Laddermill-sailing,

Ship propulsion by wind energy independent from the wind direction!

Wubbo J. Ockels
(chair holder)
AeroSpace Sustainable Engineering and Technology Chair (ASSET)
www.lr.tudelft.nl/asset
Faculty of Aerospace Engineering
Delft University of Technology
P.O.Box 5058
2600 GB Delft
Netherlands

Submitted to the Journal of the International Shipbuilding Progress.

Abstract

The use of large kites in ship propulsion has been getting a growing attention because of the urgent need to reduce the CO_2 production and thus stop the use of fossil fuels. A novel application of ship propulsion by kites is proposed based on a Laddermill apparatus mounted on a ship. Such an apparatus consist of a winch, an electric motor/generator, a kite system (including launch and retrieval) and controlling electronics.
Rather than the traditional sailing by wind force the Laddermill [2] propulsion is achieved by a combination of the production and use of electrical power and the direct pulling force from the kite system. The feasibility of this application is investigated. It is show that when the overall Laddermill to ship thrust efficiency can be made around 50% the resulting speed of the ship becomes practically independent from the wind direction! Such a capability could thus well change the world's seafaring.

Introduction

Kites have been known since thousands of years. Kites have been mainly used for pleasure and as toys. Over these many years kites have shown little development, the shapes and applications basically stayed similar. Recently kites, however, have enjoyed fast development in shape through the use in novel sports such as kite -buggying, -surfing and snow kiting. A logical extrapolation of these sports leads to kites employed as new ship propulsion. The main drive is the reduction of fuel consumption for large ocean going vessels (Skysails, http://www.skysails.com) although joyfull applications can be imagined for recreational use (http://www.kiteboat.com).

Fig.1 Kite system designed by students form the TU delft to propel a container vessel

The enabling technology for the Laddermill [2],[7] is the remote or computer control of the kite [6],[8]. Several simulation have been developed showing the dynamic behavior of a system of a number of kites attached to lines [3],[4],[5],[12]. From these simulations it is obvious that a passive stable system will be hard to design. It is therefore that control of the kites becomes essential. Recently our group has achieved adequate radio control of typical surf kites and has demonstrated the proof of concept of the Laddermill by generating over 1kW of power. [9],[16] The next step will be the Laddermill-ship application discussed below.

The Laddermill principle

The ASSET group at the Delft University of Technology has initiated the Laddermill project in 2003, sponsored by various parties, see acknowledgement below. The Laddermill project aims at the development of an electrical power generator based on the laddermill principle. The original laddermill idea was patented in 1996 (W.J. Ockels, 2001) [2] .

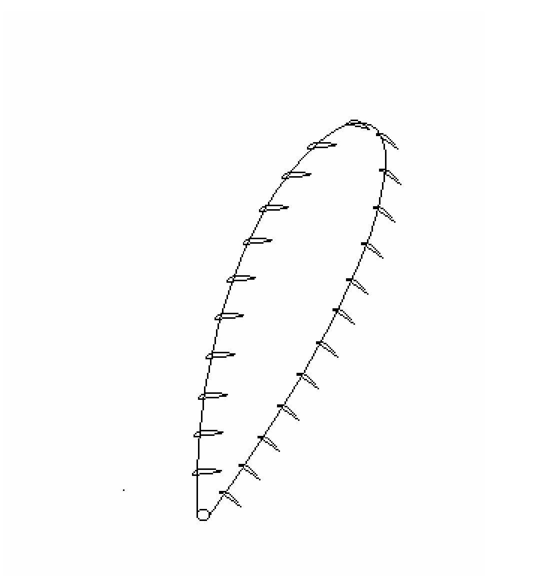

Figure 2. The Laddermill concept where ascending kites are pulling stronger then descending kites and thus drive a ground based generator

The Laddermill is using kites that are connected by a cable to a ground station, which use a real and generator to transfer the wind lifting power of the kites to electrical power. Such can be realized by kites that are connected to an endless loop, see fig 2, or in other ways, such as by a periodic operation of a single line, see fig 3. 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 [1]) or 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

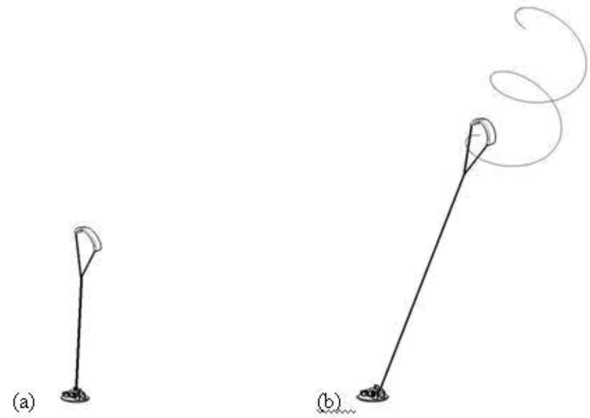

Fig.3 Pumping Laddermill concept. (a) shows the laddermill in the downgoing phase, the tension in the cable is minimized, and (b) shows the upgoing phase where the kite creates maximum cable tension by flying at high speed (crosswind power)

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 [18]

Several applications of the Laddermill system are under investigation such as a high altitude power station (up to 9000 m).

Recent studies in our group [13] showed that a two stage pumping laddermill configuration is more practical in this early stage of development and simpler 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. During the ascending phase the kites are brought in a position to provide maximum tension in the cable. Such is obtained by a combination of an increased angle of attack and a particular flight path. The latter augments the apparent wind and creates so-called crosswind power"[1].

The high cable tension is than subsequently converted into rotary motion of the drum. During this upstroke energy is produced. When all the kite line is rolled off 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 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.

Once the pumping Laddermill system is developed and experience has been obtained in control and stability, other concept will be investigated. Next to using existing kites or optimizing those for Laddermill use, another approach is also taken. Here the development starting point is the airplane [8]. The controllability airplanes is known and can easily be adapted to the kite application. The challenge for this approach is the lightweight construction and attachment to the cable, with or without bridle lines.

Simple formula's:

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 4)

For the sake of simplicity the masses of the kite and cable are ignored.

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:

$$\frac{V_a}{\sin\beta} = \frac{V_t}{\sin\varphi} = \frac{V_k}{\sin\gamma} \qquad (1)$$

Where

$\varphi = \beta + \gamma$

$\tan\varphi = \frac{c_l}{c_d}$ (=the lift over drag of the kite system)

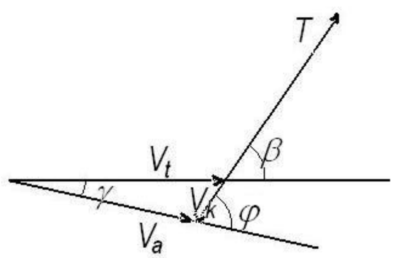

Figure 4, force vectors of an upgoing kite, showing apparent wind and related

The aerodynamic forces of the kite system with total surface S will be given as:

$q = \frac{1}{2}\rho \cdot (V_a)^2$

$L = q \cdot c_l \cdot S$

$D = q \cdot c_d \cdot S$

$T = \sqrt{L^2 + D^2}$

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

$$P = T \cdot V_k \qquad (2)$$

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

$$P \sim V_a^2 \cdot V_k \qquad (3)$$

Using (1) and (3) and the condition for maximum power is:

$$\frac{d(\sin\beta)^2\sin\gamma}{d\beta}=0 \qquad (4)$$

Or,

$$2\cos\beta\sin\gamma-\sin\beta\cos\gamma=0$$

With some rewriting the result is:

$$3\sin(2\beta-\varphi)-\sin\varphi=0 \qquad (5)$$

(5) shows 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:

$$\boxed{\beta=\tfrac{1}{2}\varphi+\tfrac{1}{2}\arcsin(\frac{\sin\varphi}{3})} \qquad (6)$$

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

Laddermill Sailing

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 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 make maneuvers perpendicular to the wind to increase the apparent wind speed. Both effects increase the maximum forces that are available for ship propulsion compared to classical sailing technique. The heel caused by the wind force be generally less for kites because the cable attachment and thus center of effort will be lower than is the case when the force is due to a traditional sail. The vertical component of the kite pulling force can also assist in lowering the heel by moving the attachment point to lee. In addition to the mentioned advantages, can the Laddermill on a ship continue its electrical power production while the ship is stationary, i.e. being anchored.

The intriguing result of the Laddermill propulsion is that this type of ship propulsion drives ship on wind energy more or less independent of the wind direction. The relationship between the performance of Laddermill sailing and the overall efficiency is developed below.

Using the vectors of figure 2 one can write (we do not consider the side force)[1]:

$$D_s \cdot V_s = \eta \cdot T \cdot V_k - \cos\theta \cos\beta \cdot T \cdot V_s \qquad (7)$$

Where
D_s is the drag of the ship
V_s is the ship speed
η is the overall system efficiency
θ is the relative wind angle to the ship speed direction (in horizontal plane)

The overall system efficiency η is defined as the ratio of net ship propulsion in thrust times speed and the net kite power in cable tension multiplied by the 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, see figure 5.

From figure 5 is becomes clear that the ship speed in the upwind directions will strongly depend on the overall system efficiency.

[1] Side force is normally compensated by a keel, which acts like a wing in the water. The lift created will induce resistance. As the ship speed is normally higher at intermediate wind angles, this extra resistance is compensated.

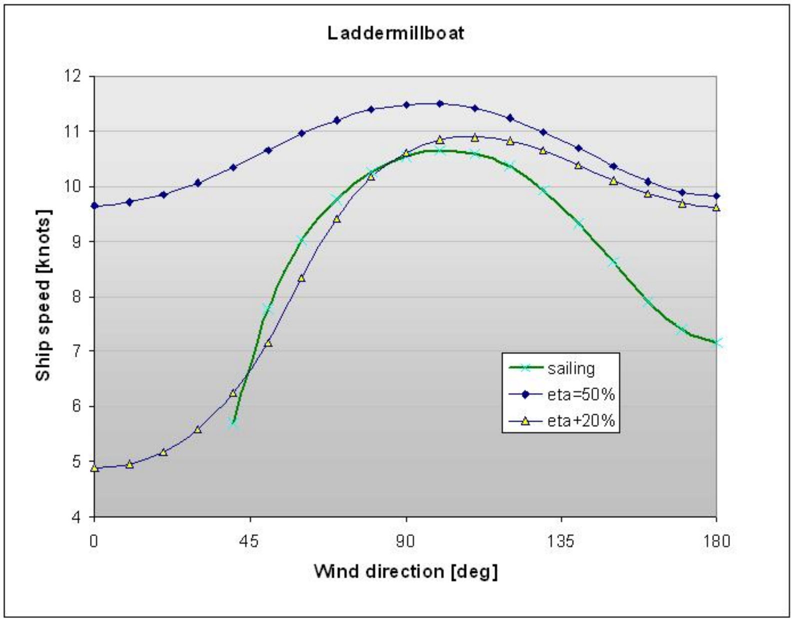

Fig.5 Ship speed as function of true wind angle for a traditional sailing ship (green) and for Laddermill sailing.. For the latter case ship speed is more or less independent of wind direction when the efficiency reaches 50%.

Intriguingly one notices that for η 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.

Next we will derive a 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 independent of the ship characteristics.

For the upwind direction we have according (7):

$$D_s \cdot V_s = \eta \cdot T^- \cdot V^-{}_k - \cos\beta^- \cdot T^- \cdot V_s \qquad \text{(8a)}$$

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

$$D_s \cdot V_s = \eta \cdot T^+ \cdot V_k^+ + \cos\beta^+ \cdot T^+ \cdot V_s \qquad \text{(8b)}$$

The $T^{\pm}, V^{\pm}, \beta^{\pm}$ indicate that these parameters differ for the upwind and downwind direction.

To derive the expression for $\beta^{\pm}$ for the Laddermill-sailing case one needs to optimize $\eta \cdot T^- \cdot V^-{}_k - \cos\beta^- \cdot T^- \cdot V_s$ for the upwind case and

$\eta \cdot T^{+} \cdot V_k^{+} + \cos\beta^{+} \cdot T^{+} \cdot V_s$ for the downwind case rather than optimizing the power $\eta \cdot T \cdot V_k$ as was done in (6).

Similarly to (5) the derivative of (7) leads to:

$$\frac{\eta}{2}(\sin\varphi - 3\sin(2\beta - \varphi)) - \cos\theta \cdot \sin\varphi \cdot \frac{V_s}{V_t} \cdot (2 - 3(\sin\beta)^2) = 0 \qquad (9)$$

The solutions of (9), i.e. β^{+} and β^{-} for $\cos\theta = \mp 1$, will be different form β_0. Some inspection of the second term in (9) will show that this difference is more for the up wind (-) case than for down wind case (+). Herethe value of β_0 is taken in (8a) and (8b) , because that allows the elimination of the ship related part (left hand side of 8a en 8b). The result would give a minimum effeciency is slightly higher than the minimum obtained by using (9).

Having said this, one can now continue and subtract (8a) and (8b) and eliminate the ships part.

We define the ratio of the ship speed and wind speed:

$$f = \frac{V_s}{V_w}$$

And thus:

$$\frac{T^{+}}{T^{-}} = \left(\frac{V_t^{+}}{V_t^{-}}\right)^2 = \left(\frac{V_w - V_s}{V_w + V_s}\right)^2 = \left(\frac{1-f}{1+f}\right)^2$$

$$\frac{V_k^{+}}{V_k^{-}} = \left(\frac{V_w - V_s}{V_w + V_s}\right) = \left(\frac{1-f}{1+f}\right)$$

Subtracting both (8a) and (8b) with $\beta^{+} = \beta^{-} = \beta_0$ now yields:

$$0 = \eta \cdot V_k^{-}\left(1 - \left(\frac{1-f}{1+f}\right)^3\right) - \cos\beta \cdot V_s\left(1 + \left(\frac{1-f}{1+f}\right)^2\right) \qquad (10)$$

The ratio V_k^{-} and V_s can be written as (using (1)):

$$\frac{V_k^{-}}{V_s} = \frac{\sin\gamma}{\sin\varphi} \cdot \frac{V_t^{-}}{V_s} = \frac{\sin\gamma}{\sin\varphi} \cdot \left(1 + \frac{1}{f}\right)$$

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

$$\eta = \frac{1+f^2}{3+f^2} \cdot \frac{\sin\varphi \sin\beta}{\sin(\varphi-\beta)} \quad (11)$$

This result (11) is independent on the type of ship and of the speed of the ship. The validity is obviously restricted to a ship speed less than the wind speed.

In the table below the results using (6) and (11) 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	0.3	0.4	0.5	0.6	0.7	0.8
1	29.3	0.78	0.80	0.84	0.88	0.92	0.97	1.03
2	40.4	0.60	0.61	0.64	0.67	0.70	0.74	0.78
3	45.0	0.51	0.53	0.55	0.58	0.61	0.64	0.68
4	47.4	0.47	0.48	0.50	0.53	0.56	0.59	0.62
5	48.9	0.44	0.46	0.48	0.50	0.53	0.55	0.58
6	49.9	0.43	0.44	0.46	0.48	0.50	0.53	0.56
7	50.6	0.41	0.43	0.44	0.47	0.49	0.52	0.55
8	51.1	0.40	0.42	0.43	0.46	0.48	0.51	0.53
9	51.5	0.40	0.41	0.43	0.45	0.47	0.50	0.52
10	51.8	0.39	0.40	0.42	0.44	0.46	0.49	0.52
11	52.1	0.39	0.40	0.42	0.44	0.46	0.48	0.51
12	52.3	0.38	0.40	0.41	0.43	0.45	0.48	0.51

Table 1, the minimum efficiencies needed for reaching up wind ship speed equal to the down wind speed ship speed for various kite quality (e.g. lift over drag ration)

From the numbers in table 1 one can conclude that a typical system efficiency of 50% (green area) 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 ships while not impairing 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 (Aeolus, European Space Agency) and weather prediction models will favor the Laddermill sailing concept.

Practical demonstrations:

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 sea 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.

References

1. Loyd, M.L., 1980, “Crosswind Kite Power”, Journal of Energy, vol. 4, No. 3, pp 106-111.
2. Laddermill Patent Ned. 1004508. Nov. 1996
3. Meijaard J.P., Ockels W.J., Schwab A.L. Modelling of the Dynamic Behaviour of a Laddermill, A Novel Concept to Exploit Wind Energy // Proceedings of the Third International Symposium on Cable Dynamics, 1999, pp. 229-234
4. Delhaes G.M.J., Meijers P., Meijaard J.P., Ockels W.J., van Woerkom P.T.L.M. O-Mill: Study of the behaviour of a Laddermill. Report LTM-1220. Delft, Netherlands: TU Delft, 1999
5. Delhaes G.M.J., Meijers P., Meijaard J.P., Ockels W.J., van Woerkom P.T.L.M. O-Mill: Manual for the program OMILL3. Delft, Netherlands: TU Delft, 1999
6. Ockels W.J. Knowledge status December 1998 and baseline Laddermill test model functional requirements. Technical note TN-O-mill 99/01, ESA: ESTEC, 1999
7. Ockels W.J. Laddermill, a novel concept to exploit the energy in the airspace // Aircraft Design, 2001, No. 4, pp. 81-97
8. Ockels W. J., Gool H. J. van , Laddermill, a novel concept to exploit the engergy in the airspace, European Wind Energy Conference, Nice, 1-5 March, 1999
9. Ockels W.J., Lansdorp B., Breukels J.; The Laddermill Development, Proceedings of the European Wind Energy Conference 2004, London-UK.
10. Lansdorp B., Ockels W.J., Remmes B.; Design and testing of a remotely controlled surfkite for the Laddermill, World Wind Energy Conference 2005, Melbourne, Australia.
11. Lansdorp B., Ockels W.J. Design of a 100 MW Laddermill // Electronic Proceedings of 7th World Congress on Recovery, Recycling and Re-integration, 2005
12. Williams P., Sgarioto D., Trivailo P. Motion Planning for an Aerial-Towed Cable System // AIAA Guidance, Navigation and Control Conference, 2005, AIAA 2005-6267
13. B. Lansdorp, W.J. Ockels; Comparison of concepts for high-altitude wind energy generation with ground based generator, 2nd China International Renewable Energy Equipment & Technology Exhibition & Conference Proceedings (pp 409-417), Beijing, China 2005.
14. B. Lansdorp, W.J. Ockels; Design of a 100 MW Laddermill for wind energy generation from 5 km altitude, 7th World Congress on Recovery Recycling and Reintegration 2005, Beijing China.
15. J. Breukels, W.J. Ockels; Tethered Wing Design for the Laddermill Project, Proceedings World Wind Energy Conference 2005, Melbourne, Australia.
16. LansdorpB., Ockels W.J., Design of a 2kW Laddemill groundstation, Conference on Wind Power Asia, Beijing 2006
17. Mulder J.A., van Staveren W.H.J.J., van der Vaart J.C., de Weerdt E. Flight dynamics lecture notes. Delft: TU Delft, 2006 10. Sedov L.I. A course in continuum mechanics. Vols. 1-4. Groningen: Wolters-Noordhoff, 1971–1972
18. Breukels, J. Kitelab, internal report April 2006

Acknowledgment

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.

Appendix, the derivations in the paper (for referee ease, not for publication):

For equation (5):

$$\frac{d}{d\beta}(\sin\beta)^2\sin\gamma = 0$$

$$2\cos\beta\cdot\sin\beta\cdot\sin\gamma - \cos\gamma\cdot(\sin\beta)^2 =$$

$$\sin\beta\cdot(2\cos\beta\cdot\sin\gamma - \sin\beta\cdot\cos\gamma) =$$

$$\sin\beta\cdot(\sin(\beta+\gamma) - \sin(\beta-\gamma) - 1/2(\sin(\beta+\gamma)+\sin(\beta-\gamma))) =$$

$$1/2\sin\beta\cdot(\sin(\varphi) - 3\sin(2\beta-\varphi))$$

For equation (9):

To maximize $D_s\cdot V_s = \eta\cdot T\cdot V_k - \cos\theta\cos\beta\cdot T\cdot V_s$

$$T = K\cdot V_a^2$$

$$V_a = \frac{\sin\beta}{\sin\varphi}\cdot V_t$$

$$V_k = \frac{\sin\gamma}{\sin\varphi}\cdot V_t$$

$$D_s\cdot V_s = \eta\cdot T\cdot V_k - \cos\theta\cos\beta\cdot T\cdot V_s$$

$$D_s\cdot V_s = \eta\cdot K\cdot\frac{\sin^2\beta}{\sin^2\varphi}\cdot V_t^2\cdot\frac{\sin\gamma}{\sin\varphi}V_t - \cos\theta\cdot\cos\beta\cdot K\cdot\frac{\sin^2\beta}{\sin^2\varphi}\cdot V_t^2\cdot V_s$$

$$\frac{d}{d\beta}(\eta\cdot\sin^2\beta\cdot\frac{\sin\gamma}{\sin\varphi}\cdot V_t - \cos\theta\cdot\cos\beta\cdot\sin^2\beta\cdot V_s) = 0$$

$$\frac{d}{d\beta}\cos\beta\cdot(\sin\beta)^2 =$$

$$-(\sin\beta)^3 + 2(\cos\beta)^2\sin\beta =$$

$$-(\sin\beta)^3 + 2\sin\beta - 2(\sin\beta)^2\sin\beta =$$

$$\sin\beta\cdot(2 - 3(\sin\beta)^2)$$

And from above the derivation of (5):

$$\frac{\eta}{2}\cdot\sin\beta\cdot(\sin\varphi-3\sin(2\beta-\varphi))-\cos\theta\cdot\sin\varphi\cdot\frac{V_s}{V_t}\cdot\sin\beta\cdot(2-3(\sin\beta)^2)=0$$

For equation (10):

$$0=\eta\cdot V_k^{-}(1-\left(\frac{1-f}{1+f}\right)^3)-\cos\beta\cdot V_s(1+\left(\frac{1-f}{1+f}\right)^2)$$

$$\frac{V_k^{-}}{V_s}=\frac{\sin\gamma}{\sin\varphi}\cdot\frac{V_t^{-}}{V_s}=\frac{\sin\gamma}{\sin\varphi}\cdot\frac{(1+f)}{f}$$

$$0=\eta\cdot\frac{\sin\gamma}{\sin\varphi}\cdot\frac{(1+f)}{f}\cdot(1-\left(\frac{1-f}{1+f}\right)^3)-\cos\beta\cdot(1+\left(\frac{1-f}{1+f}\right)^2)$$

$$0=\eta\cdot\frac{\sin\gamma}{\sin\varphi}\cdot\frac{((1+f)^3-(1-f)^3)}{f}-\cos\beta\cdot((1+f)^2+(1-f)^2)$$

$$0=\eta\cdot\frac{\sin\gamma}{\sin\varphi}\cdot\frac{(6f-2f^3)}{f}-\cos\beta\cdot(2+2f^2)$$

$$\eta=\frac{\cos\beta\cdot\sin\varphi\cdot(1+f^2)}{\sin(\varphi-\beta)\cdot(3+f^2)}$$