Ship propulsion by Kites combining energy production by Laddermill principle and direct kite propulsion

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Submitted for publication:
Kite Sailing Symposium
September 28/29/30th 2006
Center for Wooden Boats/South Lake Union
Seattle, Washington
USA
www.drachen.org

Abstract
The use of large kites in ship propulsion has been shown as both feasible and spectacular. Here we propose an even more exotic propulsion mechanism based on a Laddermill apparatus mounted on a ship combining production of electrical power from wind and the more traditional sailing by wind force. The feasibility of this concept is investigated. The results show that with this novel concept it is possible to sail a ship straight into the wind! Even more spectacular will the method of propulsion be when the overall efficiency from kite thrust times cable speed towards ship thrust times speed can be made around 50%. In that case, and technically 50% seems feasible, the ship can be propelled by wind energy with a resulting speed that is practically independent from the wind direction! Such a capability could well change the world's seafaring.

Introduction

Kites have been in use in novel sports such as kite -buggying, -surfing and snow kiting. Recently kites have been employed as a new ship propulsion method where the aim is either the reduction of fuel consumption for large ocean going vessels (Skysails, http://www.skysails.com) or the generation of large boat speeds for recreational use (http://www.kiteboat.com,

Fig.1 Results of a student design exercise, showing a series of smart kites each fitting in a standard container. The study included the deployment and retrieval of the kit

The ASSET group at the Delft University of Technology is developing an electrical power generator based on the laddermill principle. The original laddermill idea was patented in 1998 (W.J. Ockels) .

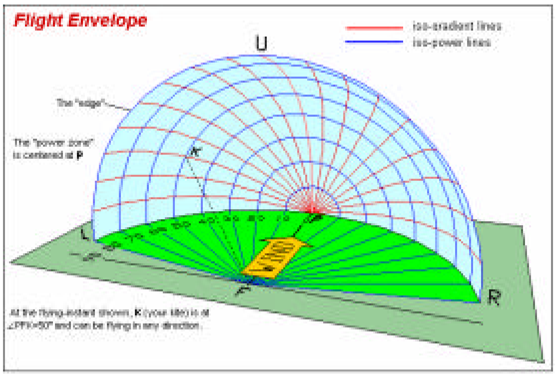


Figure 2. The flight envelope (Seattle Airgear) http://www.peterlynnkites.co.nz/vehicles/boats/boats

The Laddermill is using kites that are connected by a cable to a ground station, which using a real and generator to transfer the wind lifting power of the kites to electrical power. The ascending kites are brought in a position to create a larger force than the descending kites. Such is achieved by as example a change in attitude (AOA) or by maneuvering (crosswind power) a change in size of surface (folding) or a combination of these. The Laddermill is presently realized as a one cable system with one or more kites that will be reeled out with high force and reeled in with low pulling force. ("Pumping Laddermill") A pumping Laddermill has been build and tested. Various experiments are prepared to be performed using the newly installed "Kitelab", on the roof of the faculty building (see figure 3)

Several applications of the Laddermill system are under investigation such as a high altitude power station (up to 9000 m). Another one very intriguing application is the Laddermill propelled ship which is further elaborated in this paper.. In this application the ground station of a Laddermill is place on a ship, through which electrical power is generated. For advanced kites it can be shown that the power generating force is significantly larger than the drag. In that case the ship can sail against the wind. In fact the ship's speed against the wind enhances the wind speed to which the kites are exposed (apparent wind). As the larger part of the corresponding increase in aerodynamic force is generating electrical power rather than drag (high Lift over Drag kite) the ship takes advantage of this phenomena. In other wind directions, the Laddermill kites will next to generating electrical power also pull the ship. The result is that combined ship propulsion can be made more or less independent of the wind direction as shown below.

The Laddermill concept

The original Laddermill concept was seen to be realized in a closed loop system of ascending and descending kites that provided a constant power to drive the generator. However recent studies in our group showed that a two stage pumping laddermill configuration is more practical and more simple to realize. In this configuration there is an upstroke where energy is produced and a down stroke that resets the apparatus into its original state. In the initial state a large portion of the kite line is wrapped around a drum that is connected to a generator/motor combination. The combined action of kite motion and large angle of attack provides a large line tension that is converted into rotary motion by pulling line off the drum. During this upstroke energy is produced. When all the kite line is rolled of the drum, the kites are kept stationary in the flight envelope and are configured for minimum pulling force, i.e. angle of attack. Now a portion of the generated energy is used to drive the drum and retrieve

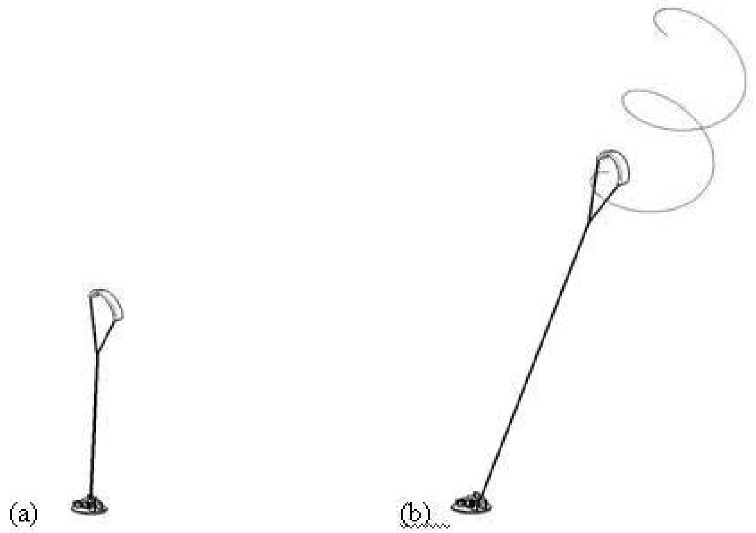
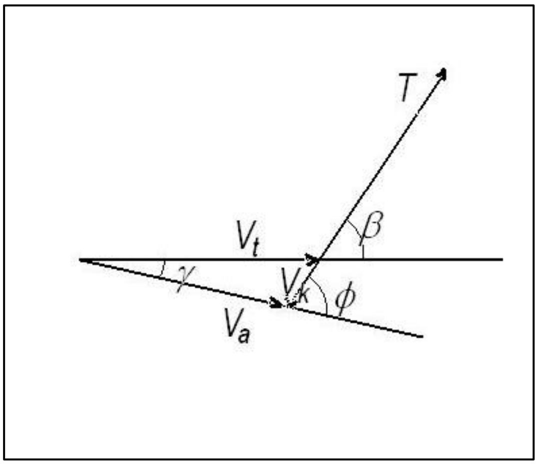


Figure 3. Laddermill concept. Panel (a) shows the laddermill in the downstroke phase, the kite is kept stationary with minimum angle of attack to minimize the line tension during retraction. The right panel shows the laddermill in the upstroke, the kite is moved through the flight envelope to generate a higher apparent wind speed and in combination with a high angle of attack generates a high line tension. During this phase the Laddermill generates electricity

the kite line. During this phase the apparatus consumes energy, but much less than generated during the upstroke. The Laddermill is now in its initial configuration and ready for a new cycle while there is a net energy surplus.

From basic principles one can derive the angle at which the Laddermill kites and its connecting cable will be for optimal power production.(see figure)



From the triangle of apparent wind speed V_a, the cable speed V_k and the ship's wind speed V_t which is the vector sum of the wind V_w and the ship speed V_s we have:

$$\frac{V_a}{\sin b} = \frac{V_t}{\sin f} = \frac{V_k}{\sin g}$$

Where

$$f = b + g$$

$\tan f = \dfrac{c_l}{c_d}$ the lift over drag of the kite system.

The aerodynamic forces of the kite system will be given as:

$$q = \tfrac{1}{2} r \cdot (V_a)^2$$

$$L = q \cdot c_l \cdot S$$

$$D = q \cdot c_d \cdot S$$

$$T = L^2 + D^2$$

Now the power that the Laddermill kites deliver is given by:

$$P = T \cdot V_k \tag{2}$$

And to optimize this power one needs to maximize the product of tension T and cable speed V_k. As the tension results form the aerodynamic force, T is proportional to the square of the apparent wind, thus:

$$P \sim V_a^2 \cdot V_k \tag{3}$$

Using (1) and (3) and set the derivative to zero gives:

$$\frac{d(\sin b)^2 \sin g}{db} = 0 \tag{4}$$

$$2\cos b \sin g - \sin b \cos g = 0$$

Which with some rewriting results in:

$$3\sin(2b - f) - \sin f = 0 \tag{5}$$

So that we have found that the optimal angle for the kite cable is only dependent on the lift over drag of the kite system and can be calculated as:

$$\boxed{b = \tfrac{1}{2} f + \tfrac{1}{2}\arcsin\left(\frac{\sin f}{3}\right)} \tag{6}$$

In the table 1 a list of L/D values and corresponding beta values are shown. As seen for typical kites this value will be around 50 degrees.

Laddermill Sailing

One of the more intriguing applications of the Laddermill is to propel a ship.
The use of kites as main ship propulsion method provides a number of advantages over the use of a normal sail fixed to a mast. The main advantage is that the kite can use the higher wind speeds that are found at higher altitudes and that the kite can move through the flight envelope to increase the apparent wind speed. Both effects increase the maximum forces that are available for ship propulsion compared to classical sailing techniques.

In this application the ground station of a Laddermill is place on a ship, through which electrical power is generated. For advanced kites it can be shown that the power generating force is significantly larger than the drag. In that case the ship can sail against the wind. In fact the ship’s speed against the wind enhances the wind speed to which the kites are exposed (apparent wind). As the larger part of the corresponding increased force is generating electrical power rather than drag (high Lift over Drag kite) the ship takes advantage of this phenomena. In the down wind directions, the Laddermill kites will next to generating electrical power also pull the ship. The intriguing result is that a combined ship propulsion can be imagined such that the ships speed is more or less independent of the wind direction. How this reasoning results in some fundamental minimum boundaries on the overall system efficiency is now shown:

Using the vectors of figure 2 one can write:

$$D_s \cdot V_s = h \cdot T \cdot V_k - \cos q \cos b \cdot T \cdot V_s \qquad (7)$$

Where

D_s is the drag of the ship

V_s is the ship speed

h is the overall system efficiency

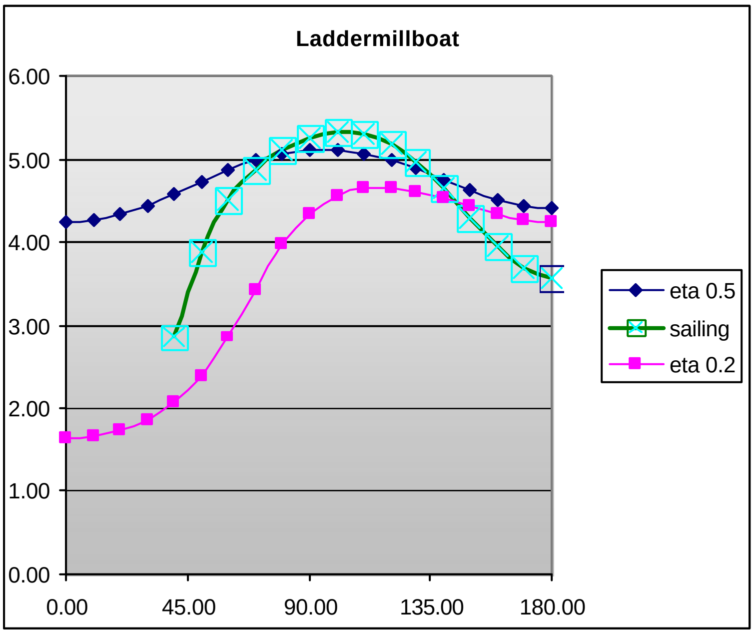
q is the relative wind angle to the ship speed direction

The overall system efficiency h is defined as the ratio of net ship propulsion in thrust times speed and the net kite power in cable tension times cable speed. The power chain comprised of the kites and cable, the mechanical transfer of the power to a generator, the electric motor and its control and the propeller, including the propeller losses.

Using (7) some calculations where done for a 60 tons sailing ship and 300 m^2 of Laddermill kite system in 20 knots of wind. The overall system efficiency was taken 20% and 50% respectively.

From the calculation is becomes clear that the ship speed in the upwind directions will strongly depend on the overall system efficiency.

Intriguingly one notices that for h is about 50% the ship will go at the same speed towards the wind as with the wind (down wind) while at intermediate directions its speed is somewhat higher.



This calculation uses the properties of a particular ship and of particular kites. We lie here to address the question whether one can derive more general consideration for Laddermill-sailing upwind and thus give a more general insight in the feasibility and potential of the Laddermill ship propulsion.

We derive here a formula for the minimum efficiency required as to reach an upwind ship speed that is equal to the downwind speed.
For the upwind direction we have according (7):

$$D_s \cdot V_s = h \cdot T \cdot V_k - \cos b \cdot T \cdot V_s \qquad \text{(8a)}$$

And for the downwind direction (at the same ship speed):

$$D_s \cdot V_s = h \cdot T' \cdot V_k' + \cos b' \cdot T' \cdot V_s \qquad \text{(8b)}$$

When comparing (8a) and (8b) with (2), one sees that the simple relation (6) for beta giving optimal power does not apply. The reason being that for (6) we optimized the power $h \cdot T \cdot V_k$, whereas for the Laddermill-sailing case we need to optimize $h \cdot T \cdot V_k - \cos b \cdot T \cdot V_s$ for the upwind case and $h \cdot T' \cdot V_k' + \cos b' \cdot T' \cdot V_s$ for the downwind case.

(5) becomes therefore

$$3\sin(2b - f) - \sin f + \cos q \cdot \frac{V_s}{V_w + \cos q \cdot V_s}(1 - 3\cos^2 b) = 0 \qquad \text{(9)}$$

Let b_0 be the solution of (5), which in fact corresponds to the solution of (9) for

q equals 90 degrees. Than when b_0 is substituted in (9a) the result would give a ship driving power that is slightly less than the maximum, as b_0 is the solution of (5) rather than of (9). This reasoning is based on the fact that there is only one maximum of the driving power as function of b and that the power is zero for b is zero and for b is 90 degrees. Having said this, one can now continue with (9a) and (9b) and take b for both the same and equal to b_0.

We now can treat both vector triangles congruently as in figure??.
Realizing that the apparent wind $V_w + V_s$ respectively $V_w - V_s$ is responsible for the tension will, one can define:

$$p = \frac{V_w - V_s}{V_w + V_s}$$

And thus:

$$T^{'} = p^2 \cdot T$$
$$V_k^{'} = p \cdot V_k$$

Subtracting both (8a) and (8b) and use the fact that b is taken the same than yields:

$$0 = h \cdot T \cdot V_k (1 - p^3) - \cos b \cdot T \cdot V_s (1 - p^2) \qquad (9)$$

The ration V_k and V_s can be written as (using (1)):

$$\frac{V_k}{V_s} = \frac{\sin(f - b)}{\sin f} \cdot \frac{2}{1 - p}$$

Substituting this in (9) and some rewriting results in:

$$\boxed{h = \frac{1 + f^2}{3 + f^2} \cdot \frac{\sin f \sin b}{\sin(f - b)}} \qquad (10)$$

with $f = \frac{V_s}{V_w}$, the ration of ship speed and wind speed.

This result is independent on the type of ship and of the speed of the ship. The validity is restricted to a ship speed less than the wind speed.

In the table below the results using (6) and (10) are shown for some practical values of L/D and the ration of ship speed and wind speed.

Minimum efficiency Laddermill ship with Vupwind=Vdownwind

		f=Vs/Vw			
L/D	beta(deg)	0.2	0.4	0.6	0.8
1	29.3	0.78	0.84	0.92	1.03
2	40.4	0.60	0.64	0.70	0.78
3	45.0	0.51	0.55	0.61	0.68
4	47.4	0.47	0.50	0.56	0.62
5	48.9	0.44	0.48	0.53	0.58
6	49.9	0.43	0.46	0.50	0.56
7	50.6	0.41	0.44	0.49	0.55
8	51.1	0.40	0.43	0.48	0.53
9	51.5	0.40	0.43	0.47	0.52
10	51.8	0.39	0.42	0.46	0.52
11	52.1	0.39	0.42	0.46	0.51
12	52.3	0.38	0.41	0.45	0.51

From these numbers one can conclude that a typical system efficiency of 50% would be sufficient for a Laddermill ship to sail at a speed independent of the wind direction. Such an efficiency will , although large diameter propellers and very efficient electric motors and converters are required, be feasible.

Conslusions

We conclude that Laddermill-sailing is feasible for existing kites (kites with a Lift over Drag ratio of typically > 5) and provides an unequalled potential for sustainable seafaring. The implementation is facilitated by the development of diesel-electric ships, as one can add the Laddermill system to those ship, not imparing the basic propulsion system and its corresponding reliability. Further studies can be undertaken to investigate and map the favorable wind conditions and its predictability. Recent developments in weather observing satellites and weather prediction models will favour the Laddermill sailing concept.

Next plans:

Using a simple ground station and surf kites, we are planning to demonstrate power-generating capability of several 100's of kW's in the near future. This level seems just right for a 100 tons displacement tourist boat. Negotiations are ongoing with the Port of Rotterdam to start such project, which then will also be the proof-of-concept for the application at larger vessels. The corresponding typical pulling force of the kite is planned around 20000 N which can be reached with winds of typically 25 knots . At altitudes of 100-500 m such wind speeds are very common, also at night when the surface winds tend to lay down. Even for inland trips the Laddermill can provide power and propulsion. When stationary the Laddermill can be used for battery charge and hotel power. Inland restrictions for the kite altitude are mostly 150m. At see these restrictions relax, although specific cases need to be investigated. Controllable kites form the enabling technology for wind energy production and ship propulsion by kites. We have developed several electromechanical control mechanisms and are currently testing autonomous control of a kite through a software routine. Once these routines are optimized we can ensure fully automatic functioning of a laddermill. This enables us to realize a test for laddermill-sailing in the near future. The construction

of a kite based propulsion that allows a ship to sail straight upwind will hopefully provoke a large interest for kites, kite-sailing and laddermill-sailing.
A 1kW demonstration and proof-of-concept Laddermill has already been built and tested. The results are reported elsewhere (ref?)

Acknowlegdment
This work is part of the Laddermill project that is sponsored by the Delft University of Technology, the University of Groningen, Gasunie, Fugro, Shell Research, the Town and Province of Groningen.