Fluid-Dynamic of the VINDSKIP^{TM}
v1.1

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Hamburg, 2016

Contents

1 Introduction

VINDSKIP^{TM} is a project of the norwegian engineer Terje Lade, who proposed a ships hull in the shape of a symmetrical airfoil that should exploit aerodynamic effects of a headwind component to augment the vessels propulsion system. Therefore allowing the vessel to save fuel even while sailing against the wind. He describes it as follows: *"A vessel with a hull shaped like a symmetrical airfoil going in the relative wind, will generate an aerodynamic lift giving a pull in the ships direction, within an angular sector of the course. This is Vindskip's Wind Power System. With an LNG propulsion system in addition, starting the ship from zero up to the desired speed, the aerodynamic lift now generated can be exploited to generate pull and thus saving fuel: Forming a dynamic system that maintains a constant speed of the ship."*[1]. In combination with weather routing Lade exspects huge fuel savings.

The question is: Does the ship really move ahead? The intention of this document is to answer this question by calculating the aerodynamic and hydrodynamic forces and speeds of a simplified model of the VINDSKIP^{TM}. This model uses one symmetrical airfoil (NACA0015) for the shape of the superstructure as well as for the hull of the ship below water.

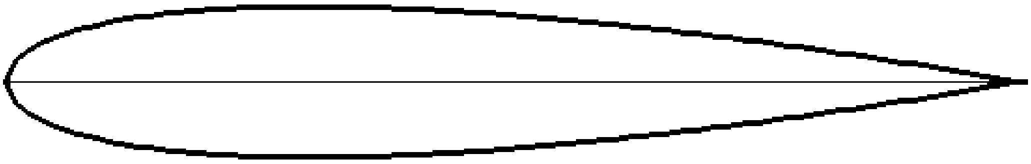

Figure 1: Symmetrical airfoil NACA0015.

This well-researched symmetrical airfoil has a thickness of 15% and no camber. The original shapes of the ship are not available due to patents belonging to Lade AS.

2 VINDSKIP^{TM} Concept and Data

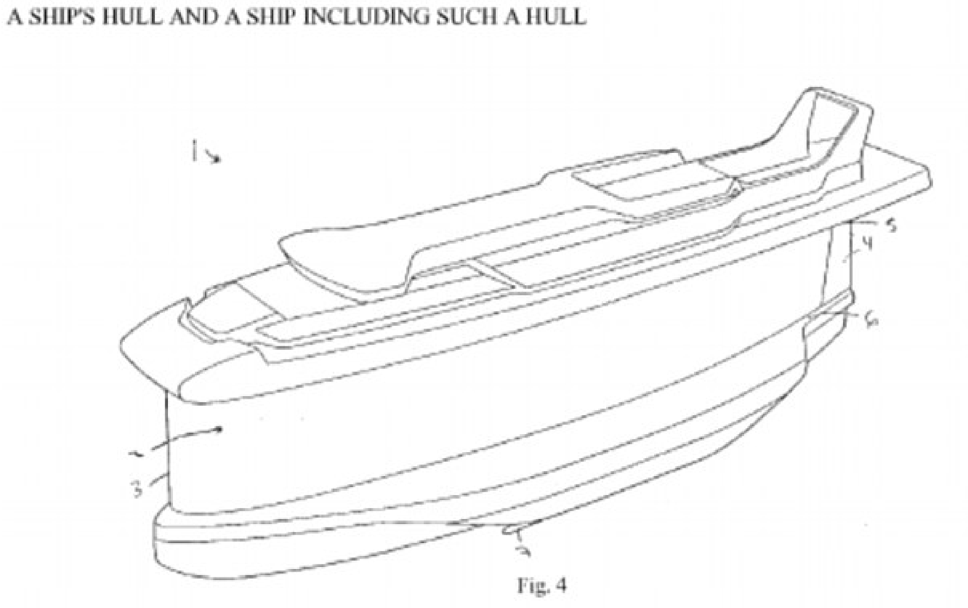

Figure 2: Concept drawing of the VINDSKIP^{TM}.

Figure 3: Computer graphic of the vessel.

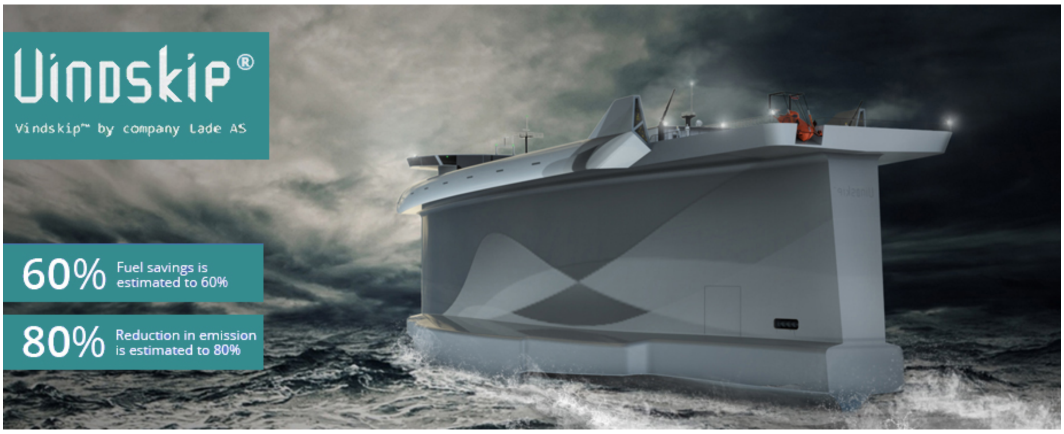

Figure 4: Proposed savings.

The proposed vessel is a kind of vertical wing with symmetrical airfoil, partly over and partly under water. We will use this simplified concept to calculate the fluid-dynamical properties.

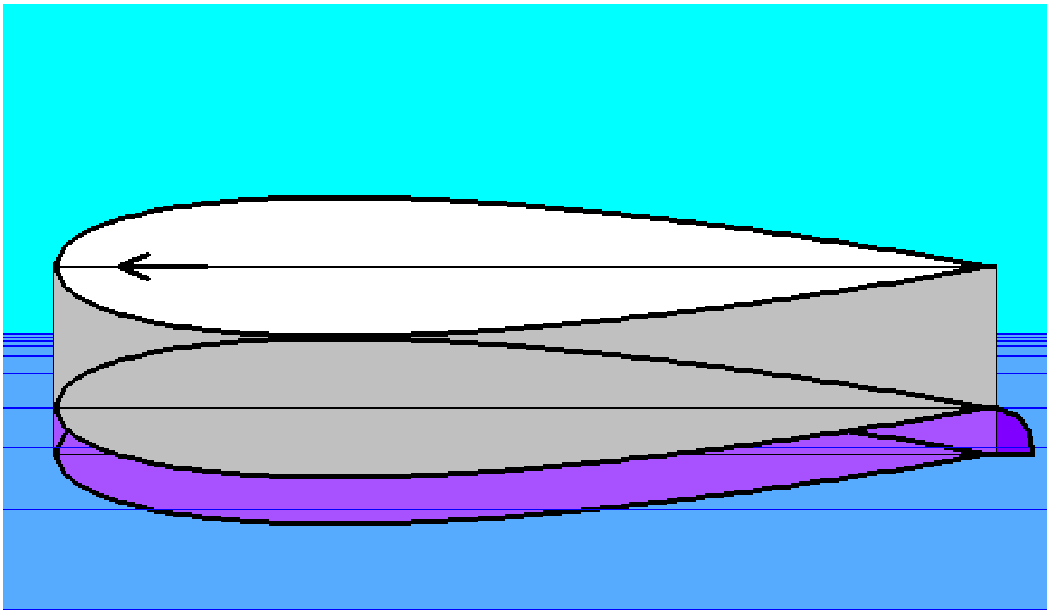

Figure 5: Simplified model, using the airfoil NACA0015.

Here, the part above the waterline is shaded in gray while the underwater-hull is colored magenta. Note the hydrodynamic rudder.

For the dimensions of the model, we will utilize the data of the comparable car-carrier "MAERSK WIND".

Figure 6: Car-carrier "MAERSK WIND".

From the data of this ship we derive the following values for our model:

`VINDSKIP`

`Length`	`L 200 m`
`Breadth`	`B 30 m`
`Height`	`H 30 m`
`Draft`	`T 10`
`Grossweight`	`W 20000 t`
`Side-Area air`	Aa 6000 $\mathtt{m}^2$
`Side-Area water`	Aw 2000 $\mathtt{m}^2$

The "thickness" of the hull is $\frac{30\,m}{200\,m} = 0.15 = 15\%$, fitting well the parameters of our chosen airfoil.

3 Fluid-Dynamic of the VINDSKIP^{TM}

To guess the behavior of the VINDSKIP^{TM} correctly, we have to calculate the Reynold numbers (Re) for the expected velocities of the air and the water.

There are two formulas for the Reynold number:

$$Re = L \cdot \varrho \cdot \frac{v}{\eta}$$

or

$$Re = L \cdot \frac{v}{\nu}$$

where L is the characteristic length, in our case the ship length $L = 200\,m$. ϱ is the density of the fluid, η is the dynamic viscosity, $\nu = \frac{\eta}{\varrho}$ is the kinematic viscosity, and v is the speed of the fluid.

We have to chose the proper values at mean sea level and for usual temperatures. The according values for freshwater are:

$$\varrho_W = 1000 \, \frac{kg}{m^3}$$

$$\eta_W = 1000 \cdot 10^{-6} \, \frac{kg}{ms}$$

$$\nu_W = 1.0 \cdot 10^{-6} \, \frac{m^2}{s}$$

$$v_W = 2 \, kt = 1.03 \frac{m}{s}$$

The values for air are:

$$\varrho_A = 1.25 \, \frac{kg}{m^3}$$

$$\eta_A = 17.5 \cdot 10^{-6} \, \frac{kg}{ms}$$

$$\nu_A = 14.0 \cdot 10^{-6} \, \frac{m^2}{s}$$

$$v_A = 23 \, kt = 11.83 \frac{m}{s}$$

We do not expect great velocities through the water even at wind speeds up to Bft 6.

The Reynold numbers calculated with this values are:

$$Re_W = 206 \cdot 10^6$$

$$Re_A = 169 \cdot 10^6$$

Therefore, in the case of both fluids, water and air, the Reynold number is about 200 Million.

3.1 Fluid-Dynamic Properties of a Symmetric Airfoil

The fluid-dynamic properties of a symmetric airfoil like NACA0015 are well known and are summarized in the lift- and drag-coefficients, that depend on the angle of attack (AoA or α) and Re.

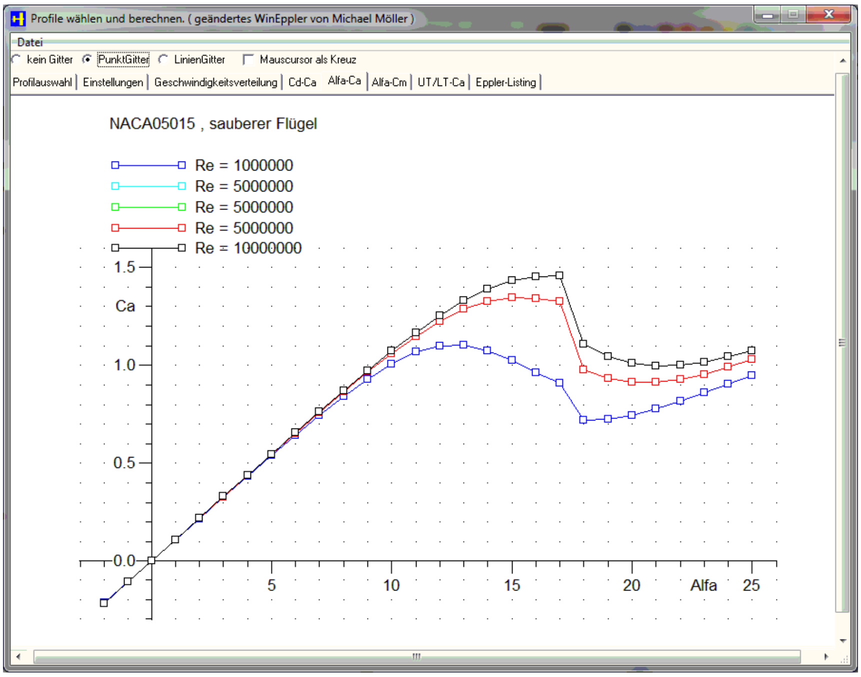

Figure 7: The Lift Coefficient ($Ca = C_L$) of the Airfoil NACA05015.

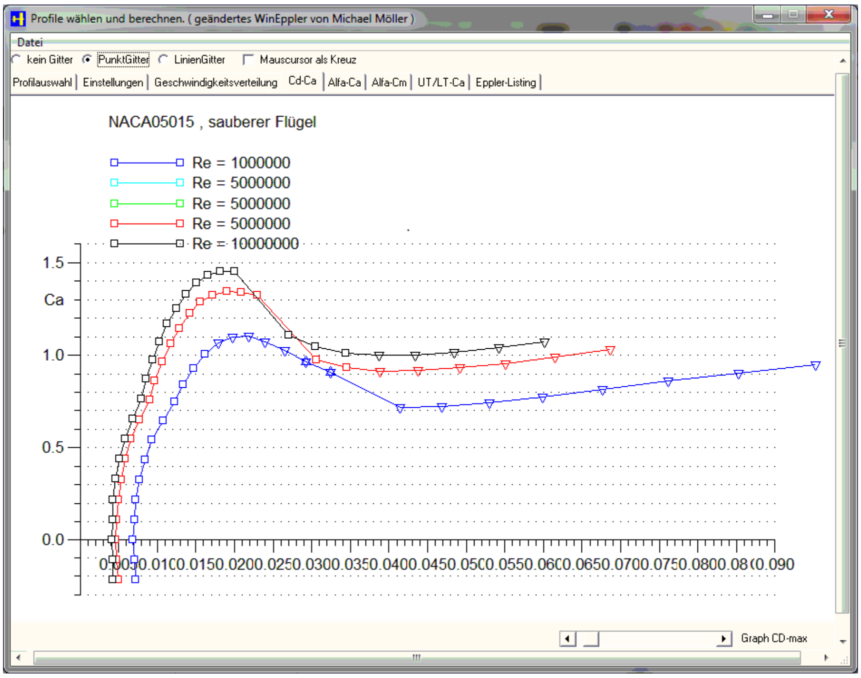

Figure 8: The Polar Curve of NACA05015: C_L vs Drag Coefficient C_D.

As we see from the above figures, the coefficients are usually not calculated for AoA's greater than 30^o [2] but we need the functions up to angles of 90^o because we want to investigate headwind angles from right ahead to abeam of the ship. Also the greatest Reynolds number provided is only $10 \cdot 10^6$ but we may be able to guess an extrapolation.

From Theory [3] we know that for an $AoA = \alpha$ up to 15^o the lift coefficient follows a linear function:

$$C_L(\alpha) = 2\pi \cdot \alpha,\ \alpha < 15^0$$

Therefore, we calculate C_L according to the above equation until $C_L(15^o) = 1.6$ for $\alpha = 15^o$. For angles greater than 15^o the flow separates from the surface of the airfoil and the lift decreases significantly only to reach another maximum. But at $\alpha = 0^o$ and $\alpha = 90^o$ the lift is zero and therefore $C_L = 0$.

The function of C_L for AoA greater than 15^o will be modelled by a sinus function with the values $C_L(0^o) = C_L(90^o) = 0$ and $C_L(45^o) = 1.6$:

$$C_L(\alpha) = 1.6 \cdot sinus(2 \cdot \alpha),\ \alpha > 15^0$$

The drag coefficient C_D is assumed to be $C_D(0^o) = 0.02$ for $\alpha = 0^o$ and $C_{D_{max}} = C_D(90^o) = 1.0$ for $\alpha = 90^o$. The function is a sigmoidal curve as given by:

$$C_D(\alpha) = \frac{1}{1 + e^{5.493 - 0.107 \cdot \alpha[^o]}} + C_D(0^o)$$

The idealized coefficient curves for a symmetric airfoil may look as follows:

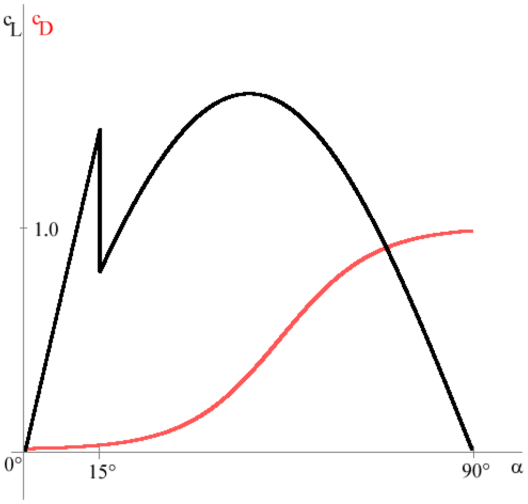

Figure 9: The idealized lift and drag coefficients for large AoA's.

Different from the common use of an airfoil where the AoA is usually kept below 15^o the wind may attack the ships hull from all angles. While the drag is working in the direction of the flow of the fluid, the lift is perpendicular to the flow direction.

Our model of the coefficients allows us to calculate easily the forces for all AoA's up to 90^o. This is sufficient because we are mainly interested in cruising under headwind conditions. Tailwind pushes the vessel foreward, regardless of its shape.

The lifting force is given by:

$$F_L = \frac{1}{2}\varrho \cdot v^2 \cdot A \cdot C_L$$

And the drag is calculated by:

$$F_D = \frac{1}{2}\varrho \cdot v^2 \cdot A \cdot C_D$$

Here, ϱ is the density, v is the speed of the fluid, and A denotes the lateral area exposed to the flow.

Lift and drag are components of the fluid-dynamic force $F_F = (F_L, F_D)$. More important for the evaluation of the movement of the ship is the distribution of the components of the fluid-dynamic force in the direction of the chord line of the airfoil (the keel direction of the ship) and the abeam direction: $F_F = (F_x, F_y)$.

The transformation is given by:

$$F_x = F_L \cdot sinus(\alpha) - F_D \cdot cosinus(\alpha)$$

$$F_y = F_L \cdot cosinus(\alpha) + F_D \cdot sinus(\alpha)$$

The figure next page shows the distribution of fluid-dynamic forces for all AoA's in relations to the keel direction.

The same calculations apply for aerodynamic as well as for hydrodynamic forces on the ships hull.

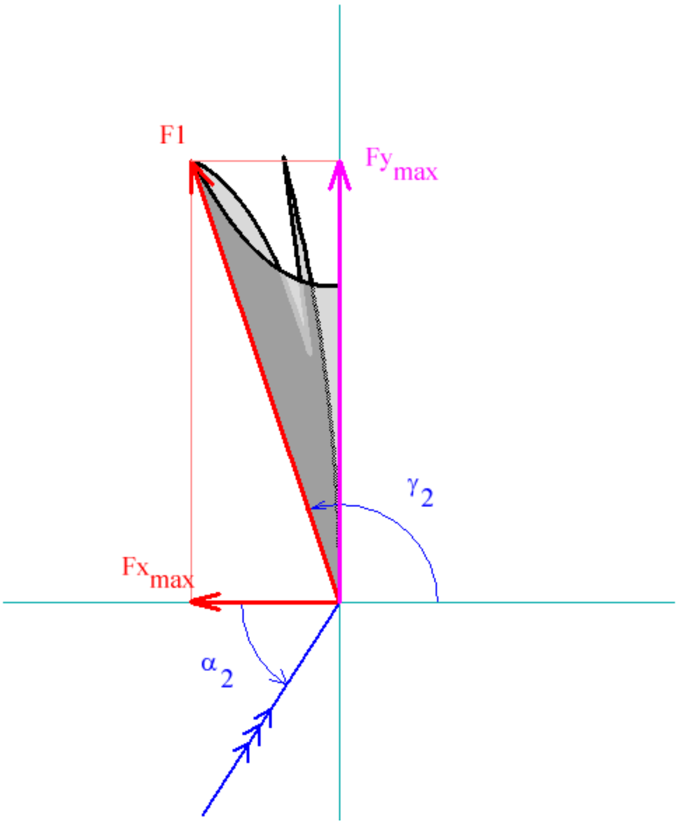

Figure 10: Aerodynamic forces on the ships hull depending on the AoA.

3.2 Aerodynamic of the VINDSKIP^{TM}

The question is now: At what $AoA = \alpha_2$ the aerodynamic force working on the surface hull of the VINDSKIP^{TM} has the greatest component $F_x = Fx_{max}$ pushing in the keel direction ahead? With a little QBasic-program all angles α were checked from 0^o to 90^o to determine the optimum.

According to the calculations for the figure above the optimum relative wind direction is given for $\alpha_2 = 50^o$. Here F_x is at its maximum and the total aerodynamic force F_1 is pushing the vessel to the leeward side under an angel of $\beta = 57^o$, which corresponds as complement to the angel $\gamma_2 = 123^o$.

Symmetric airfoils which we use here are no zero-moment airfoils. That means, that beside a translatory motion also a rotation will be observed. We neglect the rotation because every ship is equipped with a sufficient steering gear, a hydrodynamic rudder.

This can be used in our case to avoid any rotation away from the intended heading. This measure will cause a slightly higher hydrodynamic drag than without a rudder, but we neglect this also in our simplified model.

3.2.1 Example

Let us calculate the aerodynamic forces for the air flow values given in chapter 3.

We assume a constantly steered ships heading of 270^o. Further the wind direction shall provide an optimum AoA of $\alpha_2 = 50^o$ from the port side and the absolute wind direction therefore is 220^o. The wind speed is set to Bft6 or $v_A = 23\,kt = 11.83\,\frac{m}{s}$.

Our simplified formulas calculate the aerodynamic coefficients to:

$$C_{L_1} = 1.575692$$

$$C_{D_1} = 0.4841701$$

With the side area of the upper hull, the "Sail Area" $A_a = L \cdot H = 6000\,m^2$ and an air density of $\varrho_A = 1.25\,\frac{kg}{m^3}$ the lifting force is:

$$F_{L_1} = \frac{1}{2}\varrho_A \cdot v_A^2 \cdot A_a \cdot C_{L_1} = \frac{1}{2} \cdot 1.25[\frac{kg}{m^3}] \cdot 11.83^2[(\frac{m}{s})^2] \cdot 6000[m^2] \cdot 1.576 = 827.247[kN]$$

and the drag is:

$$F_{D_1} = \frac{1}{2}\varrho_A \cdot v_A^2 \cdot A_a \cdot C_{D_1} = \frac{1}{2} \cdot 1.25[\frac{kg}{m^3}] \cdot 11.83^2[(\frac{m}{s})^2] \cdot 6000[m^2] \cdot 0.484 = 254.192[kN]$$

We calculate the total aerodynamic force $F_1 = \sqrt{F_{L_1}^2 + F_{D_1}^2} = 865.420kN$. The force F_1 can be split into the component ahead $Fx_1 = 470.317\,kN$ and the component abeam $Fy_1 = 726.467\,kN$.

This force pushes the vessel under the angle $\beta = 57.08^o$ to the leeward side while the ship should maintain a heading of 270^o. So, the drift course through the water will be 327^o.

The ship will be accelerated by the aerodynamic force F_1 until a hydrodynamic F_2 working on the underwater hull counters it and the system approaches a steady state.

3.3 Hydrodynamic of the VINDSKIP^{TM}

Pushed by the wind the ship will drift with a particular speed v_W into the reative direction $\beta = 57^o$ from ahead. This speed v_W is determined by the hydrodynamic properties of the underwater hull of our vessel. Because we asume the hull to be of the same shape as the "sail", the hull above the water surface, we can use the same fluid-dynamic approach.

To find this speed v_W we used another QBasic-program to try in a simple iteration all speeds from zero upward to find the force abeam, that is, within a small limit, equal and opposite to the aerodynamic force abeam.

3.3.1 Example

In our number crunching example we found the following results:

While drifting to the starboard side the water flow hits the underwater hull from starboard ahead under an an AoA of $\alpha = \beta = 57^o$ at a speed $v_W = 1.423\,kt = 0.732\,\frac{m}{s}$ and the values $\varrho_W = 1000\,\frac{kg}{m^3}$ for freshwater and the side area $A_w = L \cdot T = 2000\,m^2$ of the underwater hull we got:

$$C_{L_2} = 1.461673$$

$$C_{D_2} = 0.6668804$$

and the hydrodynamic lift

$$F_{L_2} = \frac{1}{2}\varrho_W \cdot v_W^2 \cdot A_w \cdot C_{L_2} = \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 0.732^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot 1.462 = 783.542[kN]$$

and drag

$$F_{D_2} = \frac{1}{2}\varrho_W \cdot v_W^2 \cdot A_w \cdot C_{D_2} = \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 0.732^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot 0.667 = 357.487[kN]$$

We calculate the total aerodynamic force $F_2 = \sqrt{F_{L_2}^2 + F_{D_2}^2} = 861.241kN$. The force F_2 can be split into the component ahead $Fx_2 = 462.432\,kN$ and the component abeam $Fy_2 = -726.561\,kN$ that counters the aerodynamic force abeam $Fy_1 = 726.5\,kN$.

The force thrusting the vessel ahead is therefore $F_T = Fx_1 + Fx_2 = 470.317\,kN + 462.432\,kN = 932.7\,kN$ that is comparable to the weight of 93 metric tons.

The remaining questions are:

1. What maximum speed under sailing conditions will we get?
2. What is the drift angle in steady wind conditions?
3. Is tacking upwind possible without engine support?

3.3.2 Maximum Speed under Sailing Conditions

To guess about the final ship speed we first can calculate the theoretical maximum ("*Rumpfgeschwindigkeit*", hull speed, in German), which is the speed at the Froude-number 0.564 [4]:

$$v_R = \sqrt{\frac{g \cdot L}{2\pi}} = \sqrt{\frac{9.81[\frac{m}{s^2}] \cdot 200[m]}{2\pi}} = 17.67[\frac{m}{s}] = 34.3[kt]$$

We can take this speed as upper limit for our vessel, but it is way to much.

As a rule of thumb for sailing ships the best speed in knots corresponds to the wind force in Bft. So, our maximum speed may not exceed *6 kt*!

The next step is to utilize the same method and the same program we used to find the drift speed. This time the AoA is set to 0^o and we have to match the drag with the thrust. We get for $\alpha = 0^o$ and the values $\varrho_W = 1000\,\frac{kg}{m^3}$ for freshwater and the side area $A_w = L \cdot T = 2000\,m^2$ of the underwater hull:

$$C_{L_3} = 0.0$$

$$C_{D_3} = 0.02409861$$

The hydrodynamic lift is as expected

$$F_{L_3} = \frac{1}{2}\varrho_W \cdot v_W^2 \cdot A_w \cdot C_{L_3} = \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 6.221^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot 0.0 = 0.0[kN]$$

and the drag

$$F_{D_3} = \frac{1}{2}\varrho_W \cdot v_W^2 \cdot A_w \cdot C_{D_3} = \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 6.221^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot 0.024 = 932.755[kN]$$

at a speed $v_W = v_{ahead} = 12.093\ kt = 6.221\ \frac{m}{s}$ where the drag $F_{D3} = -932.755\ kN$ matches the thrust $F_T = 932.7\ kN$. For an experienced sailor and mariner on traditional tall sailing ships this speed of *12 kt* seems way too optimistic.

This method takes only one fluid medium, namely water, into acount. In addition the resistance of the wave system on the water surface, created by the ship while moving through the water, has to be taken into the calculation.

The dimensionless coefficient that takes the effect of the wave system into account is the Froude-number [4]. It descibes the effect of trochoidal waves for scaled models:

$$F_n = \frac{v}{\sqrt{g \cdot L}}$$

where $g = 9.81[\frac{m}{s^2}]$ is the gravitational acceleration.

We add the Froude-number to the drag coefficient and run our algorithm again. All other things unchanged, we find that for the speed $v_{ahead} = 6.1[kt]$ the Froude-number is

$$F_n = 0.071$$

and the drag is

$$F_{D_4} = \frac{1}{2}\varrho_W \cdot v_{ahead}^2 \cdot A_w \cdot (C_{D_3} + F_n) =$$

$$= \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 3.135^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot (0.024 + 0.071) =$$

$$= 932.778[kN]$$

which cancelles out the thrust $F_T = 932.7\ kN$.

3.3.3 Drift Angle and Sailing Speed

This speed ahead of *6 kt* seems plausible as maximum speed under the given wind conditions. The final speed v consists of two components: The speed ahead $v_{ahead} = 6.1[kt]$ and the drift speed $v_W = 1.4[kt]$ under an angle $\beta = 57^o$ to the leeward side.

The drift component v_W may be split into a component ahead and a component abeam:

$$v_W = (1.4[kt], 57^o) = (v_x, v_y) = |v_W| \cdot (cosinus(\beta), sinus(\beta)) = (0.8[kt], 1.2[kt])$$

So the total speed at optimum AoA is

$$v = (v_{ahead} + v_x, v_y) = (6.9[kt], 1.2[kt])$$

and

$$|v| = 7.0[kt]$$

The wind drift causes a drift angle of

$$\delta = arctan(\frac{v_y}{v_{ahead} + v_x}) = arctan(\frac{1.2[kt]}{6.9[kt]}) = 9.9^o \approx 10^o$$

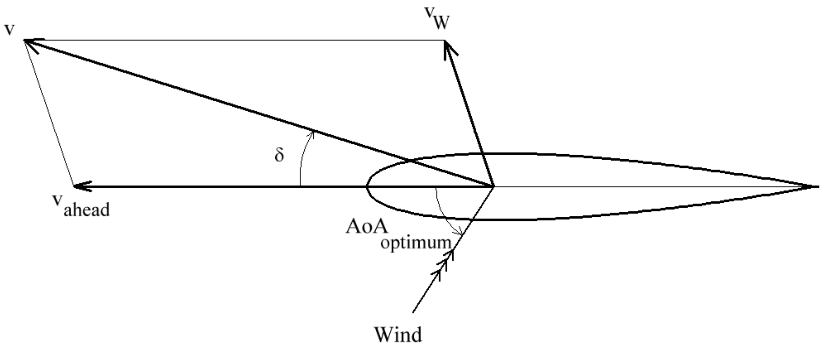

Figure 11: Speed under optimum sailing conditions. (Not to scale)

Under optimum AoA in fair wind conditions it seems to be possible to sail as high as $(AoA_{optimum} + \delta) = 50^o + 10^o = 60^o$ at the wind. Even considering the idealisations we made and the neglect of the feedback effects of the speed for the relative wind, thus changing slightly all parameters, the ship may well be able to sail all courses, if tacking is possible.

3.3.4 Example

If we take our example: While steering a heading of 270^o at a wind of Bft6 coming out of 220^o the ship will make good a course through the water of 280^o at a speed of $7[kt]$. Given unrestricted waters, this enables the ship to tack against the wind on long legs.

3.3.5 Tacking Upwind

Tacking upwind at an angle of 60^o is comparable to the abilities of traditional sailing vessels like schooners. But in confined waters like the Baltic Sea loosing headway while coming about denies the ship of effectively making good some room against the wind.

We derived the tack angle $\vartheta = \alpha + \delta = 60^o$ in our example for the optimum AoA of 50^o where the speed through the water $v = 7[kt]$ is the highest and $\delta = 10^o$. But smaller AoA's are still possible for which better tack angles might occur: While the total speed may be lower the upwind speed directly against the wind may be the same or even higher, due to the lower tack angle.

To find the best tack angle for our simplified ship model we have to iterate our calculations for all smaller AoA's to find the minimum drift angle δ or the best upwind speed. To calculate this speed we projected the total speed v through the water upon the wind direction by:

$$v_{upwind} = v \cdot cosinus(\vartheta)$$

We did this and the other calculations by means of the QBasic-program that is listed in the appendix. The result is shown here:

```
alfa[°] delta[°]  Tack[°] v[kt] vAhead[kt] UpWind[]kt
 50      9.8       59.8    7.0     6.9      3.5 ca. 4
 49      9.8       58.8    7.0     6.9      3.6 ca. 4
 48      9.8       57.8    7.0     6.9      3.7 ca. 4
 47      9.8       56.8    7.0     6.9      3.8 ca. 4
 46      9.8       55.8    7.0     6.9      3.9 ca. 4
 45      9.8       54.8    7.0     6.9      4.0 ca. 4
 44      9.9       53.9    7.0     6.9      4.1 ca. 4
 43     10.1       53.1    6.9     6.7      4.1 ca. 4
 42     10.1       52.1    6.8     6.7      4.2 ca. 4
 41     10.1       51.1    6.8     6.7      4.3 ca. 4
 40     10.2       50.2    6.8     6.7      4.4 ca. 4
 39     10.2       49.2    6.8     6.7      4.5 ca. 5
 38     10.5       48.5    6.7     6.6      4.5 ca. 5
 37     10.5       47.5    6.7     6.6      4.5 ca. 5
 36     10.7       46.7    6.6     6.5      4.5 ca. 5
 35     10.8       45.8    6.6     6.5      4.6 ca. 5
 34     10.8       44.8    6.6     6.5      4.7 ca. 5
 33     11.1       44.1    6.5     6.3      4.6 ca. 5
 32     11.3       43.3    6.3     6.2      4.6 ca. 5
 31     11.4       42.4    6.3     6.2      4.7 ca. 5
 30     11.6       41.6    6.2     6.1      4.7 ca. 5
 29     11.9       40.9    6.1     6.0      4.6 ca. 5
 28     11.9       39.9    6.1     6.0      4.7 ca. 5
 27     12.2       39.2    6.0     5.8      4.6 ca. 5
 26     12.4       38.4    5.9     5.7      4.6 ca. 5
```

25	12.7	37.7	5.7	5.6	4.5	ca. 5
24	12.9	36.9	5.6	5.5	4.5	ca. 5
23	13.2	36.2	5.5	5.3	4.4	ca. 4
22	13.4	35.4	5.4	5.2	4.4	ca. 4
21	13.7	34.7	5.3	5.1	4.3	ca. 4
20	13.9	33.9	5.1	5.0	4.3	ca. 4
19	14.5	33.5	4.9	4.8	4.1	ca. 4
18	14.7	32.7	4.8	4.6	4.0	ca. 4
17	15.3	32.3	4.6	4.4	3.9	ca. 4
16	15.4	31.4	4.4	4.3	3.8	ca. 4
15	16.5	31.5	5.7	5.5	4.9	ca. 5
14	16.9	30.9	5.5	5.3	4.7	ca. 5
13	17.6	30.6	5.2	4.9	4.4	ca. 4
12	17.9	29.9	4.9	4.7	4.3	ca. 4
11	18.7	29.7	4.6	4.3	4.0	ca. 4
10	19.4	29.4	4.2	4.0	3.7	ca. 4
9	20.2	29.2	3.9	3.7	3.4	ca. 3
8	21.6	29.6	3.5	3.2	3.0	ca. 3
7	23.3	30.3	3.1	2.8	2.6	ca. 3
6	25.4	31.4	2.6	2.4	2.2	ca. 2
5	29.2	34.2	2.1	1.8	1.7	ca. 2
4	44.7	48.7	1.4	1.0	0.9	ca. 1

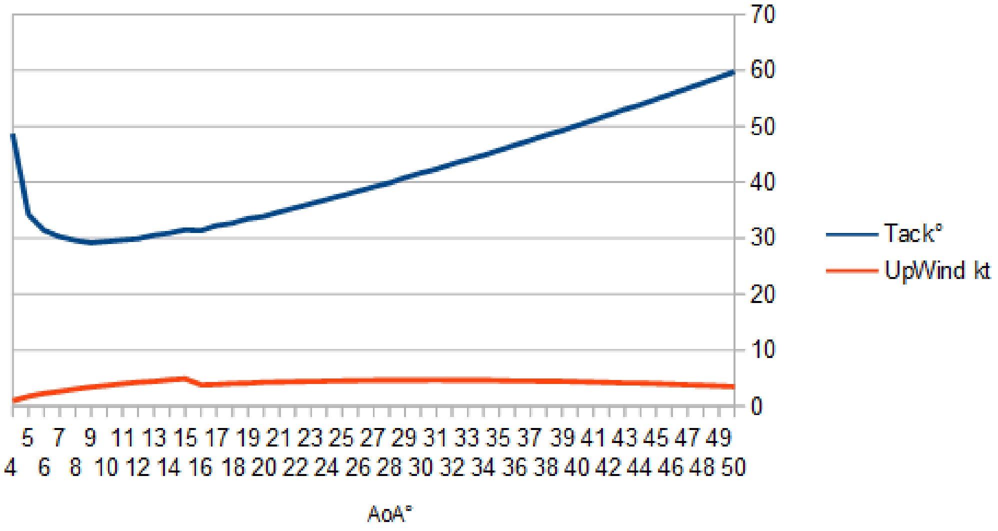

Figure 12: Tack angle and upwind speed over AoA.

The graphic display of the data reveals something surprising: The upwind speed is nearly constant about $4 - 5\ kt$ over a wide range of AoA, actually for $AoA = 10^o$ to $AoA = 50^o$!

This unexpected result means, that the ship is able to tack upwind as hard as $30 - 40^o$ at the wind and even making room with about 4 - 5 kt while the AoA is in the interval of $10^o - 30^0$ - harder pressing than any traditional sailing vessel. The performance seems best close to the $AoA = 15^o$ at wich the airfoil stalls.

The wide range of angles provides a great flexibility to navigation!

4 Summary

To study the VINDSKIP^{TM}concept, we made some simplifying assumptions:

- We expected no significant speed through the water, what seems to be false. This will change the Reynolds-number, and so the fluid-dynamical coefficients C_L, C_D to higher values. This will change the quantitative, but not the qualitative results!
- The Rudder drag was neglected. The speeds may be somewhat slower.
- The feedback effects where not taken into account, that will change to some extend the quantitative results of parameters, speeds and angles.
- The underwater hull was supposed to be of the same shape like the superstructure, the "sail". But shipbuilder's experience may create a more efficient hull, therefore improving the hydrodynamic performance.

These simplifications may change the overall efficiency of the vessel to some degree - it can be expected, a little to the worst.

Nevertheless, the proposed hull-sail seems to be as efficient as a wingsail, which is mechanically much more complicated. There will be issues like reefing or not beeing able to take away the "sail", stability at sea and problems on berthing in strong winds. But similar problems do have conventional vessels with large side areas like the car-carrier "MAERSK WIND" or passenger vessels, so this should not be a big disadvantage.

According to our research the VINDSKIP^{TM}concept should actually allow the ship at quite small wind angles to sail and tack efficiently against the wind. With optimized weather routing, compared with the route of a pure motor vessel detours may be kept small. With an auxiliary engine it should actually be able to fulfill the claims of Terje Lade to safe great amounts of fuel.

Finally, VINDSKIP^{TM} looks like being a concept worth to be studied further and to be realized in a prototype.

5 Tests with a VINDSKIP^{TM}-Model

We will perform tests with a simplified, scaled model of the VINDSKIP^{TM} and qualitatively evaluate the performance. The results will be described in a later version of this document.

(*TEST RESULTS WILL BE PUBLISHED HERE*)

6 Appendix

The following is the QBasic-program we used to perform all our herein described calculations:

```
'VINDSKIP6.BAS
'Kapt.Wolf Scheuermann 2016

CLS

OPEN "Speed.txt" FOR OUTPUT AS #1
OPEN "Speed1.txt" FOR OUTPUT AS #2
PRINT #2, "alfa           delta          Tack           v              vAhead"

PI = ATN(1) * 4
RAD = PI / 180

'Physikalische Parameter
g = 9.81'm/s^2 Erdbeschleunigung
rhoLuft = 1.25'kg/m^3
rhoWasser = 1025'kg/m^3
L = 200'm Schiffslänge
b = 30'm Breite
H = 30'm Seitenhöhe
T = 10'm Tiefgang
Lr = b'm Antriebsruder Sehnenlänge
Tr = 5'm Antriebsruder Blatt-Tiefe
W = 20000't Masse
A1 = L * H'm^2 Segelfläche
A2 = L * T'Unterwasserfläche
AR = 1 / 6.7'Segel Aspect Ratio Seitenverhältnis
cD0 = .02'Reibungswiderstandsbeiwert

'Windstärke 6
vLuft = 23! * 1852 / 3600 'm/sec Windgeschwindigkeit 23 kt -> Re 10 000 000
PRINT #1, "vLuft= 23 kt"

'Hauptschleife: prfe AoA
FOR alfa1 = 50 * RAD TO 10 * RAD STEP -1 * RAD
'alfa1 = 50 * RAD'° optimaler Windeinfallswinkel (relativer Wind)
CLS
```

```
PRINT
PRINT
PRINT
PRINT "vLuft= 23 kt ="; vLuft; "m/s"
PRINT "alfa1="; alfa1 / RAD; "°"
PRINT

’cLmax= 1.6 bei 15° AoA
’Auftriebsbeiwerte
IF alfa1 <= 15 * RAD THEN
  cL1 = 2 * PI * alfa1
ELSE
  cL1 = 1.6 * SIN(2 * alfa1)
END IF
’cWmax =1 bei 90°
’Widerstandsbeiwert
cD1 = 1 / (1 + EXP(5.493 - 6.13 * alfa1)) + cD0
PRINT "cL1="; cL1
PRINT "cD1="; cD1
PRINT "A1="; A1; "m"
PRINT

FLift1 = 1 / 2 * rhoLuft * vLuft ^ 2 * A1 * cL1’Auftrieb am Segel
FDrag1 = 1 / 2 * rhoLuft * vLuft ^ 2 * A1 * cD1’Widerstand am Segel
PRINT "FLiftAir = 1 / 2 *"; rhoLuft; " *"; vLuft; " ^ 2 *"; A1; " *";
PRINT cL1; " ="; FLift1 / 1000; "kN"
PRINT "FDragAir = 1 / 2 *"; rhoLuft; " *"; vLuft; " ^ 2 *"; A1; " *";
PRINT cD1; " ="; FDrag1 / 1000; "kN"
F1 = SQR(FLift1 ^ 2 + FDrag1 ^ 2)
PRINT "F1="; F1 / 1000; "kN"
PRINT

Fy = FLift1 * COS(alfa1) + FDrag1 * SIN(alfa1)
Fx = FLift1 * SIN(alfa1) - FDrag1 * COS(alfa1)
F1 = SQR(Fx ^ 2 + Fy ^ 2)
PRINT "Fxmax="; Fx / 1000; "kN"
PRINT "Fymax="; Fy / 1000; "kN"
PRINT
PRINT "F1="; F1 / 1000; "kN"
beta = ATN(Fy / Fx)
PRINT "beta="; beta / RAD; "°"
```

```
PRINT #1, "beta="; beta / RAD; "°"
PRINT
Fymax = Fy
Fxmax = Fx

SLEEP

'Driftgeschwindigkeit durchs Wasser bestimmen
FOR vWasser = 1 TO 10 STEP .01'.0001
  CLS

  alfa2 = beta'° Anströmung (relativ)
  PRINT "vWasser="; vWasser; "kt"
  vW = vWasser * 1852 / 3600'm/s
  PRINT "alfa2="; alfa2 / RAD; "°"
  PRINT

  'cLmax= 1.6 bei 15° AoA
  'Auftriebsbeiwerte
  IF alfa2 <= 15 * RAD THEN
    cL2 = 2 * PI * alfa2
  ELSE
    cL2 = 1.6 * SIN(2 * alfa2)
  END IF
  'cWmax =1 bei 90°
  'Widerstandsbeiwert
  cD2 = 1 / (1 + EXP(5.493 - 6.13 * alfa2)) + cD0
  PRINT "cL2="; cL2
  PRINT "cD2="; cD2
  PRINT "A2="; A2; "m²"
  PRINT

  FLift2 = 1 / 2 * rhoWasser * vW ^ 2 * A2 * cL2'Auftrieb am Rumpf
  FDrag2 = 1 / 2 * rhoWasser * vW ^ 2 * A2 * cD2'Widerstand am Rumpf
  PRINT "FLiftWasser = 1 / 2 *"; rhoWasser; " *"; vW; " ^ 2 *"; A2; " *";
  PRINT cL2; " ="; FLift2 / 1000; "kN"
  PRINT "FDragWasser = 1 / 2 *"; rhoWasser; " *"; vW; " ^ 2 *"; A2; " *";
  PRINT cD2; " ="; FDrag2 / 1000; "kN"
  F2 = SQR(FLift2 ^ 2 + FDrag2 ^ 2)
  PRINT "F2="; F2 / 1000; "kN"
  PRINT
```

```
  Fy = FLift2 * COS(alfa2) + FDrag2 * SIN(alfa2)
  Fx = FLift2 * SIN(alfa2) - FDrag2 * COS(alfa2)
  F2 = SQR(Fx ^ 2 + Fy ^ 2)
  PRINT "Fxmax="; Fx / 1000; "kN"
  PRINT "Fymax="; Fy / 1000; "kN  Ziel: "; Fymax / 1000; " kN"
  PRINT
  PRINT "F2="; F2 / 1000; "kN"

  IF Fx <> 0 THEN
    beta1 = ATN(Fy / Fx) / RAD
  END IF
  PRINT "beta1="; beta1; "°"
  PRINT

  IF Fy > Fymax THEN
    EXIT FOR
  END IF

NEXT
Fxmax = Fxmax + Fx

vDrift = vWasser
vx = vDrift * COS(beta)
vy = vDrift * SIN(beta)
PRINT "vDrift ="; vDrift; "kt"
PRINT "vx ="; vx; "kt"
PRINT "vy ="; vy; "kt"

SLEEP

'Vorausgeschwindigkeit berechnen
FOR vAhead = 1 TO 10 STEP .1 '.0001
  CLS

  alfa2 = 0 * RAD'° Anströmung (relativ)
  PRINT "vAhead="; vAhead; "kt"
  vW = vAhead * 1852 / 3600'm/s
  PRINT "alfa2="; alfa2 / RAD; "°"

  'cLmax= 1.6 bei 15° AoA
```

```
'Auftriebsbeiwerte
IF alfa2 <= 15 * RAD THEN
  cL2 = 2 * PI * alfa2
ELSE
  cL2 = 1.6 * SIN(2 * alfa2)
END IF
'cWmax =1 bei 90°
'Widerstandsbeiwert
cD2 = 1 / (1 + EXP(5.493 - 6.13 * alfa2)) + cD0
F = vW / SQR(g * L)'Froude-Zahl
cV = F '  Wellenwiderstandsbeiwert
PRINT "cL2="; cL2
PRINT "cD2="; cD2
PRINT "cV ="; cV
PRINT "A2="; A2; "m²”

FLift2 = 1 / 2 * rhoWasser * vW ^ 2 * A2 * cL2'Auftrieb am Rumpf
FDrag2 = 1 / 2 * rhoWasser * vW ^ 2 * A2 * (cD2 + cV)'Widerstand am Rumpf
PRINT "FLiftWasser = 1 / 2 *"; rhoWasser; " *"; vW; " ^ 2 *"; A2; " *";
PRINT cL2; " ="; FLift2 / 1000; "kN"
PRINT "FDragWasser = 1 / 2 *"; rhoWasser; " *"; vW; " ^ 2 *"; A2; " *";
PRINT (cD2 + cV); " ="; FDrag2 / 1000; "kN"
F2 = SQR(FLift2 ^ 2 + FDrag2 ^ 2)
PRINT "F2="; F2 / 1000; "kN"

Fy = FLift2 * COS(alfa2) + FDrag2 * SIN(alfa2)
Fx = FLift2 * SIN(alfa2) - FDrag2 * COS(alfa2)
F2 = SQR(Fx ^ 2 + Fy ^ 2)
PRINT "Fxmax="; Fx / 1000; "kN  Ziel: "; Fxmax / 1000; " kN"
PRINT "Fymax="; Fy / 1000; "kN"
PRINT "F2="; F2 / 1000; "kN"
IF Fx <> 0 THEN
  beta2 = ATN(Fy / Fx) / RAD
END IF
PRINT "beta2="; beta2; "°"
PRINT

IF Fx < -Fxmax THEN
  EXIT FOR
END IF
```

```
NEXT

PRINT "alfa1="; alfa1 / RAD; "°"
delta = ATN(vy / (vAhead + vx)) / RAD
PRINT #1, "vWasser="; vWasser; "kt"
PRINT #1, "vDrift ="; vDrift; "kt"
PRINT #1, "vx ="; vx; "kt"
PRINT #1, "vy ="; vy; "kt"
PRINT "vDrift ="; vDrift; "kt"
PRINT "vx ="; vx; "kt"
PRINT "vy ="; vy; "kt"
v = SQR((vAhead + vx) ^ 2 + vy ^ 2)
PRINT #1, "alfa1="; alfa1 / RAD; "°"
PRINT #1, "v ="; v; "kt"
PRINT #1, "beta="; beta / RAD; "°"
PRINT #1, "vAhead="; vAhead + vx; "kt"
PRINT #1, "delta ="; delta; "°"
PRINT #1, ""
PRINT "v ="; v; "kt"
PRINT "beta="; beta / RAD; "°"
PRINT "vAhead="; vAhead + vx; "kt"
PRINT "delta ="; delta; "°"
PRINT
PRINT #2, alfa1 / RAD,
PRINT #2, delta,
PRINT #2, alfa1 / RAD + delta,
PRINT #2, v,
PRINT #2, vAhead + vx

SLEEP
'EXIT FOR
NEXT
CLOSE #1
CLOSE #2

END
```

7 Literature

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