Kite launch using an aerostat

Ir. J. Breukels
Delft University of Technology
Faculty of Aerospace Engineering
The Netherlands

Kite launch using an aerostat

Ir. J. Breukels

ASSET Chair
Faculty of Aerospace Engineering
Delft University of Technology, the Netherlands
Kluyverweg 1
2629HS Delft
The Netherlands

Tel: 0152585571
j.breukels@tudelft.nl

Delft, August 21st 2007

Table of contents

Nomenclature

B	-	The upward buoyancy force acting on a body
C_d	-	Drag coefficient
C_f	-	Friction coefficient
d	-	Diameter of the aerostat
D_f	-	Friction drag
D_p	-	Preddure drag
L_d	-	Disposable or net lift
L_g	-	Gross or total buoyancy lift of the enclosed gas
R_e	-	Reynolds number
S_{wetted}	-	Wetted surface of the body
V	-	Volume
W	-	Total weight of the system
W_0	-	The weight of the envelope
ρ_a	-	Air density of the local atmosphere
ρ_g	-	Air density of the internal gas volume

1. Introduction

The Laddermill, a high altitude wind energy system using controlled kites, is a system which was devised specifically to extract energy from the winds at high altitude. Winds at high altitude are much stronger and more consistent than they are close to the ground. Close to the ground, wind speeds can be erratic. Obstructions such as buildings and trees can have a severely detrimental effect on the "cleanliness" of the wind. The cleanliness of the air flow is a term which reflects the amount of gusts and turbulence in the wind. The more uniform the wind flow field is, the more "clean" the wind is considered. Close to the ground, the wind cleanliness can be severely disturbed by ground obstruction to such a level that it is almost impossible to properly launch a kite. Once the kite is above a certain altitude, the wind is clean enough to provide the kite with sufficient lift to keep it aloft. Getting the kite to this altitude is often the problem. The first 30 meters in altitude is often a barrier which is difficult to negotiate.

In order to penetrate this barrier, a kite launch system was devised using either a balloon or an aerostat. These devices do not use aerodynamic lift but use the buoyancy of a lighter-than-air gas (mostly helium) to carry the craft aloft. Therefore, even in a zero-wind situation, an aerostat is able to ascend to the altitude where there is enough clean wind for kite flight. In this respect, an aerostat would seem ideally suited.

This report reflects the considerations and observations that were made during the design, preparation and testing of a kite launch system using an aerostat. The entire project took place between July 21st 2007 and August 21st 2007. The main purpose for initializing this project is to be able to launch a kite during the sustain rock concert on August 28th 2007 in Groningen, the Netherlands. During this festivity, the laddermill prototype will make its first public appearance. In order to launch a kite, even when the winds are unfavorable close to the ground, the design of this system was initialized. In a meeting on July 20th 2007, the suggestion of an aerostat was first made. The author of this report was not present at this meeting, he was made responsible for this project shortly afterwards. Together with Roland Verheul, the project started on July 21st 2007.

2. Requirements

Requirements for the system can be broken down into a number of sections.

2.1 Operational requirements

2.1.1 The system must be able to lift a kite, a portion of its line and all its control devices (a total mass of no more than 10kg) to an altitude of at least 30 meters in a controlled manner.
2.1.2 Carrying the kite to its target altitude should take no longer than one minute.
2.1.3 The system must provide a stable enough platform from which to launch the kite
2.1.4 After launch, the system must be able to be brought back down to the ground in less than 30 seconds.
2.1.5 The system must be weathercock stable.

2.2 Docking and release requirements

2.2.1 Release of the kite must be done in a single action to prevent the release to partially fail and pull the aerostat dangerously off course.
2.2.2 Docking the kite to the aerostat on the ground must be done without running an unacceptable risk of damaging either the aerostat or the kite.
2.2.3 The docking system must not interfere in any way with the kite's ability to fly after release.
2.2.4 During ascent, the kite must be fixed to the aerostat in such a way that it doesn't dictate the flight path of the entire system.
2.2.5 Once released, the aerostat and the docking system should not obstruct the flight path of the kite in any way.

2.3 Ground handling requirements

2.3.1 Ground handling should be possible to be performed by no more than two persons.
2.3.2 The entire system should have some sort of anchor device which can be fixed to the ground in any location where there is grass or sand.
2.3.3 The anchor device must be able to withstand the forces the aerostat is able to exert on it, with or without the kite.
2.3.4 The mooring line must be able to withstand the forces the aerostat is able to exert on it, with or without the kite.

2.4 Safety requirements

2.4.1 At no time during operation should the system pose a danger to its operators or the spectators in close proximity.
2.4.2 Apart from the control devices on the kite, the system should employ no heavy and hard parts which can swing, fall, bounce or by any other mode of motion hurt any persons in close proximity of the system.
2.4.3 Anyone operating the launch system should be briefed on its operation.
2.4.4 Once released, there should be no sturdy connection possible between the aerostat and the kite. Not by entanglement, hooking, clamping or any other way.
2.4.5 The inflation gas should be non-toxic and non-combustible.

2.5 Meteorological requirements

2.5.1 The system must be able to operate in a wind range from zero wind velocity to a wind velocity in which it is possible to launch a kite on its own.
2.5.2 Sudden wind gusts should not have a catastrophic effect on the system.
2.5.3 The system should be able to function in light rain.

3. The Aerostat

A number of options for the lifting device were open. One of the simplest options was a balloon. A balloon is the cheapest envelope to hold a lifting gas. Weather balloons are often used to carry instruments aloft and a number of commercial off-the-shelf options exist to be purchased. However, the directional or weathercock stability of a spherical balloon is insufficient, which contradicts requirement 2.1.5. It is paramount that the system points the leading edge of the kite into the wind while releasing. If it doesn't, a clean separation can not be guaranteed. Furthermore, the unstable directional motions of a balloon can make the kite and its control devices sway and possibly penetrate the envelope of the balloon. For these reasons, the balloon was no longer considered.

A second option was the use of something called a kite balloon. Kite balloons are built by a UK company called Allsop Helikites ltd. It is a combination of a small helium balloon and a delta kite. Its lift is a combination of helium buoyancy and aerodynamic lift of the wing surface of the kite. Its directional stability is far better than that of a conventional helium balloon. But in a zero or low wind situation, the aerodynamic lift is extremely low, leaving the helium balloon as the primary lifting device. In this case, the kite balloon would have to be of significant size to generate enough lift to lift the kite. Which means that once the helikite ascends to an altitude where there is wind, the lift will suddenly dramatically increase. This will put unnecessary strain on the line and the anchor. Furthermore, the helikite of sufficient size is a rather expensive solution (around 7000 euro) and it would not be possible to deliver the helium kite on time for testing. This meant the helikite was disqualified as a lifting device.

A third option was an aerostat. An aerostat is basically a blimp or zeppelin which is tethered to the ground. The United States Department of Defense makes extensive use of large aerostats as a platform for radar surveillance of its borders. Aerostats are also used as a platform for aerial photography. Commercial aerostats which are used as observation platforms are generally quite large, far too large for the purpose of launching a kite. Furthermore, it turned out that these aerostats were extremely expensive. Most commercial aerostats cost anywhere from 40.000 to 200.000 euros.

A far less expensive echelon of aerostats are the aerostats which are used for promotional purposes. They are generally a lot smaller (anywhere from 4 to 10 meters in length) and are used to fly banners during events such as sports matches or concerts. A US based company called "The blimp works" makes a wide range of aerostats for these purposes. The fact that they are designed and built to be flown over the heads of large crowds means that they are safe and stable. In order to comply with requirement 2.1.1, a lift force of 100N is required. This translates into an aerostat with a length of 7.62 meters. Table 1 gives the data on the selected blimp.

Aerostat length	7.62 m
Aerostat radius	1.3 m
Aerostat volume	22 m^3
Inflation gas	Industrial-grade helium
Body material	6 mil gauge polyurethane
Tail fins	3-piece half-round rip-stop nylon fins
Bridle lines	8 attachment points, 4 bridle line system
Valves	One inflation valve in the tail, 6 deflation valves in the nose.
Seams	Hot-sealed
Weight of the aerostat	12.5kg
Nett. lift	10.5 kg

Table 1, the aerostat data

Figure 1 shows a schematic drawing of the aerostat and all its parts

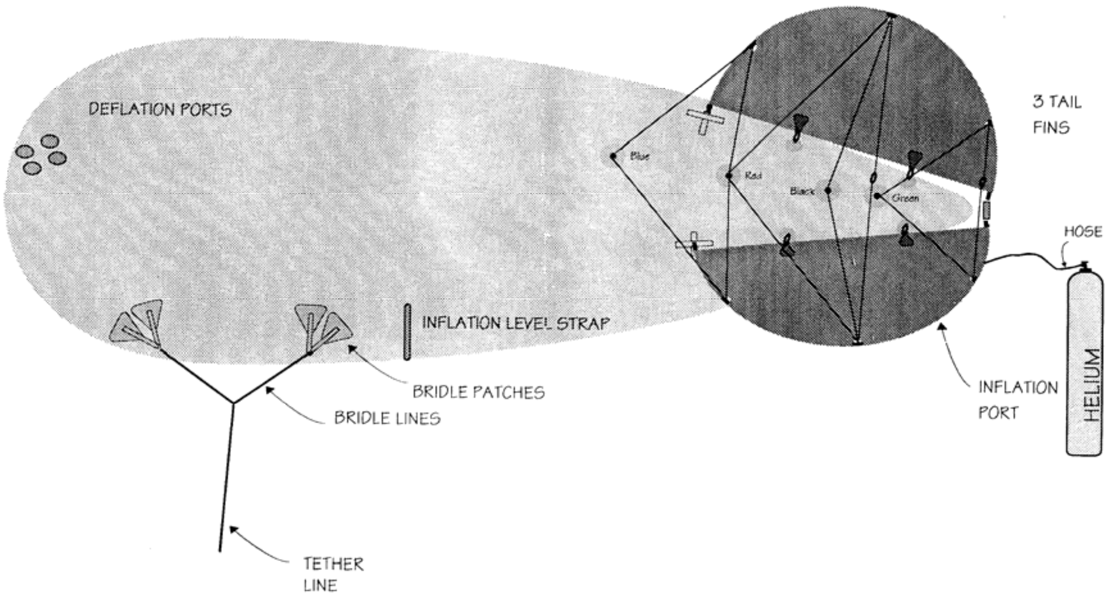

Figure 1, a schematic drawing of the aerostat.

3.1 Operating the aerostat

The aerostat requires industrial grade helium for inflation. The polyurethane material has a dissipation of approximately a 1% of the total volume per day. Normally, this means that the aerostat needs to be topped off every 3 to 5 days. Inflation of the aerostat is a two person job. One holds the inflation valve and hose while the other holds the aerostat at its bridle lines to keep it from moving too much. As inflation progresses, the aerostat will start to lift. Inflation in windy conditions deserves special attention, especially when the wind is blowing directly on the side of the aerostat. When the aerostat is fully inflated, the round body has a drag coefficient of approximately 1 [1]. But while half inflated, the fabric of the blimp can suddenly form a half-round, hollow shell which has a drag coefficient of 2.3 [1]. This means that quite suddenly, the forces on the blimp can increase during inflation. This effect can be overcome by keeping either the nose or the tail of the aerostat into the wind. If, for whatever reason, this is not possible, a third person is required during inflation. The third person will keep his arm around the deflated aerostat and slide from the tail to the nose as the aerostat is inflated. While sliding, he makes sure that the inflated part of the aerostat has sufficient pressure to assure that its shape remains circular. During inflation, the flow of helium is controlled at the reduction valve. It is important to prevent the incoming flow to be too strong. A high-pitch screeching noise will be audible if the flow is too strong. This can flap the material violently and damage the aerostat. Inflation should be continued until the red inflation strap is flush against the body of the blimp. After the blimp is inflated, the tail fins can be installed. Rain will have little effect on the blimp, the material does not adsorb large amounts of water. The tether line of the blimp will be in constant tension. It is important that the line does not rub against any sharp surfaces. A line under tension is easily severed. Lastly, the blimp should never be stored when wet. A fungus can grow which will eat holes in the polyurethane material.

3.2 Aerostatics

The buoyancy force is defined as: [4]

$$B = V\rho_a \tag{1}$$

This force is usually quite low compared to the weight of the body. But if the weight of the body is lower than the weight of the displaced air, a net upward lift will exist. For a balloon or aerostat filled with a lighter-than-air gas, the total weight of the system will be:

$$W = V\rho_g + W_0 \tag{2}$$

This results in:

$$L_d = V(\rho_a - \rho_g) - W_0 = L_g - W_0 \tag{3}$$

The unit (ρ_a- ρ_g) represents the gross lift per unit volume. At sea level where the temperature of the internal gas is equal to the temperature of the outside gas, hydrogen gives a unit lift of 11.183 N/m^3 [4]. But hydrogen is a combustible gas and therefore violates requirement 2.4.5. At 10.359 N/m^3 [4], Helium has a somewhat lower unit lift value. But helium is an inert gas, which makes it safe during operation. Therefore, helium was selected as a lifting gas.

The selected blimp has a W_0 of 12.5 kg and the volume is 22m^3. This means that the disposable lift equals:

$$L_d = 22 * [1.225 - 0.1786] - 12.5 = 10.5kg \tag{4}$$

This is enough to lift the kite and its control devices to an altitude of 30 meters. Therefore, this blimp complies with requirement 2.1.1.

3.3 Aerodynamics

When the aerostat is in flight, its body will generate a certain amount of aerodynamic lift and drag. The drag consists of three components: 1) the pressure drag, 2) the friction drag and 3) the induced drag. The induced drag is a drag as a result of the creation of aerodynamic lift. During the creation of aerodynamic lift, a downwash is created which results in an induced drag. For an aerostat, this induced drag is very small and can be neglected [4]. The friction drag is a result of the no-slip condition in the boundary layer of the flow around the aerostat. The pressure drag is a result of the displaced air as the wind rushes past the blimp. For the friction drag we can write [4]:

$$C_f = \frac{0.043}{R_e^{\frac{1}{6}}} \tag{5}$$

$$D_f = \tfrac{1}{2}\rho V^2 S_{wetted} \tag{6}$$

Where [4]:

$$S_{wetted} = 2.33dl \tag{7}$$

Figure 2 shows the friction drag as a function of wind velocity.

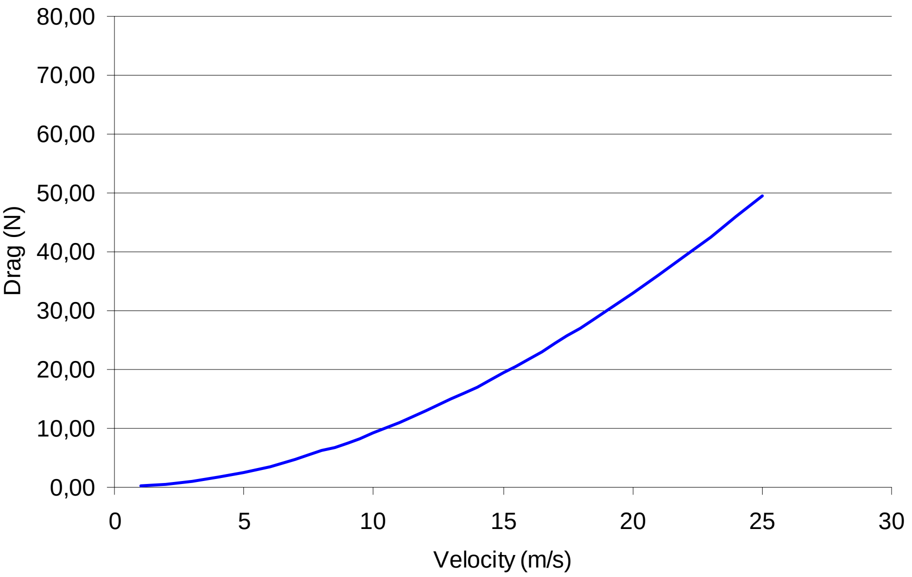

Figure 2, friction drag as a function of wind velocity.

The pressure drag is governed by the shape of the aerostat, or more specifically, its fineness ratio l/d. For the pressure drag of the blimp, we can write [4]:

$$C_d = \frac{\left(0.172 * \left(\frac{l}{d}\right)^{1/3} + 0.252 * \left(\frac{d}{l}\right)^{1.2} + 1.032 * \left(\frac{d}{l}\right)^{2.7}\right)}{R_e^{1/6}} \tag{8}$$

$$D_p = \tfrac{1}{2}\rho V^2 V^{2/3} \tag{9}$$

Figure 3 shows the pressure drag as a function of wind velocity.

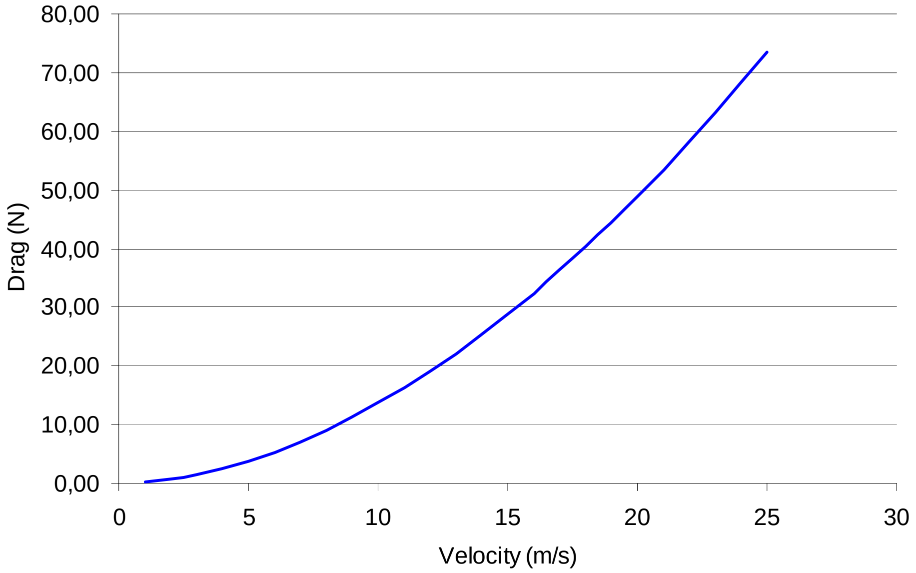

Figure 3, pressure drag as a function of wind velocity.

Superposition of figures 2 and 3 give the total amount of drag as a function of wind speed:

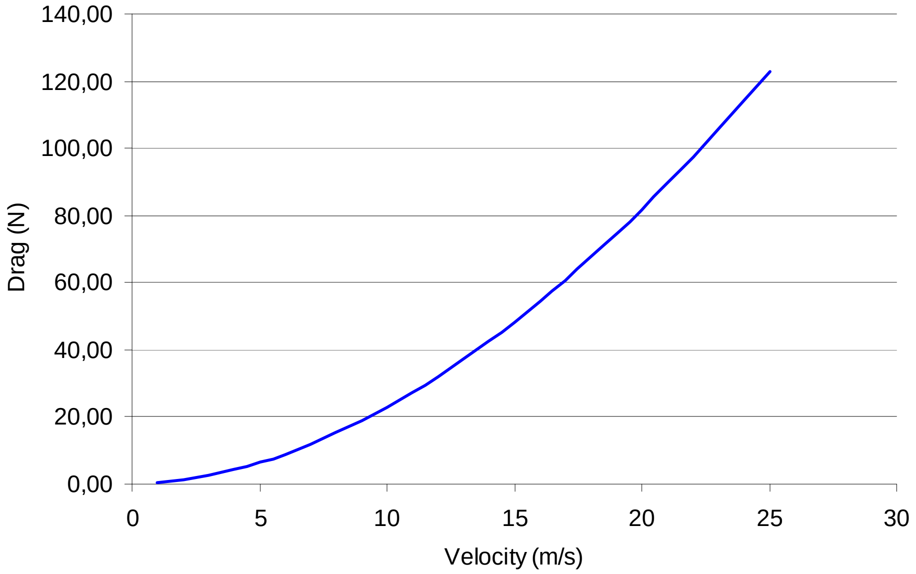

Figure 4, Total drag as a function of wind velocity.

The lift of the blimp is a function of its angle of attack and its wind velocity. [2] States a lift coefficient as a linear function of the angle of attack from 0^o to 12^0 with a $C_L = 0$ at zero angle of attack and a $C_L = 0.2$ at 12 degrees angle of attack. In figure 5, the lift is plotted as a function of wind velocity for different values of angle of attack.

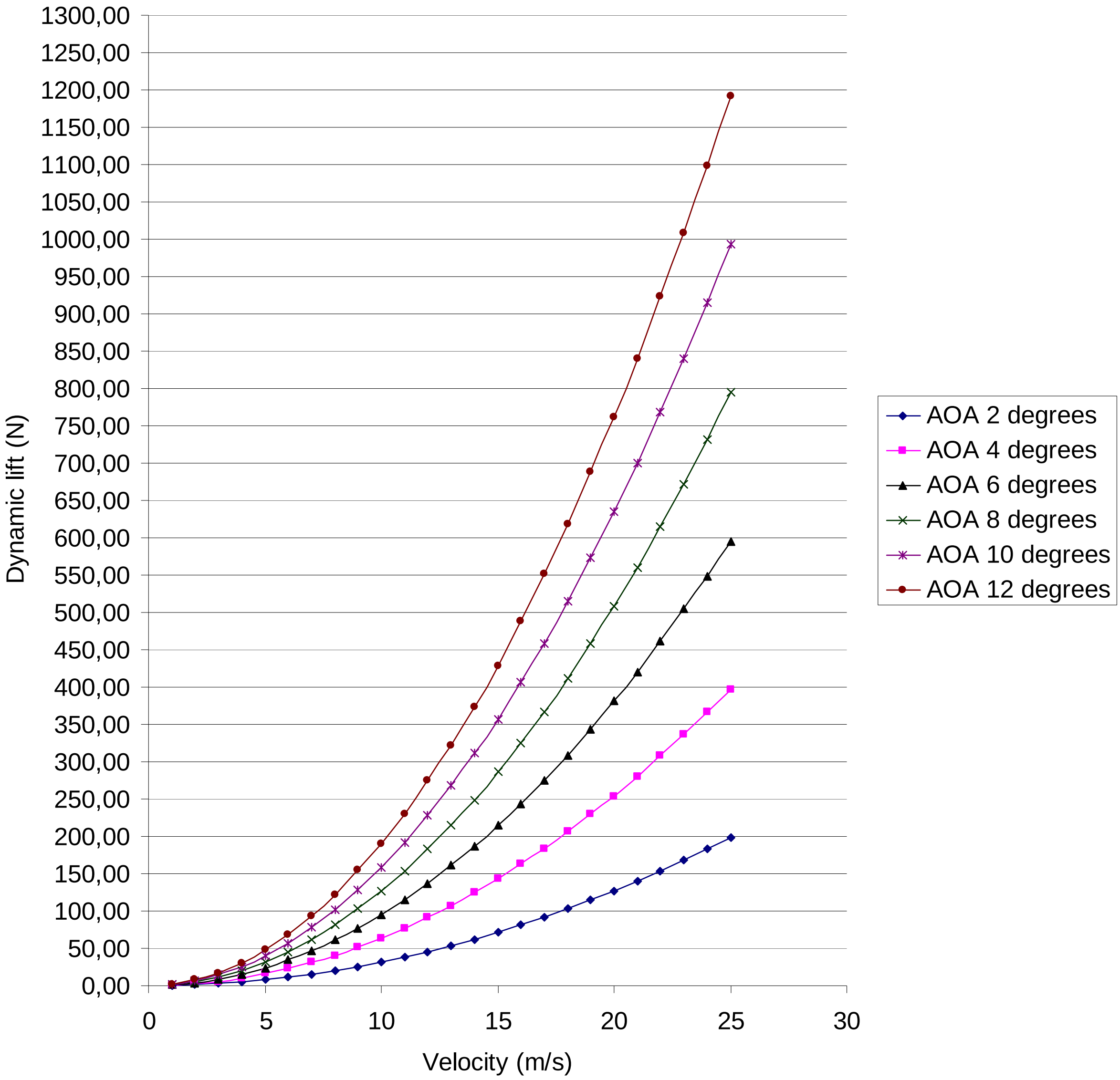

Figure 5, the dynamic lift as a function of wind velocity for different values of angle of attack.

It can be seen that both the lift and the drag forces increase rapidly with increasing wind velocity. Structurally, the blimp is capable of withstanding winds up to 15m/s. it is not advised to fly a blimp in winds stronger than 10 m/s. This launch system is meant to be used in low wind conditions where a kite cannot take off on its own. At 10 m/s wind, a kite is certainly capable of taking off by itself, therefore the system shouldn't be used in the first place.

4. The kite release system

4.1 Chin docking

Per requirement 2.2.4, the kite must be sufficiently fixed to the aerostat during ascent that the kite does not dictate the flight path of the aerostat itself. The kite which has to be lifted is a conventional surf kite. In the first tests, an oxbow tube kite was used for testing. As the name already suggests, this kite has an inflatable tube in the leading edge which gives it its rigidity. The kite was attached to the chin of the aerostat as indicated in figure 6.

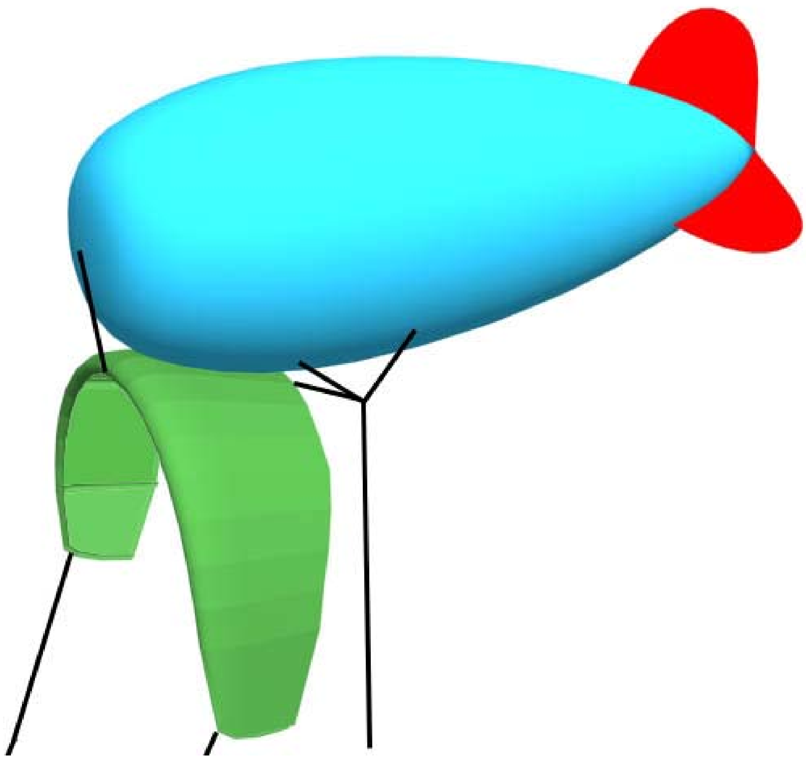

Figure 6, the chin docking of the kite to the aerostat

The kite was held in place by a line which connected to the nose of the aerostat at one end, and to the middle of the leading edge of the kite on the other end. The connection at the aerostat nose ran through a quick release system commonly employed in kite surfing. It is a loop which is easily opened by pulling on a plastic cap, releasing a safety pin. The quick release was operated via a long wire on the ground. Pulling on the release wire meant opening the quick release system and launching the kite.

This test was somewhat successful with a tube kite. The ascent wasn't uneventful as the kite had a lot of freedom to move with respect to the aerostat. Also, the large amount of surface of the kite exposed to the wind flow meant that the kite behaved erratically, dragging the aerostat with it. This is a clear violation of requirement 2.2.4. Furthermore, this system only works with a kite which has a closed and pressurized envelope as a structural member. Later tests were conducted on a Peter Lynn Venom Kite, which is a ram-air inflated kite. This meant that if there was too much pressure on the surface of the kite, it would deflate, loose its rigidity and its ability to fly.

4.2 Piggy-back docking

A second evolution of a docking system was devised with the necessity to launch a ram-air inflated kite in mind. In order to keep the kite inflated, it could only be fixed to either the upper or the lower surface. No pressure was allowed which would squeeze out the air. It was decided to piggy-back the kite on top of the aerostat. This meant fixing the kite at the lower surface. For this purpose, a number of plastic rings were attached to the lower surface of the kite. These rings have a very low mass and had no noticeable effect on the flight performance of the kite. Figure 7 shows the principle of the piggy-back docking system.

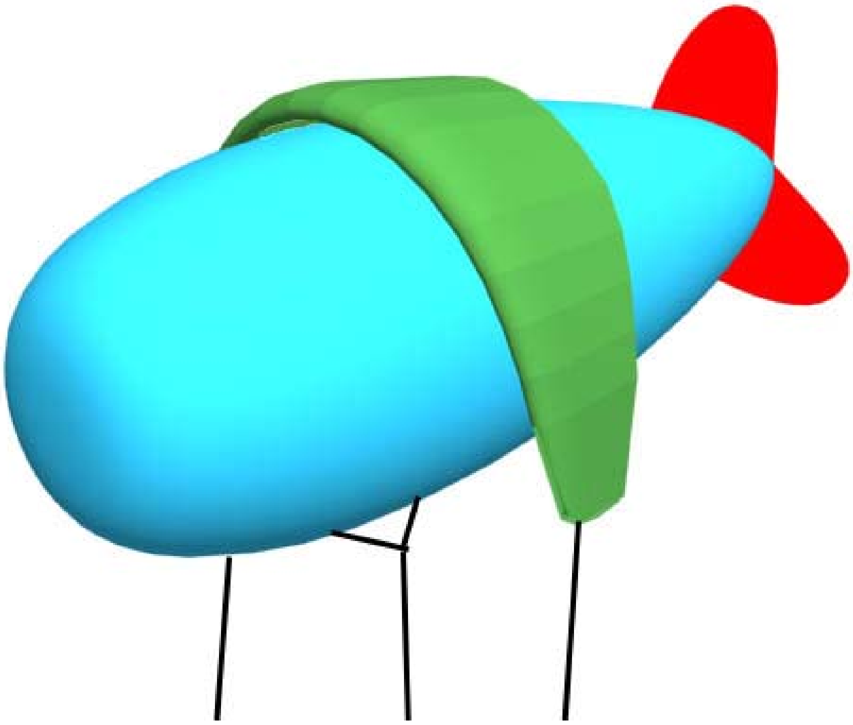

Figure 7, piggy-back chin docking of the kite to the aerostat.

In order to keep the kite securely docked, it was decided that the kite should be held into place in three places, in the center of the kite along the root chord and on each of the tips of the kite along the tip chord. The fins on the blimp are secured by a number of lines from the edge of the fin to the surface of the blimp (see figure 1). There are four hard points between each of the fins. The most forward hard points were used to secure the kite, one between each of the fins. Lines are tensioned in longitudinal direction along the body of the aerostat. These lines, henceforth called "kite fixation lines", pass through the rings on the kite, fixing the kite in place. Figure 8 shows the rigging of one of the kite fixation lines. There are a total of three kite fixation lines which all meet at the nose of the aerostat. The middle kite fixation line passes over the top of the aerostat, and the other two pass along the aerostat body at +120 and -120 degrees.

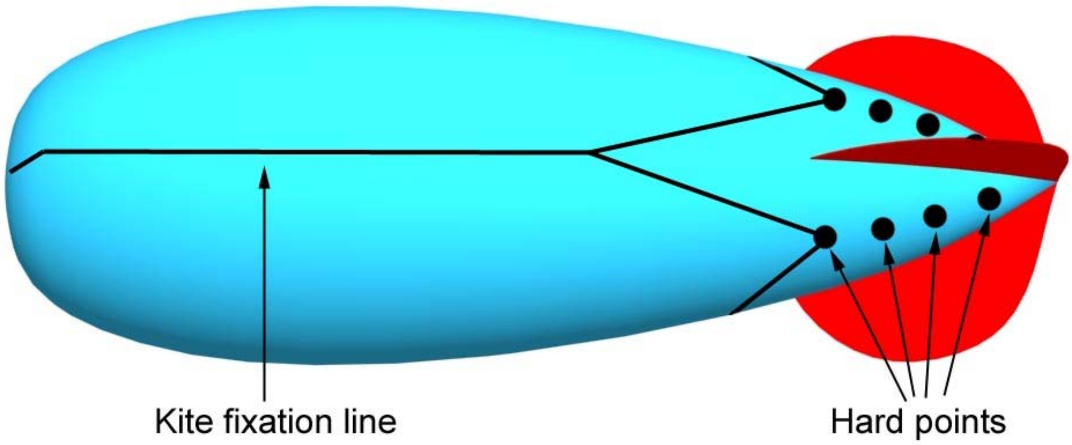

Figure 8, one of the kite fixation lines.

At the nose, the three kite fixation lines meet. On the end of the kite fixation lines there are loops which are hooked together using a quick release system. By pulling back on a plastic hood, a pin is released which opens the quick release and simultaneously release all three kite fixation lines. The quick release is operated from the ground by a separate line. Pulling on this release line opens the quick release and launches the kite. Figure 9 shows the aerostat with the kite on its back.

Figure 9, the kite on the back of the blimp

5. Kite and aerostat combined

On its own, the aerostat is very sleek and generates relatively low drag, compared to its size. In low wind conditions on a short line, it tends to gently sway from left to right. On a longer line, this motion disappears. The fins seen adequate to keep its nose in the wind and the entire aerostat is well balanced on its bridle lines, keeping its angle of attack close to constant.

With the kite attached to its chin (Chin docking, section 4.1), its behavior in flight changes drastically. In this form of docking, almost the entire surface of the kite is freely exposed to the wind. This means that the aerostat and the kite "fight" each other for control. Most of the time, the kite dictates the flight path which is in conflict with requirement 2.2.4. Because of the kite's weight, the angle of attack of the aerostat is somewhat lower, but no considerable effect was observed.

With the kite in piggy-back docking, the entire system is much less jittery. In this situation, the kite has no control over the blimp, unless the kite is attached to a conventional kite surfing control bar and the person holding the bar is actively steering the kite. In this case, the aerostat and kite can be steered gently from left to right.

In both cases, the aerostat seems to lift the extra weight of the aerostat with ease. The added mass of the kite has no direct detrimental effect on the flight characteristics of the aerostat.

6. Observations during testing

In the months of July and August of 2007, several tests were conducted at the island of Texel in the Netherlands. The location is an open field close to the NIOZ (Royal Netherlands Institute for Sea Research.

6.1 July 25th 2007

The first tests were conducted to familiarize the team with the operations of the aerostat. After inflation, the aerostat was fixed to a trailer which was already present on the field. An ozone tube kite was fixed to the chin of the aerostat (chin docking) using a quick release. A total of four tests were conducted of which, two were successful. In two unsuccessful tests, the release was prematurely initiated by an entanglement of the release line. During the successful tests, the aerostat and kite swayed violently from left to right. Only when the mooring line was longer than 20 meter the swaying subsided. After pulling the release line, the kite flew free from the aerostat. No dangerous entanglements were observed.

From this test it was concluded that it is important to keep the release line from becoming entangled. The quick release system only needs a small tug to release the kite. Furthermore, the swaying of the entire system makes an uncontrolled impression. Even though, at no time, there was a danger of crashing, the uncontrolled manner in which the ascend took place is in violation with requirement 2.1.1

6.2 July 26th 2007

During laddermill operation, it is most common to use a Peter Lynn Venom kite and not an Ozone kite. The Peter Lynn Venom is not a tube kite but a ram air inflated kite. A ram air inflated kite relies on the air inside the kite to keep its shape. Without the air inside, the kite will not fly. Due to the ram air inflation, there are three openings on the leading edge in the center where air can enter the kite. More importantly, the air can also exit the kite through these openings.

Tests were conducted to successfully launch this kite from a blimp. Early on, it was concluded that chin-docking would not work. Not only is the kite too exposed to the wind, making it drag the aerostat along. Docking it this way makes the kite flutter and deflate. The rigidity of a ram air inflated kite is far less than the rigidity of a tube kite. The rigidity is insufficient to keep its shape while chin-docked.

During these tests, the kite was piggy-backed to launch altitude. During these tests, the kite fixation lines as described in section 4.2 were not installed yet. The aerostat carried the kite to the launch altitude, but in the process, the kite was kept in place by putting tension on the kite lines and thereby deflating the kite. Furthermore, the kite was not held in place properly, making it slide to either the left or the right of the aerostat. After release, the half-filled and badly deformed kite plummeted straight to the ground.

During this test, the necessity for a proper kite fixation system became apparent. Launching a kite which has little rigidity requires extra care as to how it is fixed and at which points the fixation forces are introduced. After these tests, the lessons learned were used to design the piggy-back docking as described in section 4.2.

6.3 August 14th 2007

On this day, the first test of the new piggy-back docking system was planned. The aerostat was inflated in winds up to 20 knots. Once everything was ready, the wind was peaking 25 knots, making it extremely hard to handle the aerostat. At this point, the leader of the test made the decision to abort the test due to unfavorable weather conditions.

The aerostat launching system is meant to be employed in low wind situations where there is not enough wind to launch a kite on its own. Therefore, testing in high wind situations has no real added value. The blimp becomes hard to handle because of the high wind loads and the material is stressed quite severely. Handling the aerostat in these conditions creates an increased wear of the equipment. In short, testing in high wind conditions yields no significant results while the cost is high in terms of wear of the equipment. The test was postponed to a later date.

6.4 August 17th 2007

On this day, the winds peaked at about 10 knots with an average of 7 knots which are ideal conditions for the kite launching tests. The harsh conditions of the test on august 14th had not been without cost. In some locations, small leaks in the aerostat were discovered. These leaks were patched using duct tape. But after a few hours of inflating the blimp, it became apparent that not all leaks had been found. The aerostat was slowly loosing pressure. However, the leaking was on such a small scale, that the tests were continued as scheduled.

Installing the kite fixation lines is a three-man job, one holding the blimp and two others handling the lines. Tightening the lines was done by attaching the tree loops to the quick release and then tying the other ends to the V shaped lines which attach to the aerostat hard points (see figure 8) This worked well.

Installing the kite on the aerostat was first done by throwing one end over the blimp and then pulling it in place. Later, a more elegant way was devised. With one person on each of the tips, the kite can be held up in an arch by holding it into the wind. The kite then simply slid into place over the aerostat. Once in place, the entire system was rolled somewhat so the middle kite fixation line was pulled through the rings. Once the middle kite fixation line was installed, the other two could be pulled through the rings on the tips with ease.

While the kite is on the back of the aerostat, it remains in place very well. Furthermore, because the aerostat always points into the wind, the kite is constantly being inflated and kept under pressure by the ram air inflation of the wind. The tips of the kite were held at shoulder level, making it easy to install the control devices and the lines. The entire system sits stable on a very short line, freeing hands to do other tasks.

7. Conclusions and Recommendations

After testing it was concluded that launching a kite in a controlled manner using an aerostat is possible. The system proposed in this report adheres to all requirements. The system is only to be employed in low-wind conditions, which are ultimately the conditions for which this system is designed.

From a practical point of view, the aerostat launching system leaves something to be desired. Setting up the aerostat takes two people more than an hour. Once the aerostat is inflated, however, successive launches can be done quickly. The required helium is somewhat of a problem as well. Helium is expensive and comes in heavy, cumbersome high-pressure bottles. This makes the system not very mobile. Lastly, launching a kite using an aerostat is a relatively expensive exercise. Not only the helium is costly, a reduction valve and the blimp itself are costly. Furthermore, extensive wear on the material of the blimp was observed, giving rise to the idea that for prolonged use of this system, new aerostats will be required after a number of launches. Do note that this has not been quantified yet and it is impossible to tell at this point, how many launches an aerostat will last.

It is therefore recommended that this system be used sparsely and in situations where conventional launching is not possible. The system therefore fills a niche, being able to do something no other system is capable of: launching a kite in tight spaces and zero-wind conditions. But this capability comes at a cost. This cost is only justified in specific situations where no other system can launch the kite.

References

[1] Hoerner, S.F., “Fluid Dynamic Drag”1965.
[2] Hoerner, S.F., “Fluid Dynamic Lift”1965.
[3] Anderson, John D, “fundamentals of Aerodynamics” second edition, McGraw-Hill Inc. 1991.
[4] Khoury and Gilett, “Airship Technology”, Cambridge University Press, 1999.