

The Laddermill: work in progress

Prof. dr. Wubbo J. Ockels¹
wubbo.ockels@lr.tudelft.nl

Bas Lansdorp, M.Sc.²
bas.lansdorp@lr.tudelft.nl

Jeroen Breukels, M.Sc.³
j.breukels@lr.tudelft.nl

Gertjan Spierenburg⁴

- 1) Professor of the ASSET chair, TU Delft
- 2) PhD Researcher, ASSET, TU Delft (corresponding author)
- 3) PhD Researcher, ASSET, TU Delft
- 4) M.Sc. Student, ASSET TU Delft

Summary

The Laddermill is a new concept that provides a method for exploiting the wind energy at high altitudes up to 10 kilometer. A single laddermill could produce up to 50 MW of electrical energy. In this paper, the design options for a laddermill are presented and analyzed. A software package that simulates operation of the Laddermill is presented. It is shown that a laddermill is stable in a wide range of wind profiles and timely variations, including shear winds. In conclusion, the laddermill is an interesting new way to harvest energy from the wind.

Key words:

Laddermill, wind energy, high altitude, kites

The Laddermill: work in progress

Prof. dr. Wubbo J. Ockels¹

wubbo.ockels@lr.tudelft.nl

Bas Lansdorp, M.Sc.²

bas.lansdorp@lr.tudelft.nl

Jeroen Breukels, M.Sc.³

j.breukels@lr.tudelft.nl

Gertjan Spierenburg⁴

- 1) Professor of the ASSET chair, TU Delft
- 2) PhD Researcher, ASSET, TU Delft (corresponding author)
- 3) PhD Researcher, ASSET, TU Delft
- 4) M.Sc. Student, ASSET TU Delft

Abstract

The Laddermill is a new concept that provides a method for exploiting the wind energy at high altitudes (1-10km). The laddermill could enable wind energy generation in the order of 50 MW per Laddermill, an order of magnitude larger than current conventional windmills. The principle combines kite properties with that of airplanes. Kites go up while driving a ground based generator, and go down flying like an airplane. Development of a demonstrator of the Laddermill is one of the projects at the new chair AeroSpace Sustainable Engineering and Technology (ASSET), created under an agreement between the European Space Agency and the Delft University of Technology. ASSET promotes a general vision towards an optimistic sustainable future using hi-tech aerospace developments.

Two distinct Laddermill types are presented. The first type presented is one in which the wings are attached to a continuously rotating tether shaped as an endless loop. The kites attached to the ascending side of the loop are configured for high lift. At the top of the loop, the kites change attitude to allow them to glide down to the ground station.

The second type is the pumping Laddermill, in which the kites are attached to a single tether that goes up and down alternately, in a linear motion.

Both types will feature a ground station where the generator is located. In general, the tether will provide the ground station with mechanical power at low speeds (1/3 of the wind speed), thus with high forces. Each Laddermill type will enforce several different requirements upon the ground station. These are mechanically analyzed and an early assessment is presented. Also several types of kites are analyzed and compared.

A fully 3-D, 6 degrees of freedom simulation software package was developed. The software allows for an analysis of the dynamics of a multitude of attached kites. It is demonstrated that the Laddermill can be designed such that it is stable in a wide range of wind profiles and timely variations, including wind shear.

The wind energy at high altitudes is considerable (average 9 Beaufort at 9 km in Holland). Kite like structures are light and inexpensive and enjoy a general cultural acceptance.

1. Introduction

The Laddermill is a new concept that provides a method for exploiting the wind energy at high altitudes [1]. The wind speed at higher altitudes is illustrated in Figure 1.

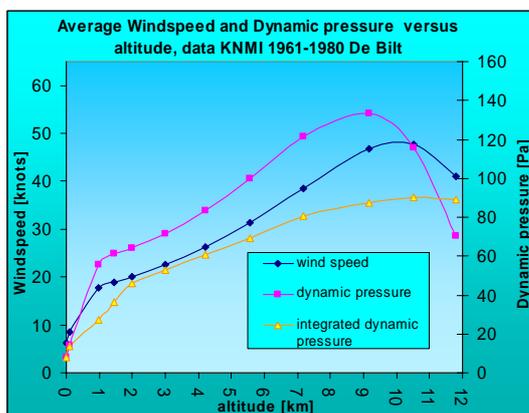


Figure 1 Wind speed and dynamic pressure vs. altitude [2]

The laddermill principle makes use of lifting bodies, called wings. The wings are connected to a tether. When the wings are pulled up by the wind they behave like kites, powering the generator. When the wings come down they behave like airplanes. Two conceptual laddermills based on this principle are presented. The laddermill should enable large-scale wind energy generation, in the order of 50 MW per Laddermill. For conventional windmills, larger single-unit outputs have proven to decrease the cost per kWh [3]. There is a minimum price per kWh for a rotor diameter of about 50 m. For higher rotor diameters the price per kWh rises [3].

In the year 2000, 1.2% of the Dutch electricity consumed, came from renewable sources [4]. In 2000, the Dutch government has set targets in order to comply with the Kyoto protocol, aimed at reducing the Dutch CO₂ emissions. The targets are to generate 5% of the electricity consumption from renewable sources by 2010 and 10% by 2020 [4]. Another target is to have 1500 MW installed power operational in 2010 [4]. In 2003, the ratio of produced power to installed power of windmills in the Netherlands was only 0.17 [5]. Applying this ratio to 1500 MW installed power for 2010, this results in 2.2% wind energy, on the current Dutch average of 11.2 GW.

The wind at higher altitudes is more constant. Current estimates show a laddermill can produce about 70% of its installed power. This will also

enable generating substantial percentages of a country's electricity requirements from wind. It will take only about 32 Laddermills to generate 10% of the Dutch electricity demand.

Development of a demonstrator of the Laddermill is one of the main tasks for the new chair AeroSpace Sustainable Engineering and Technology (ASSET) of the Faculty of Aerospace Engineering of Delft University of Technology. ASSET was created under an agreement between the European Space Agency and the Delft University of Technology. ASSET promotes a public vision towards an optimistic sustainable future using hi-tech aerospace developments. This paper explains the work in progress on the laddermill.

2. Laddermill concepts

Two different concepts for high altitude wind energy exploitation will be discussed in this section. More concepts were considered, some of them will be mentioned in other sections.

2.1. Laddermill

The first concept is the laddermill [1]. The laddermill consists of an endless tether with wings attached to it, presented in Figure 2.

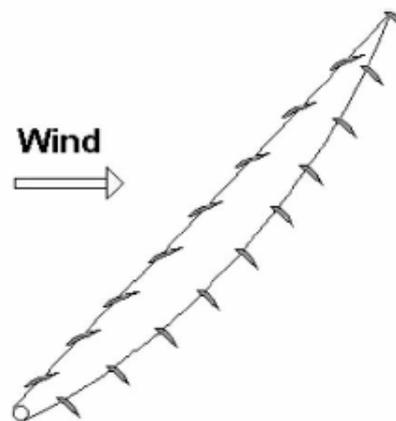


Figure 2: The laddermill concept [1]

On the ascending end, the wings are adjusted to deliver maximum lift. On the descending end, the wings deliver only just enough lift to stay up. The resulting tension difference in the rope is used to power a ground based generator.

2.2. Pumping mill

The second concept consists of a single tether, with a number of wings spread evenly over it, as

shown in Figure 3. It is in fact half a Laddermill. This concept will alternately move up and down. During the ascent, the tension in the tether drives a generator. During the descent, no power is generated.

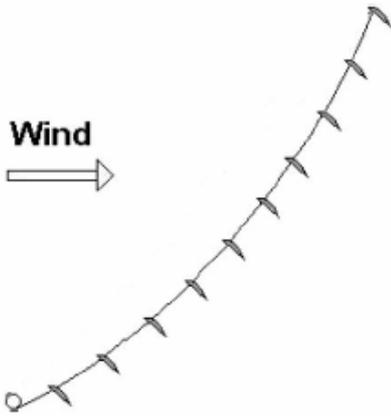


Figure 3: Pumping mill [after 1]

3. Laddermill simulation

A simulation program was written to simulate the dynamic behavior of the laddermill. It is a fully 3-D, 6 degrees of freedom simulation software package. The program allows for analysis of the dynamics of a multitude of wings attached to a tether.

The program is based on a finite element method. A laddermill can be built in the program, with nodes representing a tethered wing and the end of a cable segment. The forces on the tether and the wings are caused by gravity and aerodynamic forces. The aerodynamic forces are dependent on the attitude and the position of the wing.

The forces on the wings and the tether are transferred to the nodes to determine the dynamics with a set of first order differential equations representing Newton's 2nd law.

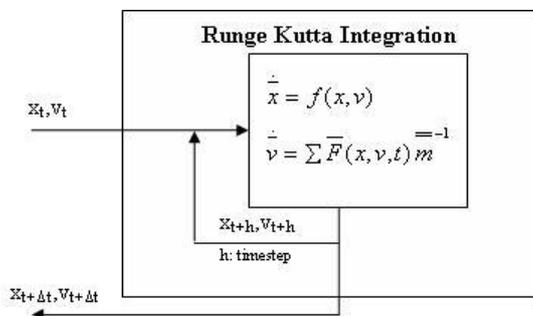


Figure 7: Runge Kutta integration according to the Fehlberg method

For the numerical integration of the differential equations the Fehlberg method is used [6]. Fehlberg uses a 5th order Runge Kutta, where the last order is used for error estimation to adjust the time step, as in figure 7.

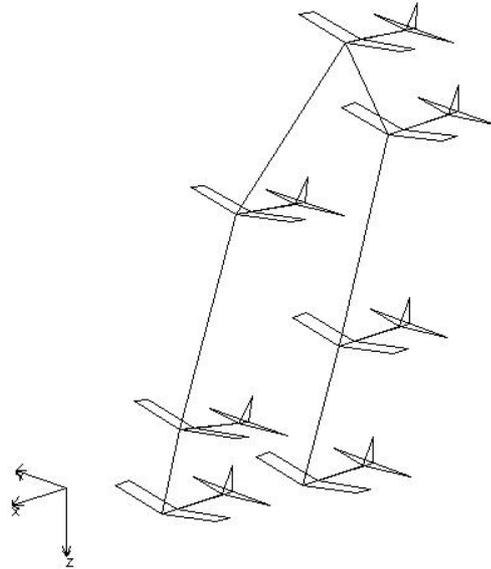


Figure 8: Simulation graphical output I

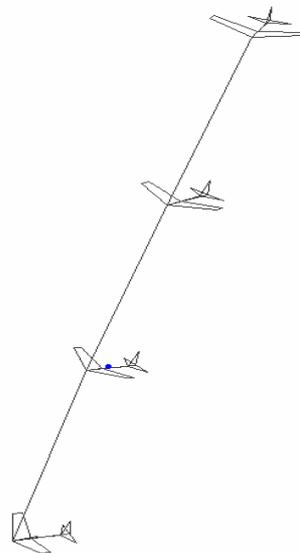


Figure 9: Simulation graphical output II

The program shows that the Laddermill can be designed such that it is stable in a wide range of wind profiles and timely variations, including shear winds. Validation of the program is part of current research. Two graphical outputs of the program are presented in Figure 8 and Figure 9.

4. Kite laboratory

In order to properly flight test the concepts which will be generated, there is a need for a proficient test platform. The construction of the kite laboratory (KiteLab) will provide such a platform. KiteLab consists of two sections. A monitoring and preparation section and a flight test section. The monitoring and preparation section will be located on the top floor of the faculty building in Delft. It will house all the meteorological computers, flight monitoring computers and data collection systems. Also, limited production and preparation will be done here.



Figure 6: Kite laboratory to be built at the roof of the faculty building

The flight test section will be located on the roof of the faculty building. The kite itself will be attached to a winch. On either side of the winch, a 25 m high tower will be placed. An illustration of the KiteLab is presented in Figure 6.

Cables will run from the top of the towers to the center of the leading edge of the kite. In the launch phase, the kite will be hoisted up. The main tether will be slack and therefore the kite will essentially behave a wind vane. Once the kite is at a safe altitude, the kite can be brought into the correct angle of attack and the generated lift force can be transferred to the main tether. Once the main tether is loaded, the cables from the towers can be kept slack. In case the kite makes a major departure from symmetric flight, the tower cables will keep it from crashing.

The towers will also be used as a platform for a number of meteorological instruments. This will allow for a complete meteorological picture during testing.

While the KiteLab is under construction, test are performed on the beach because of the stronger, more constant wind.

5. Laddermill wing tests

Current research on the Laddermill is focused on the design of the wings. Two types of wings are pursued; the first type of wing is a tethered wing that is inherently stable. The only active control required for such a wing is pitch control to change the lift. The second is a wing that is kept stable by control surfaces (ailerons, rudder and elevator). Such a wing can perform crosswind motions to increase the lift as well [7].

5.1. Theory of inherently stable wings

In the laddermill, the weight of the tether has to be carried aloft. It is therefore imperative that as little tether as possible is used. The amount of tether needed is a function of both the drag and the lift of the wing. The higher the drag on the wing, the farther away from the ground station it will position itself. It is therefore important to develop a wing with a high lift over drag ratio. These wings require a high aspect ratio to reduce the induced drag. Such wings will resemble those of sailplanes.

The increased aerodynamic efficiency puts a strain on the stability of the tethered wing. Conventional kites deduce a large amount of their stability from their drag. Lowering the drag makes the wing less stable. In [8] a theory is outlined to predict the stability of a single wing on a single tether. This theory states that the longitudinal stability is easily reached at low altitudes. Only at high altitude the wing becomes less stable. At low altitude the longitudinal motion of the wing approximates a pitching rotation about the point of attachment of the wing to the main tether. The horizontal stabilizer counters this rotation. As altitude increases, so does the force the tether exerts on the wing. This increase has a destabilizing effect.

In [8] it is stated that there is a clear correlation between conventional kite stability and airplane stability, in the sense that properties such as wing dihedral and tail fin surface are of fundamental importance. The precise relation is highly dependent on the position of the point of attachment of the wing to the main tether with respect to the position of the center of gravity. Longitudinal stability requires this point of

attachment to be positioned ahead and below the center of gravity as much as possible, lateral stability requires this point of attachment to be very little ahead of the center of gravity. For a given position of the point of attachment [8] states that a too large tail fin surface results in a continuous divergence, while a too small tail-fin surface leads to an escalating oscillation. While conditions for avoiding continuous divergence are independent of altitude, conditions for avoiding escalating oscillations are not. When the kite is at an altitude equal to roughly its own wingspan, unstable oscillations are virtually unavoidable. As altitude increases, the kite becomes more stable. [8] suggests that large dampening of angular velocities in yaw direction will increase the stability of the wing at low altitudes. For wings of low lift-over-drag ratios, instability as a result of lateral oscillation is virtually non-existent.

5.2. Testing of the inherently stable wing

To verify the theory, a test kite was constructed. This test kite was a test case for both the laddermill project, as well as, the KitEye project. The KitEye project has as its main focus the design of a high altitude kite which could break the world altitude record for a single kite on a single line.

Figure 4 shows the wing, which was built and tested in a laddermill configuration. The wing was constructed from Eperan-PP foam with glass- and carbon fiber reinforcements and has a wing span of 3 m, a wing surface of 0.75 m² and a weight of 880 grams. Figure 5 shows the kite in flight. In this figure, the main tether has been artificially thickened to make it visible.



Figure 4: A prototype for the laddermill wing

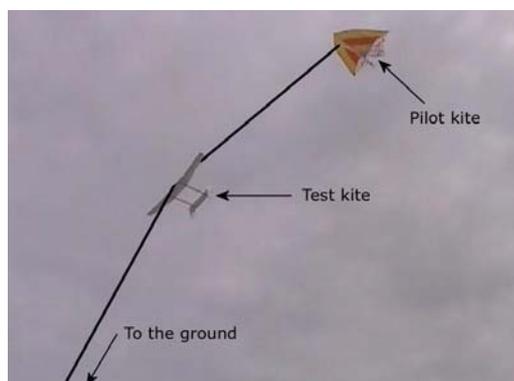


Figure 5: The test kite in flight

In the theoretical analysis according to [8], two unstable motions were identified. The first was an unstable reversed pendulum motion, which would make the kite fall to either the left or the right, and the second unstable motion was a very slight dutch roll instability. The first unstable motion is countered by the delta kite acting as a pilot kite. The test kite is attached at the leading edge and the tension in the tether keeps it from falling to the left or the right. The unstable dutch roll motion was indeed observed. However, its implications were only very minor and did not seem to escalate. The low drag properties of the test kite were quite apparent. As can be seen by the bend in the main tether (figure 5), the test kite wants to position itself at a higher angle with respect to the attachment point on the ground than the pilot kite. This indicates a higher lift over drag ratio.

Improvements of this prototype are the focus of current research. A reduction in fin size could alleviate the unstable pendulum motion, making the kite suitable to be flown as a single wing on a single tether. Furthermore, the use of carbon fiber as a reinforcement material has been proven unsatisfactory due to the fact that carbon-fiber composite is quite brittle and will fail under sudden shock loads.

Later versions of this kite will be larger and will consist of fabric and inflatable envelopes providing sufficient rigidity. To predict the behaviour of such a flexible structure, a theory is being devised. This theory will be based on fluid-structure interaction coupled with a numerical approach to flight stability; much like was done in the simulation program outlined in section 4.

5.3. Actively controlled wings

Research into laddermill wings is not limited to conventional semi-rigid wings. Fully flexible wings such as parachutes and parasails are investigated as well.

In controlling a wing, whether it is semi rigid or a flexible foil, a clear distinction can be made between the required control authority in yaw and pitch. Pitch control generally doesn't require being extremely responsive, only a very gentle change in angle of attack is required to make the kite ascend and descend. As long as the wing is longitudinally stable, the control authority for yaw has to be more substantial. Even for inherently stable wings, small course corrections will require a swift response to yaw control input. Roll control is a degree of freedom which tethered wings do not have due to the bridle lines attached to the wings.

Controlling a semi rigid kite can be done in much the same fashion as a conventional aircraft. Control surfaces provide the adequate means for control. In a flexible foil, such as a parasail, this doctrine does not hold. Parasails are generally controlled by warping the wing. But also creating drag in key locations on or below the wing is a way of creating control authority. The desire for swift response to yaw control puts a different requirement on the means of control than for the slower pitch control. Currently, several control methods are being reviewed.

6. Concluding remarks

The laddermill should enable large single unit outputs in the order of 50 MW. Such large single unit outputs would enable generating a significant portion of a country's electric energy demand.

Work on the Laddermill is in progress at Delft University of Technology. There is substantial media attention and financial support from Dutch industry. Current work involves refinement of the simulation program. So far the simulations performed were promising, both for stability and for the capacity factors.

Two concepts were presented in this paper. The two concepts each have advantages and disadvantages. At this time, both concepts are under consideration. A detailed comparison will be performed to determine which concept has higher potential.

In the construction of the laddermill, the wings are the focus of current research. An inherently stable wing was built and tested successfully. Work on actively controlled tethered wings is

ongoing, focusing on paragliders and model sailplanes.

7. Acknowledgements

The Laddermill project is sponsored by: Shell research, Fugro, Gasunie, University of Groningen, Delft University of Technology, the province of Groningen, the county of Groningen and the county of Delft.

8. References

- [1] Ockels, W.J., 2001, "Laddermill, a novel concept to exploit the energy in the airspace", *Aircraft design 4* (2001), pp 81-97.
- [2] Royal Netherlands Meteorological Institute.
- [3] EWEA, 2003, "Wind energy – The facts".
- [4] Dutch Ministry of economic affairs, 2001, "Bestuursvereenkomst Landelijke Ontwikkeling Windenergie (Blow)", accessible at <http://apps.ez.nl/publicaties/pdfs/blow-bw1.pdf>, accessed 3-11-2004.
- [5] Statistics Netherlands (Centraal Bureau voor de Statistiek), 2003, "Duurzame energie in Nederland", <http://www.cbs.nl/nl/publicaties/publicaties/bedrijfsleven/energie-water/duurzame-energie-in-nederland-2003.pdf>, accessed 3-11-2004.
- [6] Kan, J. van, 2000, Numerice wiskunde voor technici, Universiteitspers.
- [7] Loyd, M.L., 1980, "Crosswind Kite Power", *Journal of Energy*, vol. 4, No. 3, pp 106-111.
- [8] Bryant L.W., Brown W.S., Sweeting, N.E., Collected researches on the stability of kites and towed gliders, Aeronautical Research Council R&M 2303.