THE SCHOOL OF MECHANICAL ENGINEERING

AERONAUTICAL ENGINEERING I

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Group 11:

Design and Performance of a Hang Glider

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1. Introduction

Hang gliders are an unpowered aircraft, designed to carry a maximum of two passengers suspended beneath its sail. Hang gliders unlike gliders do not look like conventional aircraft but are powered by large sails or wings. Hang gliders are conventionally launched from a high point and drift through the forces generated via various meteorological phenomena to be discussed. Another important characteristic of hang gliders is that they do not have any moving control surfaces but craft control is achieved by the pilot moving his or her body mass in order to change the system centre of mass. This report will describe and discuss changes between early and modern designs, fabrication and materials used in hang glider construction.

The manner in which hang gliders are able to generate lift, control the craft among other flight characteristics will be discussed further in the Flight Mechanics and Flight Performance chapters. Another important part of hang glider design that will be discussed involves the inherent stability of modern day hang gliders that allow the pilot to be able to control the craft with far greater ease.

2. Comparisons of Early to Modern Hang Glider Design

Early hang gliders were crude machines; enthusiasts with limited knowledge of aerodynamic theory, inadequate materials and no thrust mechanism developed these gliders that used the slope of the earth and gravity to become airborne. The first aerodynamic advancements were made in the latter part of the 19th century and this led to the first practical hang gliders. In this period Otto Lilienthal studied the lifting capabilities of cambered wing surfaces. Further from this Lilienthal started experimenting with wings similar to modern day hang glider wings, where he stretched cloth over willow frameworks. There are two main types of modern hang gliders the flexible wing (Class 1) and rigid wing gliders (Class 2). The flexible wing hang glider first developed by Rogallo (1951) was marketed as a simple and inexpensive approach to recreational flying. The plan form of the Rogallo wing is shown in Figure 1. The Rogallo wing as it is known was essentially a kite which did not have any reinforcing members, that was able to be easily folded or rolled for storage purposes (US Patent 61702). This kite is formed by a quadrilateral section of material and uses the force of the wind to create an aerofoil. This shape was decided upon following an iterative design process so as to ensure stability, structural integrity and achieve the final goal of being able to carry a human pilot's weight. The Rogallo wing as it was adopted to the recreation of hang gliding was developed from the delta wing which was originally proposed it as a plan form shape to be used for returning spacecraft back to earth.

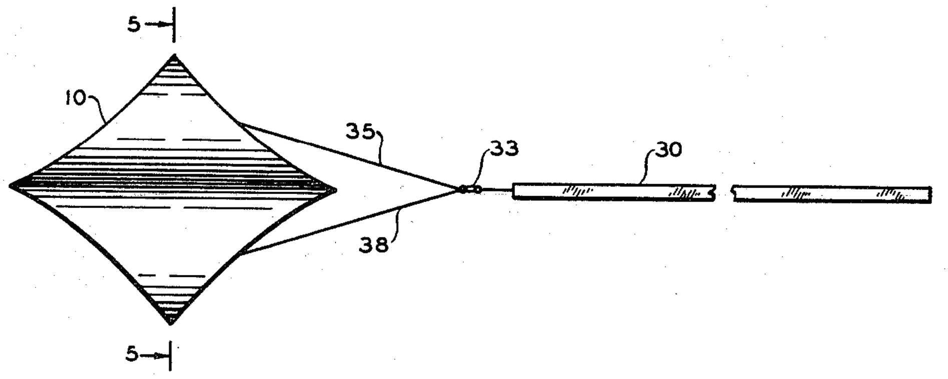

Figure 1: Rogallo wing (US Patent #61702)

The rigid wing hang glider on the other hand had its roots in a rigid wing biplane configuration. The major difference between this type of hang gliders and the more popular Rogallo wing was in the way directional control was achieved. Unlike most

current day hang gliders these rigid biplane hang gliders used control surfaces including two pilot controlled ailerons at the wing tips and were maneuvered by levers. These hang gliders need control surfaces for the pilot to be able to maneuver the craft because of the stiffness of the rigid wing. The various components and design of rigid wing hang gliders is discussed further.

3. Manufacturing

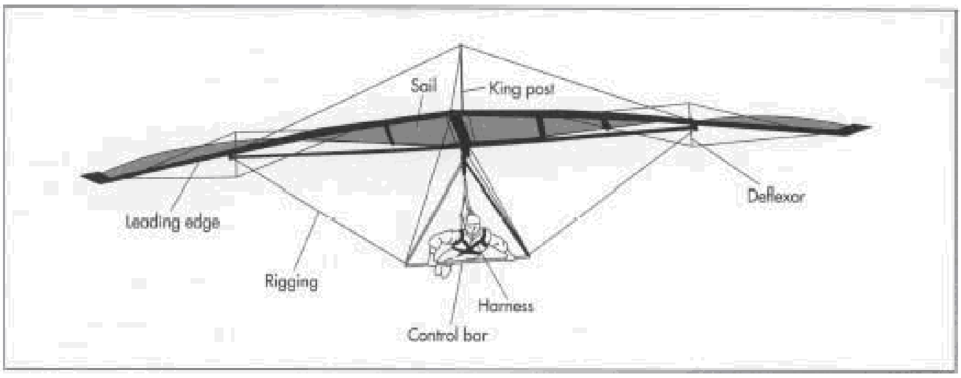

Figure 2: Parts of the fixed wing hang glider [21]

This section will detail the manufacture and the materials used in developing the different parts of a rigid wing hang glider. A primary goal of the design of a hang glider is obtaining good structural integrity and low craft mass concurrently. A rigid wing hang glider consists of a wing or sail, triangular frame control bar, cable rigging and other parts that hold these main components in place (refer Figure 2). The wing section of the hang glider is usually draped over with a polyester cloth. An important design characteristic that this cloth must meet is with regards to the porosity of the material. Low porosity allows the wing to keep its aerodynamic shape and hence generate lift efficiently. The wing of a hang glider is draped over by a kite material which has one important characteristic, that of low porosity. Low porosity material is a requirement for the wing to be able to retain its aerodynamic shape and hence generate the required lift. The cut pieces of cloth, which number in their hundreds are aligned in a pre determined fashion and then sewn together on industrial sewing machines. This process is repeated until the required thickness and shape is achieved (How Products Are Made, 2000). Upon being able to achieve the required shape with the fabric, the required shape is achieved by carbon fibre luff lines. Luff lines must have high stiffness so that they do not deflect significantly under high wing loading. High aerodynamic wing loading can result in the aerodynamic camber and spanwise twist to change significantly; hence resulting in the loss of aerodynamic shape. Carbon fibre is used as the primary material in rigid wing hang gliders due to their high strength to weight ratio. The frame of a hang glider, also known as the airframe, is made from an aircraft grade aluminium alloy for its high strength to weight ratio. The frame is made from aluminium alloy tubes and these are cut to the required length and holes are formed at the points that the frame will be held together. Figure 3 shows the method through which the various parts of the

frame are held together. The cables and the other rigging components that hold the hang glider together are usually made from stainless steel cable. These usually come in large spools and are cut to size as required. Lastly the entire craft is usually disassembled for ease of storage and transportation. This will be discussed further in Chapter 3 Hang Glider Design

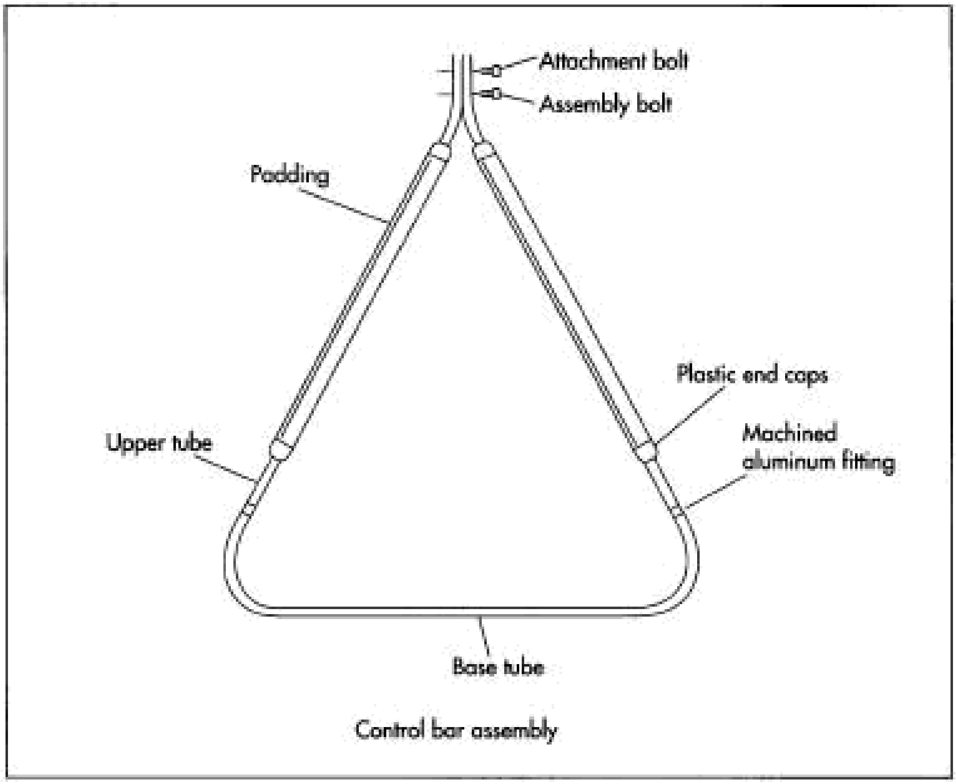

Figure 3: The frame is formed by assembling the control bar and tubing. Stainless steel nuts and bolts are used to hold the parts in place [21]

4. Hang Glider Design

The design of hang gliders has evolved greatly since their use for early manned flight tests. The wood and fabric construction of early gliders has been replaced with lightweight metal and composite frames covered with synthetic cloth. This has served to greatly reduce the weight and greatly increase the performance of modern gliders. In addition, improved understanding of the aerodynamic forces acting on a hang glider has allowed designs to be modified to improve safety while keeping costs low. The most noticeable difference between early gliders and modern performance aircraft is the wing shape. Almost all modern hang gliders use a high aspect ratio delta wing design. However, there are a number of variations on this design including single and double surface gliders as well as rigid wings. The key design features of modern hang gliders will be discussed in this section.

5. Types of Hang Glider

5.1 Delta Wing

The modern flexible wing hang glider is based on the self-inflating wing designed by Francis Rogallo in 1948. The Rogallo wing is a delta shape supported by leading edge struts, a central keel and a structural crossbar. An early hang glider based on the Rogallo wing can be seen in Figure 4.

Figure 4: Early Rogallo Hang Glider [11]

Early Rogallo hang gliders were extremely simple in their design and construction. The main struts were made from standard aluminium tubes and the sail fabric

was ripstop nylon. This allowed manufacturing costs to be minimised, however performance did not compare with that of modern gliders. The wing itself did not have any battens to provide it with camber, but instead relied on the self-inflating design to maintain its shape during flight.

Rogallo wing hang gliders suffered from a number of design problems, the most serious of which resulted in several fatal accidents in the 1970's and 1980's. Due to the lack of any wing battens, the Rogallo wing could potentially deflate during flight meaning it could no longer produce lift. This problem most commonly occurred during high speed manoeuvres, particularly tight turns and dives. Deflation was characterised by the trailing edge of the sail cloth flapping up and down instead of remaining in tension. To overcome this problem, a series of lines were added between the kingpost and the trailing edge. These "luff lines" were arranged such that when the control bar was pushed completely forward, the trailing edge of the sail was lifted upward providing a positive control surface to produce a rotational motion to lift the nose. In this way, if the wing was deflated, the nose could still be rotated upwards thus allowing the wing to reinflate.

Modern flexible wing gliders are still based on the delta wing shape but with a much higher aspect ratio and more conventional airfoil shape. Early Rogallo hang gliders had aspect ratios as low as 1 whereas modern topless gliders have aspect ratios in excess of 8.

5.2 Flexible Wing

By far the most common type of modern hang glider is the flexible wing. These gliders generally have a modified delta shaped wing which is formed from a series of aluminium struts and covered with a synthetic fabric. Additional structural strength is provided by a series of wires which also serve to change the shape of the wing when the pilot changes his/her body position. The key parts of a flexible wing hang glider are shown in Figure 5.

In most hang gliders the leading edge tubes, crossbar, keel and control bar are all made from aluminium tubing. The leading edge tubes are generally extruded to give them a cross-section suitable for the leading edge of the wing. The leading edge tubes, keel and crossbar are the main structural members of the hang glider and are rigidly fixed together. These members provide the basic shape to which the fabric of the sail can be attached. The airfoil shape of the hang glider is achieved by using a series of moulded plastic or aluminium battens which are stitched into the sail fabric. The control bar and kingpost are attached to the keel of the hang glider and

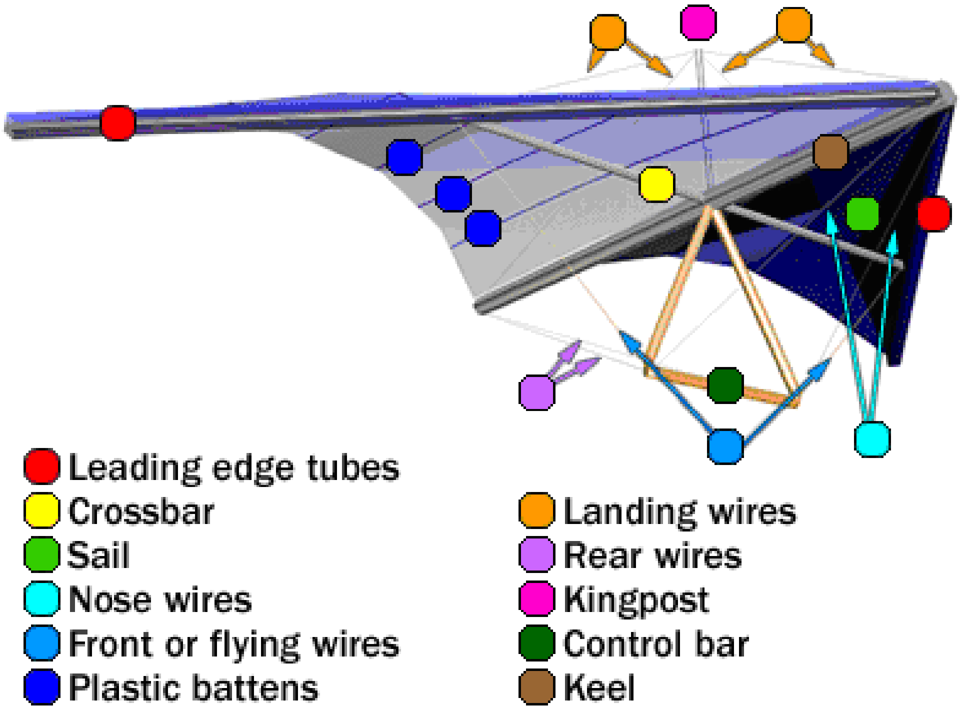

Figure 5: Key Parts of a Modern Hang Glider [1]

are secured to the wing by a series of wires.

5.3 Single Surface Gliders

The most basic flexible wing gliders are single surface. This means that only a single piece of sail fabric is used to form the wing. Generally, the wing battens are placed in stitched pockets on the underside of the sail. The key advantages of single surface gliders are the simplicity of the manufacturing process and the reduced material requirements. Hence, these gliders tend to be lower cost, lighter and more transportable. A typical single surface glider is shown in Figure 6.

The main disadvantage of single surface gliders is the reduced performance resulting from the wing shape. Single surface gliders have a highly cambered wing profile. This means that air flowing underneath the wing does not remain completely attached to the surface and this produces turbulent flow and hence increased drag. In addition, the cambered wing profile means that at high speed the flow separates from the bottom surface of the wing and thus the lift it produces is greatly reduced. This makes single surface gliders less suitable for sports or performance flying.

Figure 6: Single surface hang glider [3]

5.4 Double Surface Gliders

In 1980, Ultralight Products produced the first double surface hang glider, the Comet. This glider differed significantly from existing designs because it used two pieces of sail cloth to create an enclosed airfoil. This greatly improved hang glider performance by reducing induced drag and hence improving glide ratio. A typical modern double surface hang glider is shown in Figure 7.

Double surface gliders have a much more complicated construction and take longer to setup and dismantle. As can be seen in Figure 4, the crossbar is located within the airfoil and is set forward of the control bar connection point. This is known as a "free-floating" crossbar arrangement because the control bar and crossbar are not directly connected. The addition of the bottom wing surface also requires additional wing battens to be installed. Generally, there are many more battens used in the upper surface of the wing compared with the lower surface. This is because the camber of the wing allows the bottom surface to be sufficiently tensioned between the leading and trailing edges. The improved airfoil shape resulting from the use of two pieces of sail cloth can be clearly seen in Figure 7 when compared with a single surface or delta wing glider.

There are a wide range of double surface glider designs currently available. These

Figure 7: Modern Double Surface Hang Glider [5]

differ primarily in the extent to which the bottom surface covers the top surface of the wing. The glider shown in Figure 7 is a 70% double surface glider because the bottom piece of sail fabric covers approximately 70% of the area of the upper surface. The further the bottom wing surface extends, the more accurate the airfoil shape and hence the better the performance. However, this increased performance results in a more complicated construction and hence greater cost.

5.5 Topless Gliders

The newest generation of flexible wing hang gliders are known as topless or "kingpost-less" gliders. These hang gliders have been designed to eliminate the kingpost and associated supporting wires in order to minimise drag. While a number of experimental topless glider designs were developed in the 1980's, it was not until the advent of carbon fibre and other composite materials in the late 1990's that topless gliders became common. Removing the kingpost and associated wires from a hang glider means that additional structural strength is required in the wing itself to resist any downward forces. Topless gliders achieve this through the use of additional carbon fibre struts in the wing. This material is extremely well suited to this application due to its stiffness and high specific strength. A modern topless glider is shown in Figure 8.

Topless hang gliders significantly outperform those with a kingpost. This is due to the reduced drag of the aircraft and the increased stiffness of the wing. Virtually all topless hang gliders are double surface and usually have a bottom surface which covers in excess of 70% of the top surface. The increased performance of a topless

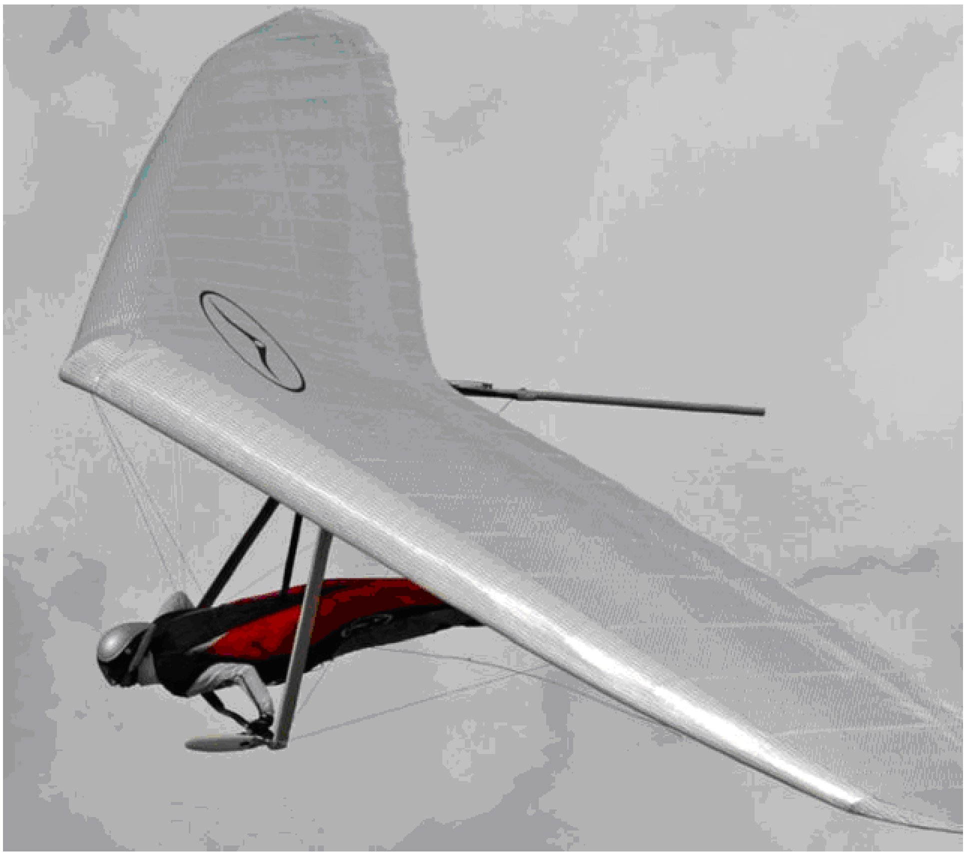

Figure 8: Topless Hang Glider [6]

hang glider comes at a significantly increased cost. In addition, topless gliders tend to be less stable in flight and more difficult to land due to their higher speed.

5.6 Rigid Wing Gliders

Some of the earliest glider designs can be classified as rigid wings. Unlike modern flexible wing hang gliders which can be manoeuvred by adjusting the position of the pilot's weight, rigid wing hang gliders use control surfaces to provide control whilst in flight. Rigid wing gliders are the closest hang gliders come to conventional aircraft and can be thought of as sailplanes without a cabin. A modern rigid wing hang glider is shown in Figure 11.

Rigid wing hang gliders are so named because a large structural member is used for the leading edge of the wing instead of a small tube. This can be seen in Figure 6, where the leading edge member is almost 25% of the length of the wing chord. The leading edge member is usually manufactured from a combination of fibreglass and carbon fibre to provide great stiffness and structural strength. The remaining wing surface is formed from standard sail cloth usually with a larger number of battens

Figure 9: Modern Rigid Wing Hang Glider [7]

than a flexible wing. Some rigid wing gliders incorporate carbon fibre wing ribs to give the wing the optimum airfoil shape. However, these gliders tend to be more expensive and significantly heavier.

Due to the stiffness of the wing, rigid wing hang gliders require control surfaces in order to be manoeuvrable in flight. The most commonly used control surfaces on rigid wing hang gliders are spoilerons. These provide both roll control and assist in slowing the glider down during landing. Other rigid wing designs use ailerons or a combination of spoilerons and ailerons to achieve roll control. Examples of spoilerons and ailerons are shown in Figure 10.

(a) Spoilerons (b) Ailerons

Figure 10: Rigid Wing Hang Glider Spoilerons (left) [8] and Ailerons (right) [9]

Rigid wing hang gliders currently offer the best glide performance of all hang glider types. However, they tend to be less manoeuvrable and not as fast as modern double surface, topless gliders. This is because the flexible wings can be more radically changed in shape to provide greater control authority and minimum drag at high speed.

5.7 Other Hang Glider Designs

There are many experimental hang glider designs currently in operation. One of the newest designs being trialled is based on a rigid wing glider but with the addition of a boom and horizontal stabiliser or v-tail. An example of this design is shown in Figure 11. The advantage of this design is that the aspect ratio of the wing can be further increased without loss of pitch stability and control. Conventional hang gliders without an empennage are limited in their aspect ratio because a wing with a very narrow chord does not offer very positive pitch stability or control.

Figure 11: Modern Rigid Wing Design with V-Tail [12]

There are numerous other modifications to hang glider designs which have been trialed. These include the use of canards, gull wings, forward swept wings, elliptical wing profiles and various vertical and horizontal control surfaces. The main problem with all of these design modifications is that they increase the complexity and cost of the hang glider and reduce its portability. Since this is one of the key attractions of hang gliding, it is unlikely that drastic modifications will become common except in the highest performance models.

6. Materials

6.1 Structural Members

The majority of flexible wing hang gliders continue to use extruded or drawn aluminium tubing for the structural members of the aircraft. This includes the leading edge tubes, keel, crossbar and control bar. Whereas early glider designs simply used circular cross-section tubing for these elements, modern gliders have specially designed cross-sections for the leadings edges and control bars which minimise drag. The most common types of aluminium used are aircraft grade 6061 and 7075.

High performance flexible wing and all rigid wing gliders substitute aluminium for carbon fibre in some of the key structural components. Flexible wing gliders designed for competition often have carbon fibre crossbars and control bars but retain the aluminium leading edges and keels. All rigid wing gliders use carbon fibre leading edges due to their superior stiffness and specific strength.

6.2 Wing Battens

The wing battens in almost all flexible wing gliders are made from either moulded plastic or aluminium. These offer good strength but are still reasonably light. Many rigid wing gliders also use these materials for wing battens, however some utilise full carbon fibre wing ribs to achieve the optimum airfoil shape. Such gliders are usually designed for cross-country flying where glide ratio is the key consideration.

6.3 Sail

The material used for the sail of a hang glider must be strong, lightweight, resistant to ripping and tearing, UV resistant and aesthetically pleasing. Early hang gliders used canvas or cotton fabric treated with dope, however this tended to rip or tear easily. The first Rogallo wing hang gliders were constructed from rip-stop nylon which met a considerable number of the above requirements. Modern gliders use a variety of synthetic sail materials, primarily various forms of polyester. The most common cloth materials are Mylar and Dacron. In order to prevent deterioration due to ultraviolet exposure, these materials are treated with titanium or zinc oxide. These treatments still allow the cloth to be manufactured in any desired colour.

6.4 Safety

Hang gliding today is a safe and enjoyable form of recreation. When hang gliding rose greatly in popularity in the 1970's and 1980's, there were many accidents. These were primarily the result of a lack of any mandatory training or licensing for pilots and of the limited understanding of glider design. Since the late 1980's, the number of hang gliding accidents has dropped markedly although like all adventure sports, accidents can still occur. Improved hang glider design means that most aircraft have a large operational envelope and are extremely stable in both pitch and roll. The move away from the early Rogallo delta wing designs means that wing deflation is no longer a problem. Virtually all hang glider pilots now carry a parachute which is designed to return the pilot and glider safely to the ground in the event of an emergency. However, if operated within their design limits, modern hang gliders can be just as safe as any other form of conventional aircraft.

6.5 Storage

Perhaps the key attraction of hang gliding is that the aircraft can be easily folded up and transported or stored. This is one reason why flexible wing gliders remain so much more popular than higher performance rigid wings. By simply removing the control bar, kingpost and crossbar, the two leading edge tubes can be folded back against the keel. This allows the hang glider to be placed in a long tube or soft cover which can be easily stored or placed on the roof rack of a car for transport, as shown in Figure 12.

Figure 12: Hang Glider Tube on Car Roof Rack [12]

7. Flight Mechanics

7.1 Changing Direction

Once airborne the pilot has the capability to change the direction of the hang glider. Unlike conventional aircraft, where the pilot can use aerodynamic control surfaces such as rudders, elevators, ailerons, etc, to change yaw, pitch and roll, a hang glider pilot can not since such features do not exist on hang gliders. Instead the pilot has to shift the centre of gravity (CG) of the vehicle to perform such operations. The CG of the vehicle, depicted in Figure 13, is the resultant between the CG of the wing, CGw, and the CG of the pilot, CGp.

Shifting the CG of a hang glider is quite simple due to its design. With reference to Figure 13, the pilot is suspended from a cable, which is attached to the keel at the hanging point and can change the orientation of the hang glider by applying lateral or longitudinal forces or a combination of both to the A-frame (in flight, the A-frame's purpose is to serve as a 'steering wheel'). Changing the orientation creates an illusion to an observer that the pilot's body has moved. Hence, colloquially speaking, people say that pilots shift their body weight to control hang gliders.

So, if a pilot shifts body weight purely in a forward or backward direction, this would mean that a longitudinal force is applied to the A-frame. This then would cause the hang glider to pitch. An upward pitch occurs when the pilot shifts weight backwards, or more correctly, by pushing against the A-frame. It is the converse

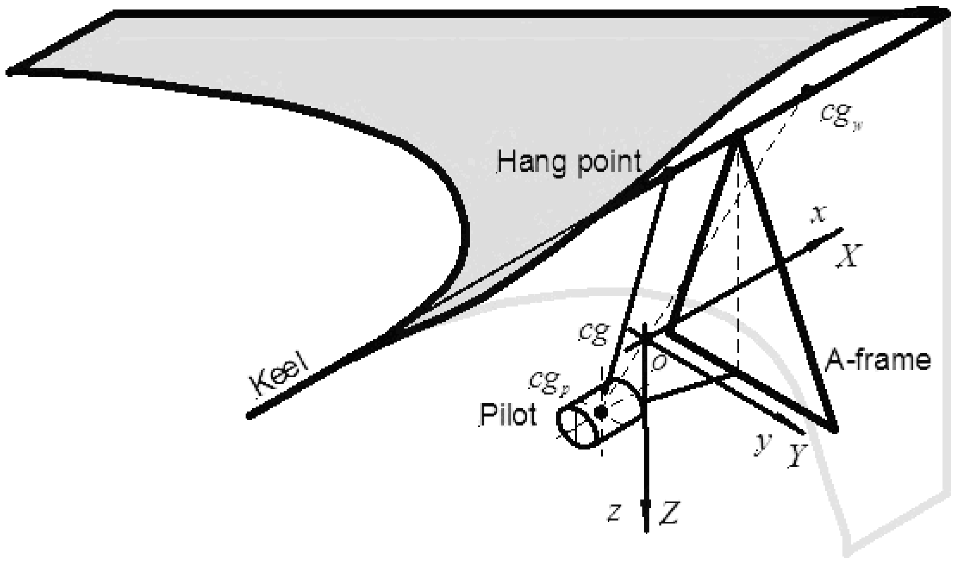

Figure 13: Hang glider body and coordinate system [14]

when the pilot wishes to cause a downward pitch. Now if the pilot shifts body weight purely to the sides, a lateral force in imparted to the A-frame. In response to the input, the hang glider will bank. If the hang glider banks to the right, this indicates that the pilot has shifted their body weight to the right by means of pulling the A-frame. The opposite occurs if the hang glider banks to the left, as shown below in Figure 14. Combining the two modes of inputs, the pilot can cause the hang glider to spiral downwards, spiral upwards, or circle.

7.2 Lift Generation

With the absence of both elevators and an engine, hang gliders are still capable of producing lift, but in still air this is not enough to overcome the influence of gravity. However, use of variable wind conditions can overcome this problem to allow an increase of altitude.

The governing principal for a hang glider to generate lift is the same for other aircraft. That is, air must flow over the wing area from the leading edge to the trailing edge. The magnitude of the lift produced is controlled by the angle of attack. For a pilot to increase the angle of attack an upward pitch input is required. Naturally, like any other aircraft, there is a critical angle of attack before stalling occurs. This is unique to each hang glider design and will be discussed further in the relevant section.

Depending on the wing design of the hang glider, the lift generated comes from dif-

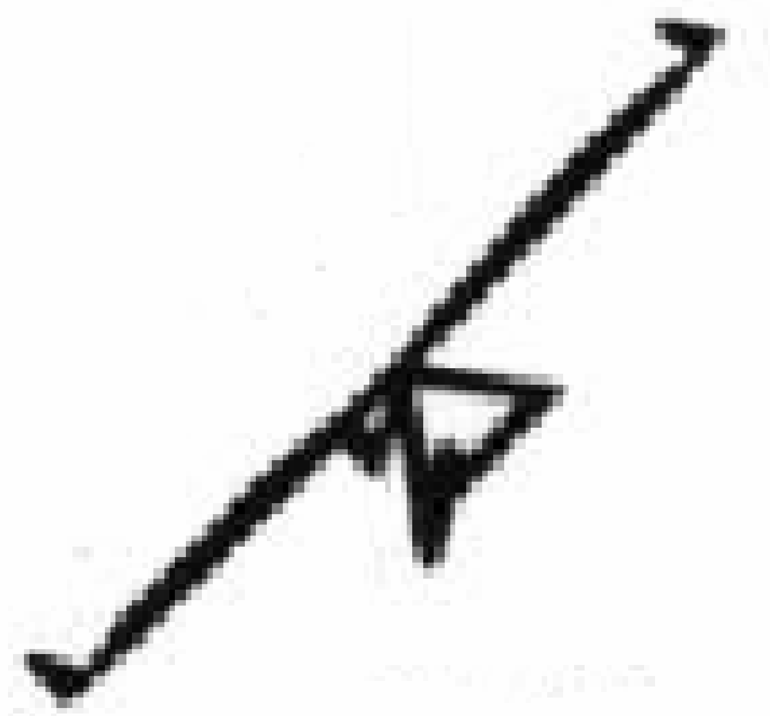

Figure 14: Hang glider flying into the page and banking left [13]

ferent contributions. For rigid wing hang gliders, there is one contribution to lift due to incidence. However, for flexible wing hang gliders, there are three contributions, which are lift due to incidence, lift due to camber and lift due to the action of luff lines. It is the latter wing design that is more complicated for determining the lift generated, as there are more parameters to consider than for a rigid wing.

Considering flexible wings, the lift due to incidence is proportional to the angle of attack, α, when it is greater than the luffing angle of attack αL. For angles of attack below the luffing angle of attack, the lift due to incidence is proportional to the square of the hang glider's air speed. According to Cook [14], the expression for the lift coefficient due to incidence is,

$$C_{L_\alpha} = a_1\alpha \qquad \text{for } \alpha > \alpha_L$$

$$C_{L_\alpha} = a_1\alpha = a_1(k_4V^2 + k_5) \qquad \text{for } \alpha \leq \alpha_L$$

where a_1 is the lift curve slope and k_4 and k_5 are constants, all of which are deter-

mined empirically from experimental data.

The lift due to camber behaves in a different manner. As the angle of attack changes, the pressure distribution on the wing, caused by the moving air, causes the shape of the wing to alter slightly (this occurs because of the wing being flexible). Because of the change of shape, loading on the wing is minimised and there is then a change in camber. A change in camber presents a change in cross sectional area to the free stream, which results in a change of lift. Hence, Powton [17] devised the following equation for the lift coefficient due to camber,

$$C_{L_c} = \frac{a_{21}\alpha + k_6}{V^2} \qquad for\ \alpha \geq 0$$

$$C_{L_c} = \frac{a_{22}\alpha + k_6}{V^2} \qquad for\ \alpha < 0$$

(2) where a_{21} and a_{22} are the effective lift curve slopes accounting for changes in incidence due to camber and k_6 is a constant, all of which are determined empirically from experimental data.

Lastly is the lift due to the action of luff lines. For all angles of attack below a pre determined value, the luff lines become taut and consequently the flexible wing adopts a reflex camber shape near the trailing edge, as shown below in Figure 15.

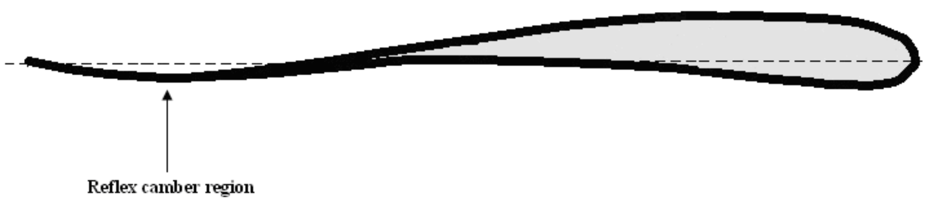

Figure 15: Taut luff line producing reflex camber region [14]

This reflex camber region produces a small negative lift component together with an upward pitching moment. The predetermined angle of attack at which the luff lines become taut is purely dependent on the incidence of the root chord of the hang glider. According to Cook [14], the incidence of the root chord is unique to each glider and is independent of the hang glider's velocity. The minimum incidence at which the reflex region first forms is denoted by αRL. The incidence at which the reflex region is a maximum is denoted by $\alpha' RL$. Thus, Cook [14]established the following formula for the lift coefficient due to the action of luff lines,

where a_3 is the equivalent lift curve slope due to the action of the luff lines and is determined empirically from experimental data.

luff lines slack:

$$C_{L_t} = 0 \qquad \text{for } \alpha_R \geq \alpha_{RI}$$

luff lines tightening:

$$C_{L_t} = \frac{a_3(\alpha_R - \alpha_{RI})}{V^2} \qquad \text{for } \alpha'_{RI} < \alpha_R < \alpha_{RI}$$

luff line taut:

$$C_{L_t} = \frac{a_3(\alpha'_R - \alpha_{RI})}{V^2} \qquad \text{for } \alpha_R \leq \alpha'_{RI}$$

7.3 Changing Air Speed

Changing the air speed of a hang glider is a simple matter of changing the pitch. Causing the hang glider to pitch down will reduce the magnitude of lift and hence increase the air speed. The longer the pitch down input is applied for the more air speed will be gained. Once the input stops the inherent pitch stability of a hang glider will cause it to return to trim flight at an increased air speed.

On the other hand, causing the hang glider to pitch up will increase the magnitude of lift and hence decrease the air speed. If the input stops before the critical speed (air speed at which stalling occurs) is reached, the hang glider will return to trim flight with a lower air speed. If the hang glider is forced to fly slower than the critical speed (which is about 10-20mph for most hang gliders) it will stall. This results in the hang glider going into a nose dive to recover air speed. Once the air speed is recovered, the hang glider will return to trim flight. The time taken for recovery is between three to five seconds, and the altitude lost is between 50 to 60 feet [15]. During that period of time the pilot has no control over the hang glider.

7.4 Take Off and Landing

The ability for a pilot to take off or land successfully should require a thorough understanding of how a hang glider operates and wind behaviour near the ground. A thorough understanding is needed as most hang gliding related accidents occur at one of these two parts of a journey.

For take off, there are different ways to achieve this. The most common ways are either to perform a foot launch from a hill, or a tow launch from a ground based tow system. Other, more sophisticated methods include slope soaring, aero-towing, and hot air balloon drops. In the methods mentioned, one key aspect common to all is that the air speed of the hang glider must be greater than the critical speed in order to achieve lift. A common mistake made by pilots, in particular beginners, when taking off from the ground is that they pitch up too early, i.e. before critical

speed is reached. As mentioned in an earlier section, this leads to stall and thus the hang glider will nose dive into the ground, possibly causing damage and or injury. Also, when pilots take off from the ground, they make sure they take off into the wind. This is a safety precaution that helps to reduce ground speed.

For the same reasoning as take off, landing is also performed into the wind. After the hang glider has manoeuvred into the correct alignment with the landing strip and begins to descend the pilot has to consider various factors which include wind gradient, air speed, critical speed and altitude. The wind gradient, which is a boundary layer over the Earth's surface, can vary in height from 30 meters to 60 meters [16]. The pilot should be aware of the height of the wind gradient either by observation of surrounding features or a reading off a variometer. Awareness is important because once the hang glider enters the wind gradient the wind speed will inevitably decrease with decreasing altitude. Thus the pilot has to decrease altitude at a rate such that the air speed will always be above the critical speed. It is common practice for pilots to set up a landing approach at an air speed well above the critical speed. If this is not performed a disastrous scenario may happen in which stall occurs, and the altitude at which it occurs is less than the altitude drop occurred after which the hang glider has stabilised. As mentioned earlier, the pilot will have no control when this happens, and the out come will be that the hang glider crashes into the ground.

7.5 Interesting Behaviour

As previously discussed, hang gliders are controlled by only two input axes, pitch and roll. Regardless of the two input axes, yawing is still possible because hang gliders are roll-yawed coupled, i.e. a roll motion always results in a corresponding yaw change. Vehicles exhibiting this behaviour are said to have no pure yaw control. The best example of when hang gliders demonstrate this behaviour is when they are forced to perform a banking turn.

When a hang glider just enters a banked turn, yawing will begin to occur (this will produce a 3-dimensional flow over the wing). Within 10 seconds the yawing will stop and the turn will be established because hang gliders are inherently stable in the yaw axis. Over the duration of the yaw motion the hang glider will undergo spanwise translation. This spanwise translation is known as sideslip and is the result of an airflow component over the wing, blowing from the lower wing tip to the higher wing tip [13].

8. Flight Performance

8.1 Lift Generation

As previously mentioned, the lift which is required is to overcome the effects of gravity on the hang glider and the pilot. Some hang gliders require the pilot to run down a slope to launch the glider. This is done to get air moving across the wing. This is the same for both flexible and rigid wing gliders. Although the pilot is airborne, the glider and pilot are in reality descending at a low rate due to the effects of gravity as well as the effects of drag. Unless the glider gains altitude, the pilot and glider will continue to descend. There are a couple of processes which can aid in the elevation, one of which being thermals. Thermals are raising columns of hot air from heated mountain tops and different topography. The other form of lift generation is called ridge lift or slope soaring. This occurs when the wind meets the ridges it gets deflected up which in turn forms lift. Figure 16 shows the optimum area of lift.

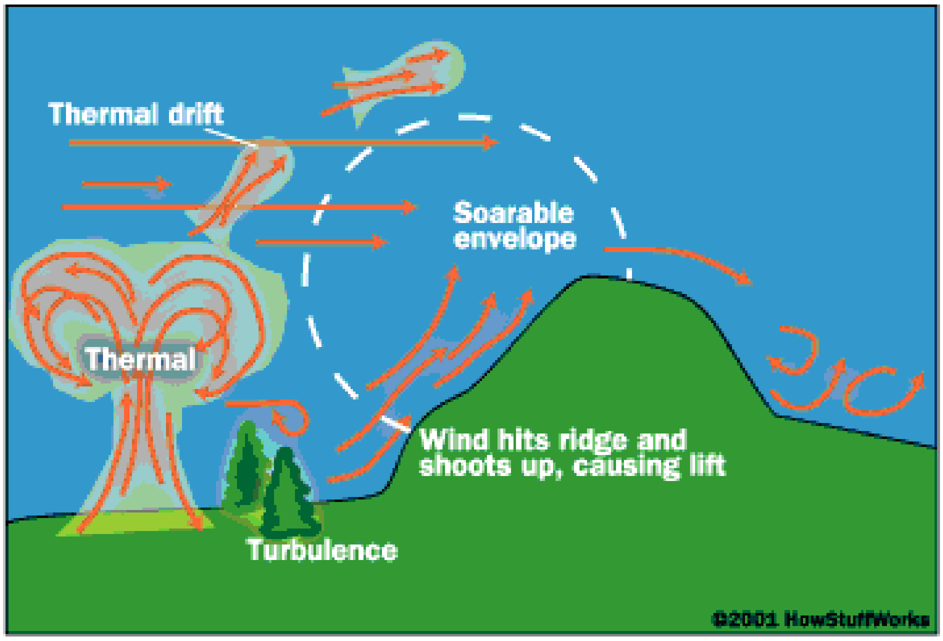

Figure 16: Optimum area of lift [1]

Another method of lift is generated is through the reaction of air hitting against the hang glider. Lift is actually created as the air is deflected downward by impacting the bottom surface of the wing and hence developing a downward momentum. Taking into account Newton's Law of momentum which states that momentum has to be conserved, the downward momentum of the air causes the aerofoil to have an upward momentum of the same amount.

8.2 Stall

The definition of angle of attack (α) is the difference between angle of thrust line (θ) and the climb angle (θc). In figure 17, the angle of attack is depicted as the angle between the angle of chord line and the angle of wind relative to the horizontal line.

Figure 17: Angle of attack definition

As the angle of attack is increased the lift generated will in turn gradually increase. The increase in angle of attack is carried out to compensate for the loss in speed of the hang glider. Slower the glider travels, higher the angle of attack has to be to keep aloft until a point where the airflow over the top surface of the foil can no longer hold a laminar system and breaks out, hence forming turbulence. This turbulence and other loses generated is larger than the lift. At this point the angle attained is called the stall angle and the speed is the stall speed and is usually between 10-15mph.

For the glider to gain lift again, the pilot will have pull back on the control bar and pitches the nose downwards and hence regaining the flying speed required to stay aloft. In the event of stall when airflow on one wingtip breaks off, a spin is induced on the hang glider. This spin is not dependant on air speed but only on wing angle of attack. However, spinning rigid wing hang gliders are often associated with slow flying due to changing glider angle of attack, while the hang glider is spinning gyro-forces are dominant and hence the pilot loses control and craft steering ability. Nevertheless, it is still possible to recover from a spin with sufficient altitude (50-60 feet) reserved by pulling on the control bar and then steering against the rotation. A disadvantage with rigid wing hang gliders is that it is far more difficult to recover from spin as compared to a flexible wing hang glider. Due to this, pilots normally fly at higher speeds at lower heights to avoid stall and crashing into the ground [20]. Theoretically, maximum speed could be obtained when the pilot is at zero angle of attack.

8.3 Stability

Inherent craft stability is of paramount importance with regards to both rigid wing and flexible wing hang gliders. This is due to the fact that any destabilising moments within the craft will result in it pitching, yawing or rolling when unintended hence resulting in loss of pilot control. Stability in all three planes of yaw, pitch and roll are governed by various control surfaces, with respect to rigid wing hang gliders and will be considered in this section.

Yaw stability is governed by the nose-angle, the sweep of the wings, and any vertical control surface behind the craft centre of gravity (cg) such as a keel pocket or a fin. If the glider begins to yaw, the drag increases behind the cg this causes a moment which returns the wing to the nose straight position, much like a weather-vane the glider in flight always points the nose into the airflow. The inherent yaw stability of the nose angle links together roll and yaw, making yaw completely dependant upon roll.

Inherent pitch stability is achieved through twist or washout in the swept-back wing and from the curve upwards on the trailing-edge called reflex. If the nose pitches down a little then the glider will pick up speed, due to the greater horizontal component of lift being generated. Therefore higher craft speed will result in a reduced angle of attack, resulting in washout at the reflex. Hence the centre of pressure will move towards the cg resulting in the nose being returned to the equilibrium position. Wing tip-struts ensure that the washout remains at higher speeds by stopping the wing-tips deflating further than a fixed amount. Beyond this speed the wing-tips will begin to have a negative angle of attack thereby producing negative lift behind the cg, resulting in a moment that would pitch the wing to more positive angles of attack.

With respect to flexible wing hang gliders, Luff-lines from the king-post perform a similar function by retaining a minimum amount of reflex on the trailing-edge. At faster speed the wings are stiffer and the reflex at the trailing edge is held, therefore negative lift behind the cg again creates a moment pitching the nose up. Pitch control is convergent around the trim-speed set by the pilot's hang-position. If the pilot pulls his weight forwards or back an increasing pressure is felt towards the set neutral trim-speed. The swept-back washout and reflex built into the wing ensure this to be so.

In order to achieve inherent roll stability two factors have to be considered. Most apparent is the pendular stability of the pilot hanging below the wing and the dihedral of the wing. Lowering the pilot by lengthening the hang-strap, will increase roll stability, and vice-versa. Although the dihedral of the wing is not as obvious a parameter when roll stability is considered it is just as important. On a hang-glider the wing dihedral is set by the length of the side wires, or base-bar length. Increasing either will angle the wings higher and thus achieve more roll stability through dihedral. A wing dihedral creates a moment from one of the lifting surfaces in order to return the craft to the equilibrium position. The reason is the same as for yaw stability from the nose-angle. When the glider is disturbed in roll from a straight glide, the lowering wing will encounter more air resistance, as the other, rising wing

encounters less. So the glider will tend to return to level flight. Inherent stability is achieved in all three planes of yaw, pitch and roll through a combination of design factors. Pitch stability through reflex and twist, yaw through nose-angle and fin, and roll by pendular and dihedral factors. They each contribute to the overall stability. Furthermore these effects are not mutually exclusive but operate simultaneously in order to achieve inherent stability in full flight. However, in designing a hang glider craft a performance penalty is incurred with increasing inherent stability.

8.4 Directional Control

Hang gliders have used various forms of pilot weight-shift control since the times of Lienthal. This section will describe the mechanisms and the theory behind control of both flexible and rigid wing hang gliders. Pilot weight-shift can change the pitch and roll of a hang glider, ie the pilot moving his/her weight forward pitches the nose of the hang glider down and moving his/her weight to the right makes the glider roll so and vice versa. Yaw stability on the other hand is governed by airflow; that is rolling the craft tends to cause a side slip in the wing where the airflow from the side makes the craft yaw and hence turn. It is important to ensure inherent yaw stability within the craft so as to make it easier for the pilot to manuever the craft.

Rogallo wing sails on the other hand control the pitch with a bridle that sets the wing's angle of attack. A bridle made of string is usually a loop reaching from the front to the end of the center strut of the A-frame. The user ties knots in the bridle to set the angle of attack. Mass-produced rogallo kites use a bridle that's a triangle of plastic film, with one edge heat-sealed to the central strut.

Steerable Rogallo kites usually have a pair of bridles setting a fixed pitch, and use two strings, one on each side of the kite, to change the roll. Rogallo also developed a series of soft foil designs in the 60's which have been modified for traction kiting. These are double keel designs with conic wings and a multiple attachment bridle which can be used with either dual line or quad line controls. They have excellent pull, but suffer from a smaller window more than modern traction designs.

The two most common mechanisms of weight-shift control in Rogallo wings are to either fly while suspended from the underarms of the pilot by two parallel bars or change the centre of gravity by shifting a payload. The payload shift is achieved through suspending it from a single point underneath the wing and then moving this pendulum to shift the weight and hence the centre of mass. However there are no flight surfaces used to control the craft as is the case with rigid wing hang gliders. The theory behind hang glider control is governed by aerodynamics. Shifting of the

weight results in the force vectors, both lift and drag being offset with respect to the craft centre of gravity. Hence control moments are created, and the above implies that these moments are created independent of altitude, given that the craft is flying normally to the flow. However the maximum control moments that can be created are limited by the geometry of the craft. The control sensitivity of a hang glider is determined by a parameter known as the pilot moment ratio; this can be varied in the design stage via varying the length of the hang strap and/or increasing the mass of the pilot. The former option is more attractive however due to the performance penalty associated with increased pilot mass. Specific details regarding flight control in pitch, yaw and roll of rigid wing hang gliders is discussed in the stability section.

8.5 Glider Flying Conditions

Hang gliding in wind speeds above 50 kph result in unpleasant and turbulent flight. This is due to the difficulties observed in travelling upwind and downwind. Travelling upwind is hindered by the drag incurred, whereas travelling downwind the glider will move very fast, at a speed equivalent to the wind plus the air speed. The best flying conditions occur when in stable atmospheric conditions [19].

During neutral or unstable atmospheric conditions where there is very high mechanical and thermal mixing of air, causing turbulence in the atmospheric boundary layer, will result in a rough flying experience. A soaring hang glider will gain little height during stable conditions due to the lack of updraft created. For example on a stable day air will tend to flow around a hill as opposed to up and over the hill due to low convective heating and mechanical mixing, hence there being no warm air currents. Whereas in unstable conditions a number of factors affect the degree of turbulence created, which in turn will cause different magnitudes of updraft at different locations. There are many obstacles, such as trees, buildings and ridges that will result in turbulence in the air. This may cause the air to be stable and unstable at different altitudes. This is dependant on the degree of temperature inversion with height.

In conclusion, it can be said that the best conditions for hang glider flight are achieved when there is low air turbulence, large updrafts and low mechanical mixing of air.

9. Design Comparison

9.1 Hang Glider Design Versus Conventional Aircraft

There are a vast number of differences between conventional powered aircraft and hang gliders. For hang gliders, gravity is the commanding force. In a steady gliding flight, The total or resultant lift must act equally and oppositely to the total weight for the glider to continues on it's glide path. The total lift can be divided into two components: the drag in line with the glide path, and the component perpendicular to it, lift. These are the three basic forces acting on the glider in flight. Comparing this with a conventional powered aircraft, powered aircraft also have a forth component in the opposite direction to travel, thrust. This design comparison between conventional powered aircraft and hang gliders will be focused mainly around flexible and rigid wing gliders. Firstly, there are a number of important aerodynamic comparisons that must be made.

9.2 Aerodynamic Comparison

The most striking difference between conventional fixed wing powered aircraft and hang gliders is the difference is the yaw motion of the crafts. Conventional aircraft have three axes of control, roll, pitch and yaw. However as previously discussed, the yaw movement (or yaw axis control) for hang gliders is completely dependent on the roll action, or couple yaw-motion. With the majority of the common flexible wing hang gliders, the craft achieves full pilot control using only a flexible wing, without using aerodynamic control surfaces such as ailerons and rudders. Rigid wing gliders require some form or combination of ailerons and/or rudder. By contrast, conventional aircraft almost exclusively use a combination of ailerons, elevators and rudder.

Interestingly, hang gliders are made stable in the roll axis in a very different way to conventional aircraft. Most conventional aircraft have dihedral, that is to say, their wingtips are higher than the root of the aerofoil. This results in inherent roll stability in the design and an overall resistance to anything other than level flight. For example, when the plane rolls a slightly, the wing rolled toward becomes more horizontal, producing more force against gravity, since the lift vector is generally perpendicular to the span of the wing. At the same time, the other wing produces much less, so the inherent stability causes the plane to want to roll back to level flight. Hang gliders however, are made with anhedral or with their wingtips below the middle of the wing root. Roll stability in hang gliders is a combination of two

factors. Most apparent is the pendulum like stability of the pilot hanging below the wing. This is then coupled with the inherently stable anhedral wing design. Hence, roll stability is only maintained in most hang gliders if the pilot maintains a constant weight balance. The hang glider will maintain level flight unless the pilot pulls his or her weight to the side. With the pilot's weight to one side, as previously mentioned the glider banks in that direction, and for flexible wing gliders, the frame flexes causing the sail to shift the load. This results in the angle of attack of the low wing increasing slightly, and that of the high wing decreasing slightly. This causes the low wing to slow down in response to an increase in angle of attack, while the high wing speeds up, and a gentle turn is the result.

The Centre of Gravity, CG, and the Centre of Pressure, CP, are two very important terms used for comparing the aerodynamic differences. Most people are familiar with the concept of the centre of gravity as the point through which all the weight of the hang glider can be thought to act. The centre of pressure, or sometimes called the centre of lift, is a very similar concept. The centre of pressure is the point in which the sum of the lift can be thought to act. Firstly we will consider these two points applied to a hang glider. Considering these two points on the hang-glider, we can begin to understand much of how the glider flies compared to a conventional aircraft. In a hang glider, the CG is changed by the pilot moving his weight in relation to the rest of the wing. Conventional aircraft have a fixed Centre of Gravity and to achieve flight, all moments about the CG must be balanced. It is desirable that when the pitch angle and angle of attack of a conventional aircraft is disturbed, the aircraft should returns to its original pitch angle and angle of attack without pilot input to change the control surface deflection. For an aircraft to achieve this, it must have what is known as a positive longitudinal static margin. The longitudinal static margin is defined as the distance from the CG to the CP. The center of pressure must lie behind the center of gravity for a positive static margin and therefore inherent static stability. If the center of pressure lies ahead of the CG, the aircraft requires active inputs to the control surfaces are required to maintain stable flight. Hang gliders are thus able to modify the longitudinal static margin by changing the CG to achieve a pitching moment. In a stable flight or glide, the CG is assumed to be directly below the CP. When the pilot alters his weight forward, this acts to change the CG towards the nose, there will be a turning moment that acts to pitch the glider nose down. In turn, an decreased angle of attack enables the glider to pick up speed, and as the speed increases, the CP moves forward until it is again above the CG. Hence, the glider is able to achieve a new faster stable glide position. Conversely, conventional aircraft must use aerodynamic control surfaces to achieve

a pitching moment.

9.3 Performance Features

The most important measure of performance for a hang glider is the glide ratio. Descent is similar to climb but uses a negative climb angle. Glide is similar to climb but sets the thrust force to zero. The glide ratio is the ratio between horizontal distance traveled and altitude lost, and is equal to the lift and drag ratio. With each generation of materials and with the improvements in aerodynamics, the performance of hang gliders has increased. This measure of performance allows for comparison between conventional aircraft and hang gliders. Table 1 below compares typical hang glider types to a conventional small powered aircraft.

Type	Glide Ratio	Speed Range	Best Glide
Topless gliders	17:1	30 to >145 km/h	45 to 60 km/h
Rigid wing gliders	20:1	35 to >130 km/h	50 to 60 km/h
Sailplane	40:1	NA	NA
Small powered aircraft	10:1	NA	NA

Table 1: Typical Glide Characteristics [9]

It must be noted that ratios provided by the manufacturers are only approximate as it is nearly impossible to measure them reliably. As the table shows, high performance sailplanes are able to achieve glide ratios of 40:1. That is to say, they are able to travel 40km for every 1km of altitude lost. Rigid wing hang gliders are able to achieve comparable glide ratios of around 20:1. Maximizing the glide ratio of a hang glider design allows for the range of the craft to be maximized. We must also consider the sink rate when comparing the performance of hang gliders. The sink rate is defined as the vertical velocity (acting downwards) of the glider. It is commonly used to determine the time a glider may remain airborne. As previously stated, soaring aircraft such as hang gliders need to be able to climb effectively if there are available thermals. This normally limits the maximum tolerable sink rate in the design of hang gliders to around 1.0 m/s. If a higher sink rate is utilised the craft generally has much poorer climbing performance as it is requires thermal or rising air to occur at higher rates, a less common phenomenon. The loss of height can be measured at several speeds and plotted on a 'polar curve' to calculate the best speed to fly in various conditions, such as when flying into wind or when in sinking air.

Sink-rates can vary from about 200 fpm, or when at minimum sink (just above stall speed) to as much as 1500 fpm for much lower performance wings when at top speed.

The performance of a hang glider is mainly due to the aerofoil profile, aspect ratio and percentage of double surface. For example, a thick cambered low aspect (e.g. 5. 5) wing with little or no double surface are generally slow and docile, usually with great low speed characteristics for beginners. On the other hand, wider (e.g. AR > 7. 5), 'blade wings' with over 80% double surface are designed for racing.

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