still approximately 12 to 1. Using a simple empirical method the estimated stall speed with a flap deflection of 60 degrees was calculated at approximately 33 km/h.

8 Aero elastic Analysis

No previous records of aero elastic problems with hang gliders were found. With an elementary analysis of the first eigen frequencies of the wing structure it was found that the first torsional eigen frequency and the first bending eigen frequency were less than a factor 3 apart. The first eigen frequency in (out of plane) bending was calculated at around 13 Hz. The first eigen frequency in torsion (of the centre-section) was calculated between 5 and 10 Hz, depending on the torsional stiffness of the centre-section. There were no simple ways of increasing the difference between these eigen frequencies without unacceptable increase of structural weight.

8.1 Method

The aero elastic behaviour with increasing torsional stiffness of the centre-spar of the three design concepts, described before, was analysed with the Finite Element Program MSC Nastran. The structure of the control frame and a model of the pilot were included. For the aerodynamic model the doublet-lattice panel method was used in view of the relatively low aspect ratio of the wing.

Using an empirical method [2] an estimate was made of the frequency range on which to focus the flutter analysis. The upper boundary was set at 20 Hz. The upper boundary for the speed range was set at approximately 200 km/h (55 m/s). In practice, hang gliders seldom exceed a speed of 120 km/h.

Due to the fact that the pilot is suspended below the wing structure and incorporates most of the total weight, the position of the pilot and the way that the pilot is connected to the wing structure are of great influence on the eigen modes and eigen frequencies of the system. The pilot can also control the speed by shifting his position. Four different pilot positions were investigated. Each position was analysed in a different speed range:

1. Trim position: This is the pilot position at trim-speed. In this "neutral" position the pilot does not have to apply any force to the control-bar. The speed range is set between 40 and 60 km/h.
2. Dive position: In this position the pilot has shifted all his weight in front of the control-bar to gain maximum speed. The speed range is set between 100 and 140 km/h.
3. Landing position: In this position the pilot has shifted his weight behind the control bar to gain maximum angle of attack and approach stall speed. The speed range is set between 30 and 40 km/h.
4. Hands-free position: The pilot is in the same position as in the trim position but does not hold the control bar. The speed range is set between 40 and 60 km/h.

8.2 Reference model

As a reference a design with a centre-section with “normal” torsional stiffness was analysed. The results are compared with the aero elastic behaviour of the different concepts, to see whether the lower torsional stiffness of the centre-section has a negative effect on the aero elastic behaviour of the glider.

Two characteristic flutter modes were found, shown in Figure 8.

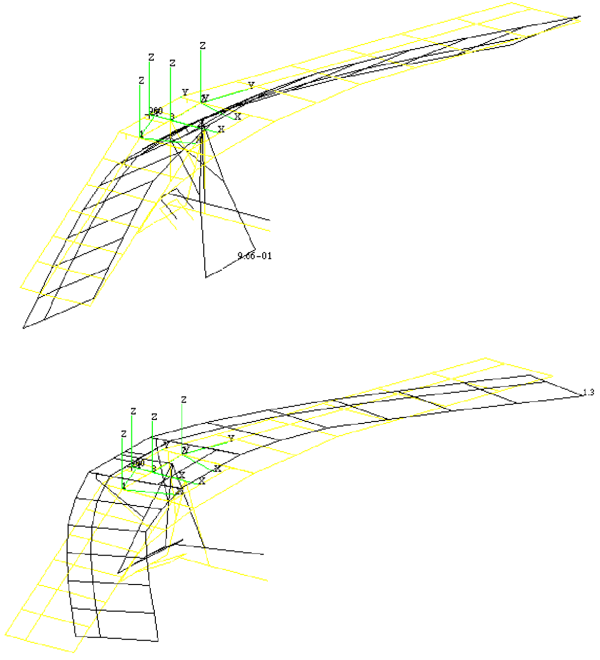

FIGURE - 8 Characteristic flutter modes

The flutter mode shown above is a 1st and 2nd order out of plane bending mode combined with a pitch vibration. This flutter mode occurred in the trim position, dive position and hands-free position at a speed of respectively 170, 173, and

62 km/h. The flutter mode shown below is a 1st order in plane bending mode combined with a small out of plane bending mode and a slight pitching vibration. This flutter mode occurred in the landing position at a speed of approximately 130 km/h

The unstable out of plane bending mode with a pitch vibration is characteristic for tailless aircraft designs. The unstable in plane bending mode combined with out of plane bending and a slight pitch vibration is difficult to explain. The speed at which the flutter modes become unstable falls for every pilot position outside the speed range of that position. This seems to agree with the fact that with the current rigid wing design, no flutter problems have been officially reported.

No divergence mode was detected with the reference model in the analysed speed range set to a maximum of 200 km/h

8.3 Divergence

As could be expected, the low torsional stiffness of the centre-section introduced a torsional divergence mode. The critical divergence mode is an anti-symmetric torsion deformation of the centre-section shown in Figure 9.

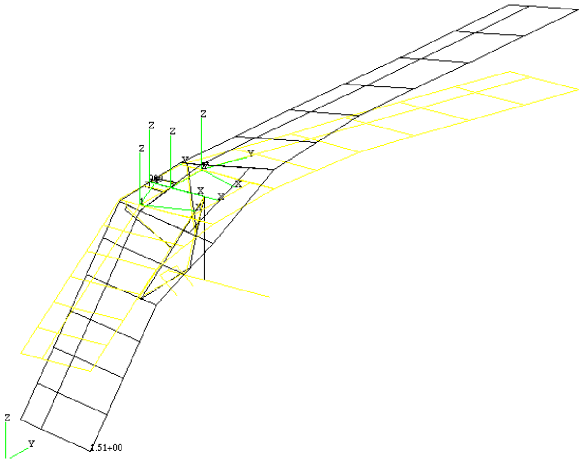

FIGURE – 9 Critical divergence mode

The divergence mode and divergence speed is not influenced by the design concept or the position of the pilot. The divergence speed depends on the torsional stiffness of the centre-section and increases with increasing stiffness. This is shown in the Figure 10. The horizontal axis represents a non-dimensional value of the torsional stiffness, described before. The vertical axis represents the flight speed.

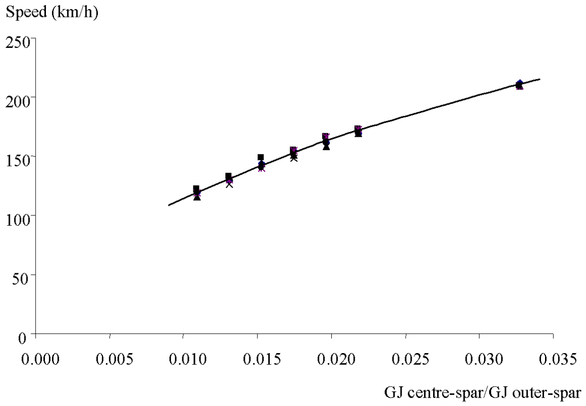

FIGURE 10 – Divergence speed versus centre-spar torsional stiffness

From this figure several things can be noted:

- Divergence occurs within the specified speed range of the glider not until the torsional stiffness of the centre-spar is only a few percent of the torsional stiffness of the outer-spars.
- Considering a minimum value for the maximum speed of 100 km/h and using a 1.2 safety factor, the minimum torsional stiffness required is approximately 1% of the torsional stiffness of the outer spars.
- By increasing the torsional stiffness to a value of about 3% the divergence speed increases to approximately 200 km/h and exceeds the speed range of the glider.

8.4 Flutter

The results from the analysis of the three design concepts showed that the flutter modes found in the analysis of the reference model reoccurred. The flutter mode with an unstable in plane and out of plane bending mode, has instead of a small pitch vibration, a symmetric torsion vibration of the centre-section. Also an additional characteristic flutter mode was found, shown in Figure 11. This is a 1st order anti-symmetric in plane bending mode, combined with the 1st anti-symmetric out of plane bending mode and a anti-symmetric torsion mode of the centre-section. This flutter mode is clearly caused by the low torsional stiffness of the centre-section.

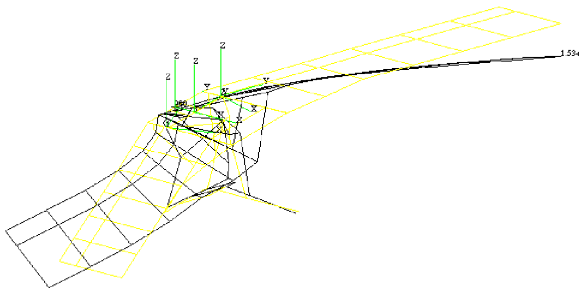

FIGURE 11 - Characteristic flutter mode caused by the low torsional stiffness of the centre-spar

An overview of the critical flutter modes per design concept and per pilot position is given in the Table 1.

Pilot position	*reference model*	*Concept 1*	*concept 2*	*Concept 3*
hands-free	S + RY	S + RY	-	-
trim	S + RY	S + RY	SZ + S + T	-
dive	S + RY	ASZ + AS + AT	ASZ + AS + AT	ASZ + AS + AT
landing	SZ + S + RY	ASZ + AS + AT	SZ + S + T	ASZ + AS + AT

Table 1 - Overview of flutter modes

S	symmetric out of plane bending
AS	anti-symmetric out of plane bending
SZ	symmetric in plane bending
ASZ	anti-symmetric in plane bending
T	symmetric torsion of centre-section
AT	anti-symmetric torsion of centre-section
RY	pitch vibration

Apparently the connection of the pilot to the wing and the position of the pilot (weight) are of great influence on the aero elastic behaviour of the design. The system of wing structure with pilot was too complex to analyse in order to explain the form of the flutter modes and the change due to change of position or change of concept.

As could be expected, the flutter speed changes with changing torsional stiffness of the centre-section. This can be seen from the results in Figure 12. The horizontal axis represents a non-dimensional value of the torsional stiffness of the centre-section, explained before. The vertical axis represents the flight speed. The flutter speed values of the reference model are marked as borderlines and the speed range for the different pilot positions are marked with boxes.

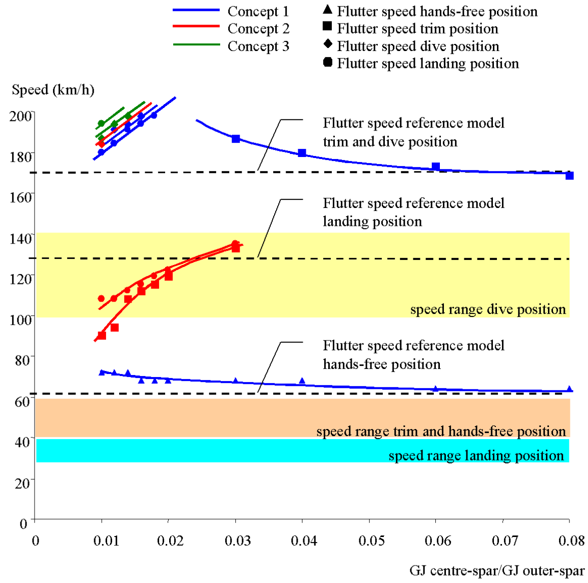

FIGURE 12 – Flutter speed versus torsional stiffness of the centre-spar

Together with the results from Table 1 several things can be noted:

- None of the occurring flutter modes in the different pilot positions appear to cause any problems in the specified speed range of those pilot positions for any of the three concepts.
- The flutter speed for the S + RY mode of concept 1 in the trim, dive and hands-free position is higher than the flutter speed for the same mode of the reference model at low torsional stiffness and approaches the flutter speed of reference model with increasing torsional stiffness.
- The flutter speed of the SZ + S + T of concept 2 is lower than the flutter speed of the comparable SZ + S + RY mode of the reference model at low torsional stiffness and approaches the flutter speed of the reference model with increasing torsional stiffness.

9 Design Evaluation

The results from the roll analysis, the aero elastic analysis and the analysis of twisting the centre-spar by weight-shift of the three different concepts are combined in Figure 13.

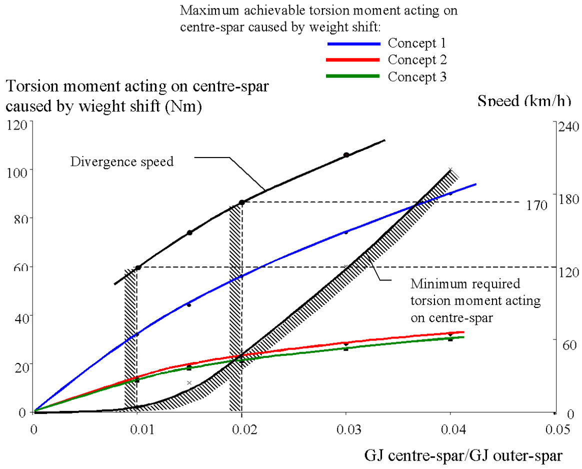

FIGURE 13 – Design evaluation graph

The results from this figure show that with Concept 1 for a much larger range of the torsional stiffness of the centre-spar, the roll performance requirement can be achieved, than with Concept 2 and 3.

At this stage of the design it is difficult to predict the maximum achievable flying speed. Therefore a design constraint attained from the minimum allowable divergence speed depends on the requirements of the user of the glider. Considering a maximum flight speed of 100 km/h with a minimum divergence speed of 120 km/h, all three concepts are possible. Above a maximum flight speed of 140 km/h with a minimum divergence speed of 170 km/h, Concepts 2 and 3 become infeasible.

In the author's opinion the minimum divergence speed must be chosen very conservatively due to the lack of experience with such an unconventional design and due to the fact that the results of the analyses of the design are based on simplified models and certain assumptions. For this a scatter in the results must be expected.

Concept 1 was chosen as the best design concept. With this concept a torsional stiffness of the centre-spar can be selected, where the divergence speed is probably well above the maximum achievable flying speed.

10 Conclusions

A preliminary design of a new concept hang glider with a rigid wing was made, which uses flexibility in the wing structure to comply with manoeuvrability requirements using pilot weight-shift as the single means of control.

A centre-section with low torsional stiffness is used, which reduces the roll damping of the wing.

Three different concepts of connecting the pilot to the centre-spar were developed, with which the pilot can twist the centre-section by shifting his weight, thus increasing the initial roll moment.

Using the specified roll performance as a constraint, the minimum required initial twisting moment acting on the centre-spar as a function of its torsional stiffness was determined.

An aero elastic analysis of the three different concepts was performed. Flutter problems are not expected. Divergence can occur within the speed range of the glider if the torsional stiffness of the centre-spar is very low.

Using the results from the roll analysis, the aero elastic analysis and the analysis of twisting the centre-spar by weight-shift of the three different concepts the three concepts were evaluated. A minimum divergence speed requirement determines the possible torsional stiffness range of the centre-spar.

The design Concept referred to as Concept 1 was chosen as best design concept.

References

[1] Massaro G.M., "Voorontwerp van een Class 1 Rigid Wing Hang Gider", TU Delft, Delft, 1998.

[2] Stender S, Kiessling F, "Aeroelastic Flutter Prevention in Gliders and Small Aircraft", DLR-Mitteilung 91-03,1991.