Tethered "kiteplane" design for the Laddermill project*

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The Laddermill is an innovative concept for generating energy from wind using large kite-like wings on a tether. The wings are able to fly in both the regime of airplanes and kites. We therefore call these structures "kiteplanes". By providing a recurring motion with a large lift during ascending and a lower lift during descending, energy can be generated. The Laddermill is currently under development at the Faculty of Aerospace Engineering at the Delft University of Technology. This paper presents the design and testing of a 3 meter span scaled model of a laddermill kiteplane. First, an introduction to the laddermill will be given. Then the sail wing will be outlined. Both aerodynamic and structural aspects will be addressed. The next section deals with the stability of the kiteplane. The eigenvalues are determined which govern the motions of the kiteplane. After the theory, the paper will go into the building of the kiteplane and the flight testing. The conclusion will go into the relevance of this wing concept to the laddermill and the eventual generation of sustainable energy.

1. Introduction

The current doctrine concerning energy seems to be that there is a shortage. This notion will lead down a path of conservative energy consumption. In reality, there exists ample energy. We simply lack the technology to tap the resources. One such untapped resource is the wind at high altitude. There is an immense amount of energy in the winds at altitudes over 1km. But no means are in place as of yet to harness this resource. Figure 1 illustrates the wind speed and dynamic pressure against altitude in kilometers.

The laddermill [1] is a concept which enables us to generate sustainable energy using the high speed winds at high altitude. By letting tethered wings or kites periodically ascend and descend while being in a position to generate a high lift force in the ascending mode and a much lower lift in the descending mode, the recurring motion can be used to drive a generator. Thus far, two versions of the laddermill have been analyzed [4]. A pumping laddermill and a rotating loop laddermill. The pumping laddermill consists of a single tether with multiple kites ascending and descending, and the rotating loop laddermill consists of a loop of kites, connected to an endless cable. It was concluded that the pumping laddermill was the more viable concept and easier to start with.

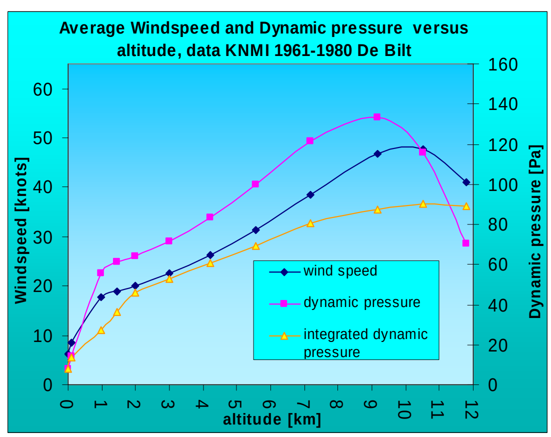

Figure 1: Wind speed and dynamic pressure vs. altitude [3]

At this moment, the laddermill is being researched at the Delft University of Technology, Faculty of Aerospace Engineering at the ASSET section (AeroSpace for Sustainable Engineering and Technology)

2. Wing design

The wing designed and tested for this paper is a kiteplane that was originally designed for breaking the world altitude record for kites. This work was performed in the KitEye project [2] under contract of the European Space Agency. In this paper, this wing structure is presented as a potential application for a laddermill.

2.1 Aerodynamic design

Figure 1 outlines the forces on the kite

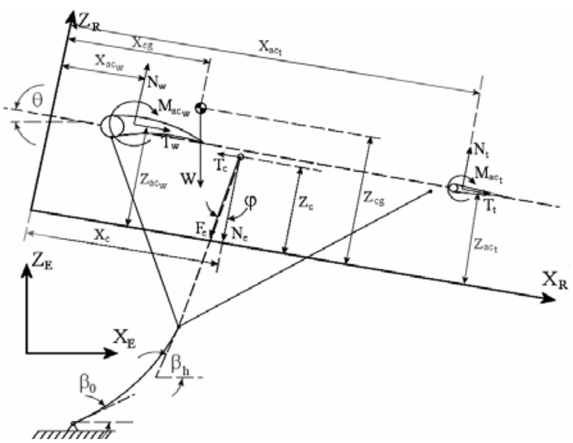

Figure 1: The forces on the kite in flight.

In [6] a design criterion was formulated for maximum obtainable altitude for a tethered wing. This was investigated using a glider which was towed by a conventional aircraft. It was found that for maximum altitude the lift would have to be equally balanced between the weight and the cable tension. Thus:

$$L = 2W \tag{1}$$

Or:

$$L = W + F_c \sin(\beta_h) \tag{2}$$

Maximum altitude can be reached when the weight of the kite equals the vertical component of the tether force introduced on the kite. For horizontal equilibrium one can write:

$$D = F_c \cos(\beta_h) \tag{3}$$

The total length of the cable depends on the angle β_h. For the altitude record, an angle close to 90 degrees is preferred, which is obtained for a wing structure with a high lift-over-drag ratio.

Previous studies [7] have shown that a double layer sail wing can have a performance close to that of a fixed wing. A double sail wing is chosen here as it allows for a simple and cheap construction (inflatable tube and sails). Figure 2 shows the airfoil cross section chosen for the design.

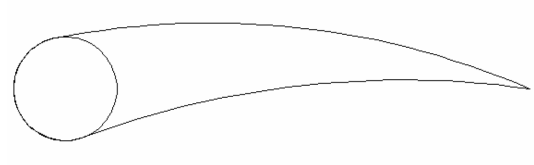

Figure 2: The airfoil cross section

The airfoil is a double membrane sail wing airfoil consisting of an inflatable member as the airfoil nose and a double membrane as an airfoil surface. Camber, a function of the pressure gradient over the airfoil, will introduce a pitch moment. This pitch moment is compensated by a horizontal stabilizer. Figure 3 shows the polar of this airfoil at a given camber value and for various Reynolds numbers. These Reynolds numbers correspond to tip- and root chords and wind speeds from 7m/s to 20 m/s.

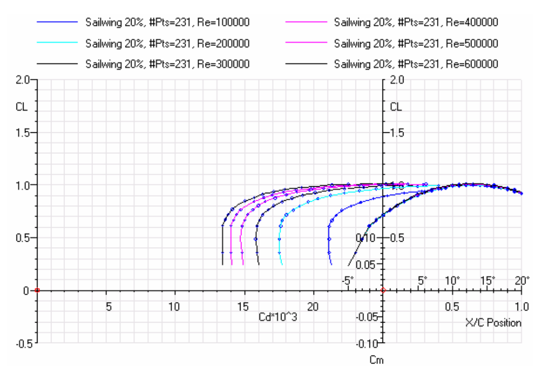

Figure 3: The sail-wing polars (designfoil™).

Figure 3 shows a large low drag region up to C_L Values of 0.7. This region corresponds to an angle of attack between -5° and 0°. The resulting main wing plan form is shown in figure 4

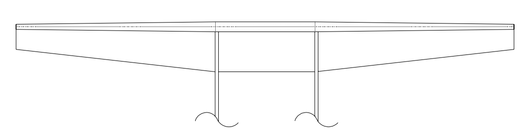

Figure 4: Test kite and final kite plan forms.

2.2 Structural design

The kiteplane presented in this paper is a scaled down version of a larger kite 15-meter span kite that was designed for the altitude record. The scaled down version is here forth called "the test kite". It has a 3-meter wing span and has a twin tail boom configuration. Figure 5 shows the final design.

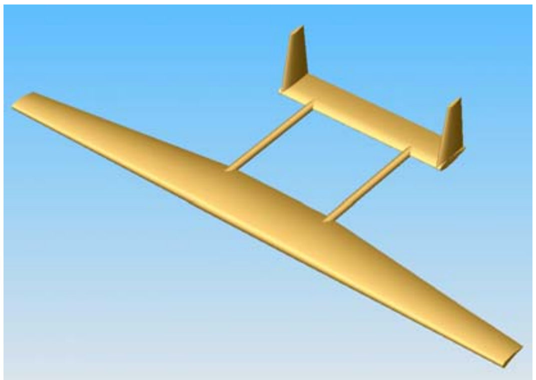

Figure 5: The test kite layout.

The long slender wing poses a structural challenge. The wing will contain a single inflatable beam, which will also double as the nose of the airfoil. For the scaled down version, one can consider the scaling effect of the inflatable beam as follows [2]

$$M_{wrinkle} = \frac{\pi p r^3}{2} \tag{4}$$

Rewriting equation (4) yields:

$$p = \frac{M}{\frac{1}{2}\pi r^3} \tag{5}$$

As one can see, the radius of the beam is very significant as it is present in equations (4) and (5) to the third power. To evaluate the scaling effect on an inflatable wing, we assume a simplified loading on the main spar, as is depicted in figure 6

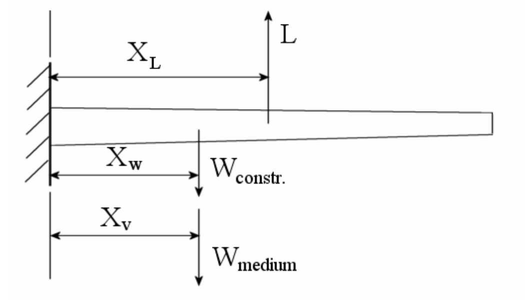

Figure 6: The loads on the main spar

The bending moment at the root can be written as:

$$M = L * X_L - W_{constr.} * X_w - W_{medium} * X_v$$
$$= L * X_L - W_{constr.} * X_w - \frac{p_i}{p_h} * \rho_h * V_{env} \tag{6}$$

Where p_i is the internal pressure inside the inflated envelope, p_h is the ambient pressure outside the inflated envelope and V_{env} is the envelope volume. Substitution of (6) into (5) yields:

$$p_i = \frac{L * X_L - W_{constr.} * X_w}{\frac{1}{2}\pi r^3} * \frac{p_h * \frac{1}{2}\pi r^3}{p_h * \frac{1}{2}\pi r^3 + \rho_h * V_{env} * X_r} \tag{7}$$

When scaling down to one fifth of the original size, the parameters change as follows:

$$L_{1:1} = C_L * \frac{1}{2}\rho V^2 S \tag{8a}$$

$$L_{1:5} = C_L * \frac{1}{2}\rho V^2 * \frac{1}{25} S = \frac{1}{25} L_{1:1} \tag{8b}$$

$$W_{constr,1:1} \approx \rho * t * surfacearea \tag{9a}$$

$$W_{constr,1:5} \approx \rho * \frac{1}{5} t * \frac{1}{25} surfacearea = \frac{1}{125} W_{constr,1:1} \tag{9b}$$

Substitution of (8) and (9) into (7) yields:

$$p_{1:5} = \frac{L * X_L - \frac{1}{5} W_{constr.} * X_w}{\frac{1}{2}\pi r^3} * \frac{p_h * \frac{1}{2}\pi r^3}{p_h * \frac{1}{2}\pi r^3 + \rho_h * V_{env} * \frac{1}{5} X_r} \qquad (10)$$

Comparing equations (10) and (7) one can conclude that the required internal pressure goes up slightly when down-scaling the construction. Figure 7 shows the change in required internal pressure from a scale of 1:100 to a scale of 4:1. Generic values were used which are comparable to the kite proposed in this paper.

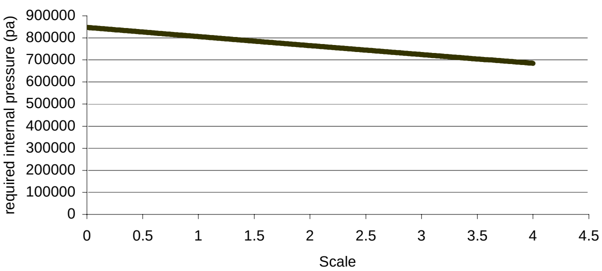

Figure 7: Required internal pressure with scaling

Figure 7 shows that the scaling of the kiteplane has only a minor effect on the required internal pressure in the inflatable tube. It can be concluded that a scaled down version of the kite is certainly feasible. However, for the study reported here, the kite was constructed from flexible foam as a material instead of an inflatable tube.

3. Stability

Stability of aircraft can be viewed in terms of static stability and dynamic stability. Where static stability requires a disturbance to be followed by a correcting momentum, the dynamic stability requires the resulting motion to converge. Therefore, static stability is a requirement for dynamic stability.

Static stability is analyzed but looking at the equilibrium of moments and forces on the kite and looking at the first derivative with respect to the degree of freedom which is being considered.

In this paper, the focus will be on dynamic stability

[5] Outlines a stability theory which is based on conventional aircraft dynamic stability theory. First the equations of motion are formulated. Then these equations are linearized. This linearization is justified for stationary flight conditions that are close to static equilibrium. The equations of motion can be written in matrix form. Using adequate transformations to the body axis system and to the stability reference system, several additional simplifications can be made. Finally, the resulting equations are written in non-dimensional form so they are independent of scale. For conventional aircraft, the resulting system of equations can be resembled by two 4th order differential equations, one for symmetric- and one for a-symmetric flight, like:

$$F(\lambda) = \lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0 \qquad (11)$$

In this equation, λ resembles the eigenvalues and B, C, D and E resemble functions of aerodynamic forces. However, a kite is attached to a tether. This tether introduces new modes of instability. Anchoring a flying object will often introduce instabilities like increased oscillations in sideslip or pure diversion as if the kite were an inverted pendulum [5]. The dynamic stability of a kite is represented by a 6th order differential equation:

$$F(\lambda) = \lambda^6 + B\lambda^5 + C\lambda^4 + D\lambda^3 + E\lambda^2 + F\lambda + G = 0 \qquad (12)$$

In equation 5, only B is independent of cable forces. All other coefficients are complicated functions of aerodynamic and cable forces. By working out all the equations, the stability coefficients can be determined. This leads to two 6 by 6 matrices, one for symmetrical motions and one for a-symmetrical motions. From these matrices, eigenvalues can be obtained, which directly relate to the stability of the kiteplane. A negative real part indicates a convergence motion and a positive real part indicates a divergent, unstable motion and the imaginary part is an indication of its oscillation characteristic.

The following values were obtained for the test kite.

$\lambda_{1,2}$	-0.00175 ±0.0978i
$\lambda_{3,4}$	-0.0529±1.36i
λ_5	-0.0114
λ_6	-0.100

Table 1: The eigenvalues relating to the symmetric motions.

$\lambda_{1,2}$	-4.501±3.026i
$\lambda_{3,4}$	1.513±3.787i
λ_5	$0.102 * 10^{-18}$
λ_6	0.375

Table 2: The eigenvalues relating to the asymmetric motions

As can be seen, some of the a-symmetric eigenvalues are positive or have a positive real part. This indicates an unstable motion. $\lambda_{3,4}$ is a complex number with a positive real part. This indicates a divergent oscillating motion. The period of motion is very short:

$$T = \frac{2\pi}{\mathrm{Re}(\lambda)} * \hat{t} \qquad (13)$$

Where $\hat{t}$ is the unit of aerodynamic time:

$$\hat{t} = \frac{V * C_L}{2 * 9.81} = 0.54s \qquad (14)$$

This motion represents the "dutch roll" motion, a coupled motion in both roll and yaw. Such a motion was confirmed during flight tests. But the motion was restricted by the bridle lines in roll. The value of λ_5 is so small, it can be neglected. λ_6 represents the inverted pendulum motion. As it's a positive real number, the motion is divergent. Therefore, active control is required to keep the kite level. This active control has been introduced in the form of ailerons acting as drag flaps in the wing tips. Figure 8 shows these flaps.

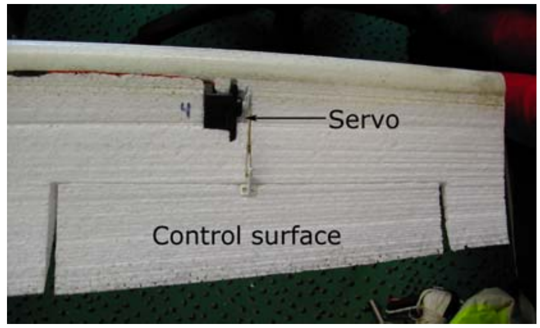

Figure 8: The drag flap.

This drag flap hinges up and creates an increased drag on one wing. This introduces a yaw moment and a roll moment. The kite is not free to roll due to the presence of the bridle lines. However, it is free to yaw. This enables the controller to steer the kite.

4. Flight tests

The test kite was built out of Eperan PP (polyprop) foam using templates and a procedure called "hot-wiring". An electric current heats a wire, enabling it to slice through the foam. Figure 9 shows the resulting kiteplane.

Figure 9: The test kite before flight.

Eperan PP foam is very flexible and lightweight. It weighs in at 20 Kg/m^3. It is suitable for use because it is able to sustain crash impacts. To give the kite rigidity comparable to that of an inflatable spar, composite spar caps were added along the lower surface of the wing in span wise direction and on the tail booms. Three different materials have been tested. The first is glass fiber. Strong enough to carry the loads on itself, but it did display the tendency to delaminate and buckle. Second was carbon fiber. This proved to be too stiff and would simply shatter on impact. The third material was Aramid. Very resistant to impact and it displayed good adhesion to the foam. This material was the better choice.

Flight tests were conducted at the beach in wind speeds ranging from 4 m/s to 7 m/s. The initial kite was uncontrolled. It displayed the instabilities which the theory indicated. A tendency to dutch roll and a "pendulum" instability. The dutch roll was not a concern because the bridle lines inhibit the rolling motion of the kite. The pendulum instability proved to be a problem. The kite would climb as a glider on a winch and then simply fall to either the left or the right. Figure 10 shows the kiteplane test.

Figure 10: The uncontrolled kite in flight.

Only slight movements of the control surfaces were sufficient to keep the kite stable. In later versions, a horizon sensor connected to an autopilot could be used to keep the wings level.

The low drag of the kite was apparent in some of the flights. A low drag kite is a less stable kite. Drag works as a dampening mechanism. Also, when the drag is high, the position of the kite is lower, causing the center of gravity to be lower with respect to the cable attachment point. Such a position of the center of gravity will cause a larger stabilizing moment.

Figure 11: The controlled kite in stable flight.

5. Conclusions

It is proven that an airplane-like kite, or kiteplane, can be built and flown in real field conditions. The configuration has demonstrated a high performance with a low drag of around C_D=0.3.
The performance of the kiteplane will also allow energy production at high wind speeds, which occur at high altitude. Therefore, this kiteplane can be considered an important candidate for the laddermill

6. References

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