Fluid-Dynamic of the VINDSKIP™ v2.1

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Content

1 Introduction

VINDSKIP™ 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™. This model uses one symmetrical airfoil (NACA0015) for the shape of the superstructure as well as for the hull of the ship below water.

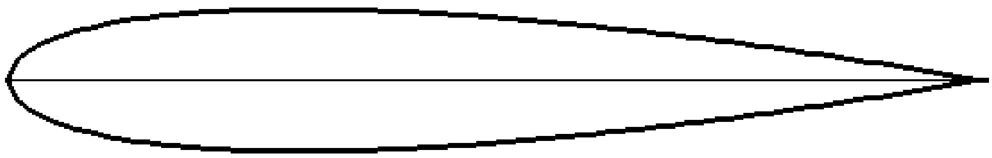


Figure 1: Symmetrical airfoil NACA0015.

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.

The previous version of this document from the year 2016 contained only the theoretical approach and calculations of this concept. Now we were able to perform some qualitative trials with a small, not-to-scale model of the VINDSKIP™. The results are shown in the final chapter.

2 VINDSKIP™ Concept and Data

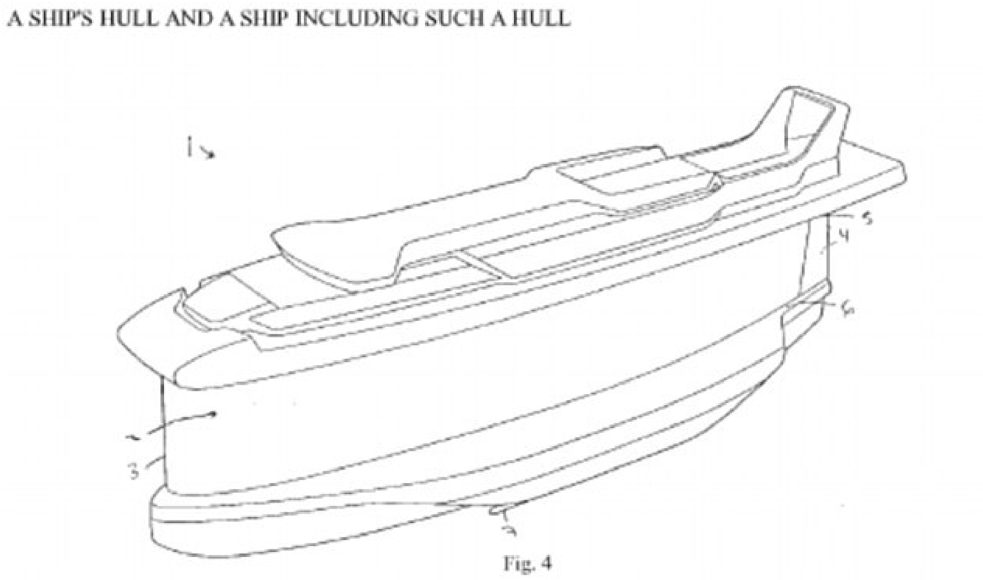


Figure 2: Concept drawing of the VINDSKIP™.

Figure 3: Computer graphic of the vessel.

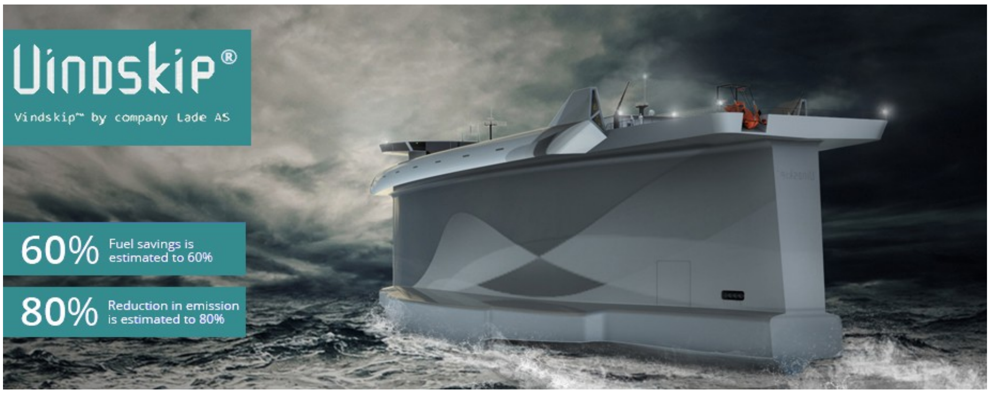


Figure 4: Proposed savings.

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.

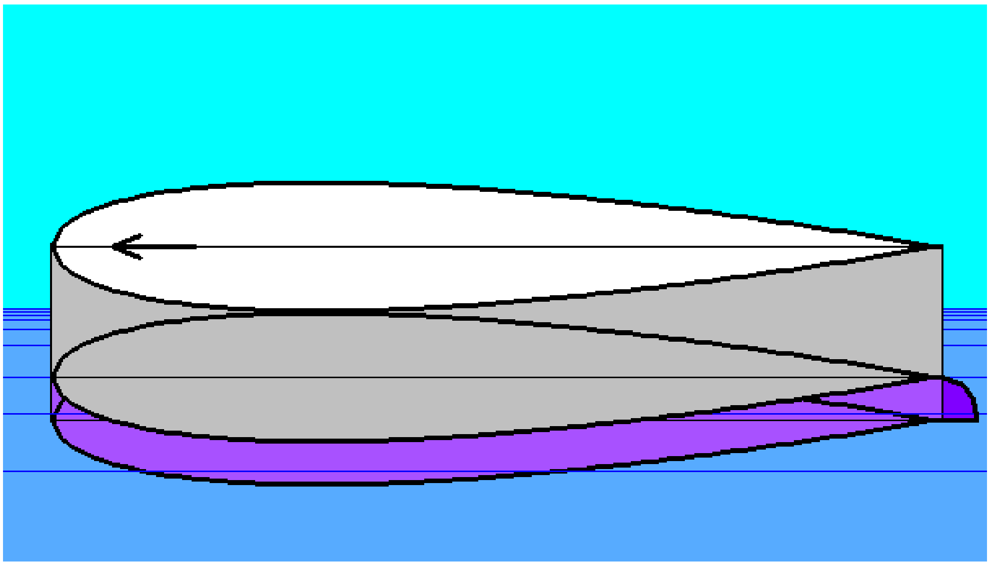


Figure 5: Simplified model, using the airfoil NACA0015.

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 m
Grossweight         W 20000 t
Side-Area air       Aa 6000 m²
Side-Area water     Aw 2000 m²
```

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

3 Fluid-Dynamic of the VINDSKIP™

To guess the behavior of the VINDSKIP™ 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:

$$\text{Re} = L \cdot \rho \cdot \frac{v}{\eta}$$

or

$$\text{Re} = L \cdot \frac{v}{\mu}$$

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, $\mu = \frac{\eta}{\rho}$ 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:

$$\rho_w = 1000 \frac{kg}{m^3}$$
$$\eta_w = 1000 \cdot 10^{-6} \frac{kg}{ms}$$
$$\mu_w = 1.0 \cdot 10^{-6} \frac{m^2}{2}$$
$$v_w = 2\text{kt} = 1.03 \frac{m}{s}$$

The values for air are:

$$\rho_A = 1.25 \frac{kg}{m^3}$$
$$\eta_A = 17.5 \cdot 10^{-6} \frac{kg}{ms}$$
$$\mu_A = 14.0 \cdot 10^{-6} \frac{m^2}{2}$$
$$v_A = 23\text{kt} = 11.83 \frac{m}{s}$$

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

The Reynold numbers calculated with these values are:

$$\text{Re}_W = 206 \cdot 10^6$$
$$\text{Re}_A = 169 \cdot 10^6$$

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.

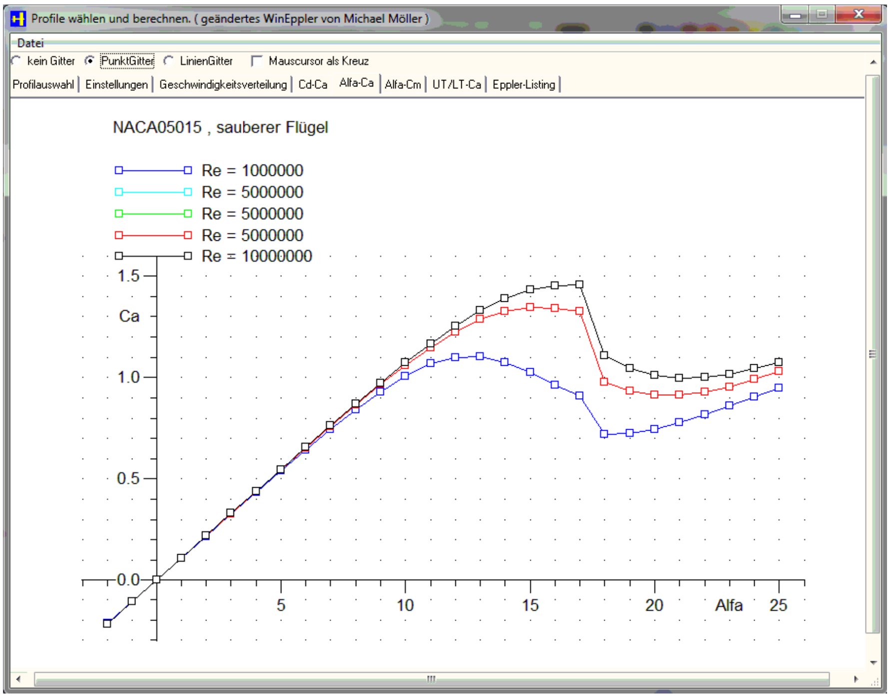


Figure 7: The Lift Coefficient (Ca = C_L) of the Airfoil NACA05015.

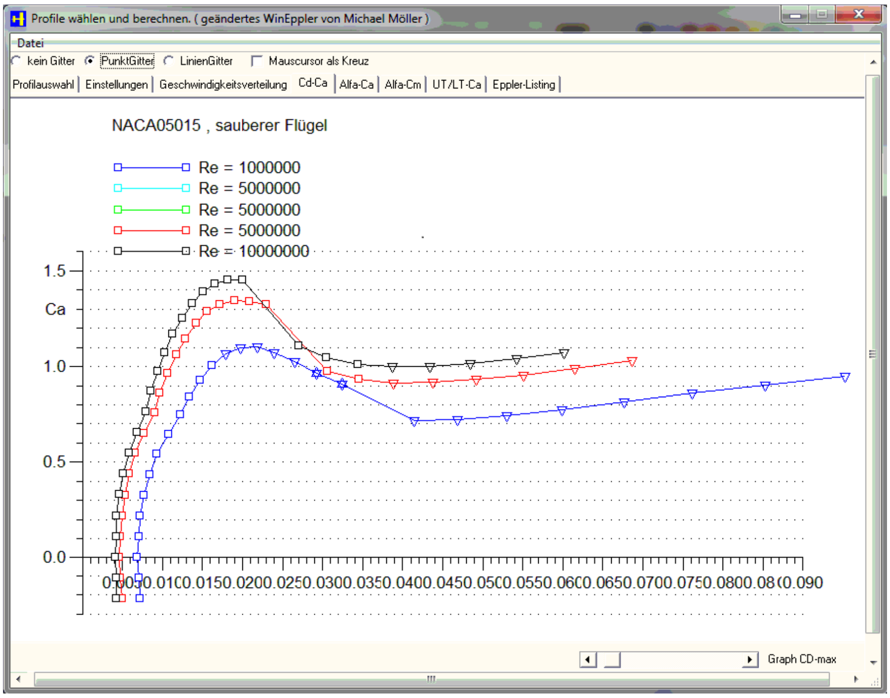


Figure 8: The Polar Curve of NACA05015: C_L vs Drag Coefficient C_D.

As we see from the above figures, the coefficients are usually not calculated for AoA's greater than 30° [2] but we need the functions up to angles of 90° 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 = up to 15° the lift coefficient follows a linear function:

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

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

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

$$C_L(\alpha) = 1.6 \cdot \text{sinus}(2 \cdot \alpha),\ \alpha > 15°$$

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

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

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

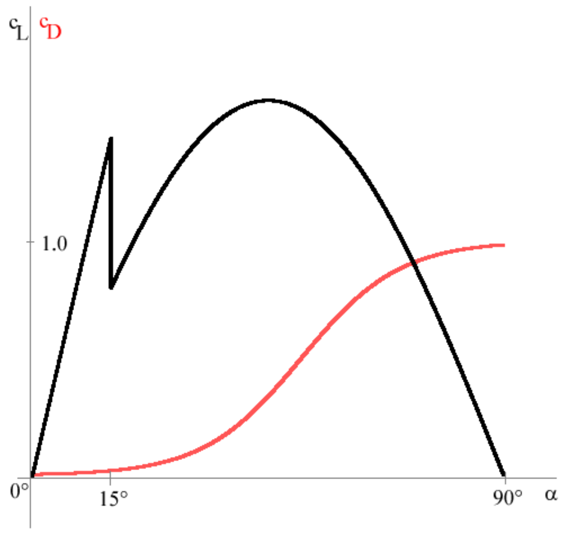


Figure 9: The idealized lift and drag coefficients for large AoA's.

Different from the common use of an airfoil where the AoA is usually kept below 15° 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°. 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:

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

And the drag is calculated by:

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

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.

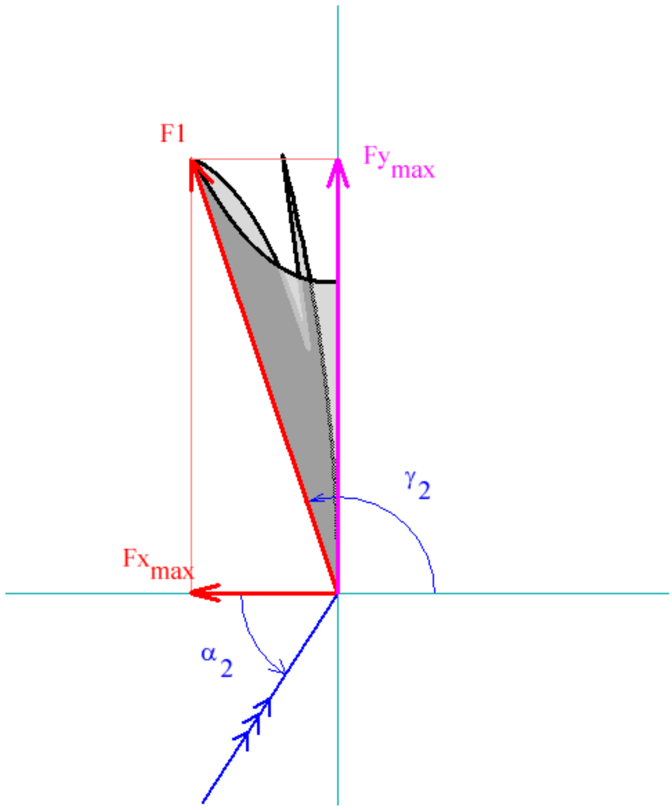


Figure 10: Aerodynamic forces on the ships hull depending on the AoA.

3.2 Aerodynamic of the VINDSKIP™

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

According to the calculations for the figure above the optimum relative wind direction is given for $\alpha_2 = 50°$. 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 $\alpha = 57°$, which corresponds as complement to the angel $\alpha_2 = 123°$.

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 simplied 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°. Furthermore, the wind direction shall provide an optimum *AoA* of α_2 = 50° from the port side and the absolute wind direction therefore is 220°. The wind speed is set to Bft 6 or v_A = 23 kt = 11.83 $\frac{m}{s}$.

Our simplified formulas calculate the aerodynamic coefficients to:

$$C_{L1} = 1.575692$$

$$C_{D1} = 0.4841701$$

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

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

and the drag is:

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

We calculate the total aerodynamic force $F_1 = \sqrt{F_{L_1}^2 + F_{D_1}^2} = 865.420 [kN]$. The force F_1 can be split into the component ahead F_{x1} = 470.317 [*kN]* and the component abeam F_{y1} = 726.467 [*kN]*.

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

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 β = 57° 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 $\alpha = \beta = 57°$ at a speed v_W = 1.423 *kt* = 0.732 $\frac{m}{s}$ and the values $\rho_W = 1000\frac{kg}{m^3}$ for freshwater and the side area $A_W = L \cdot T = 2000\,m^2$ of the underwater hull we got:

C_{L2} = 1.461673

C_{D2} = 0.6668804

and the hydrodynamic lift

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

and drag

$$F_{D_2} = \frac{1}{2} \cdot \rho_W \cdot v_W^2 \cdot A_w \cdot C_{D_2} = \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 0.732^2[(\frac{m}{s})^2] \cdot 2000[m^2] \cdot 0.667 = 487.192[kN]$$

We calculate the total aerodynamic force $F_2 = \sqrt{F_{L_2}^2 + F_{D_2}^2} = 861.241[kN]$. The force F_2 can be split into the component ahead F_{x2} = 462.432 *kN* and the component abeam F_{y2} = -726.561 *kN* that counters the aerodynamic force abeam F_{y1} = 726.5 *kN*.

The force thrusting the vessel ahead is therefore $F_T = F_{x1} + F_{x2}$ = 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° and we have to match the drag with the thrust. We get for α = 0° and the values ρ_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_{L3} = 0.0

C_{D3} = 0.02409861

The hydrodynamic lift is as expected

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

and the drag

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

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 (the energy dissipation) 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

$$F_{D_4} = \frac{1}{2} \cdot \rho_W \cdot v_W^2 \cdot A_w \cdot (C_{D_3} + F_n) =$$

$$= \frac{1}{2} \cdot 1000[\frac{kg}{m^3}] \cdot 3.135^2 [(\frac{m}{s})^2] \cdot 2000[m^2] \cdot (0.024 + 0.071) = 932.778[kN]$$

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 β = 57° to the leeward side.

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

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

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

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

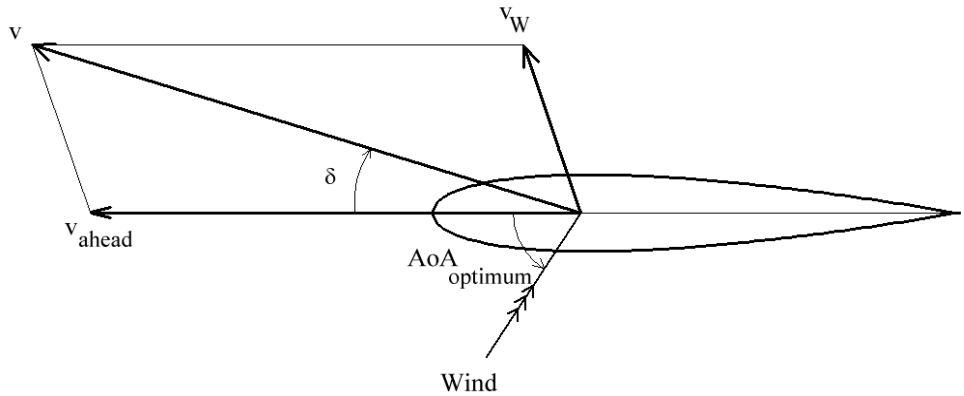


Figure 11: Speed under optimum sailing conditions. (Not to scale)

Under optimum *AoA* in fair wind conditions it seems to be possible to sail as high as ($AoA_{optimum} + \delta$) = 50° +10° = 60° 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° at a wind of Bft 6 coming out of 220° the ship will make good a course through the water of 280° 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° 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 $\vartheta = \alpha + \delta = 60°$ in our example for the optimum AoA of 50° where the speed through the water $v = 7[kt]$ is the highest and $\delta = 10°$. 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 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
alfa[°] delta[°] Tack[°] v[kt] vAhead[kt] UpWind[kt]
```

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

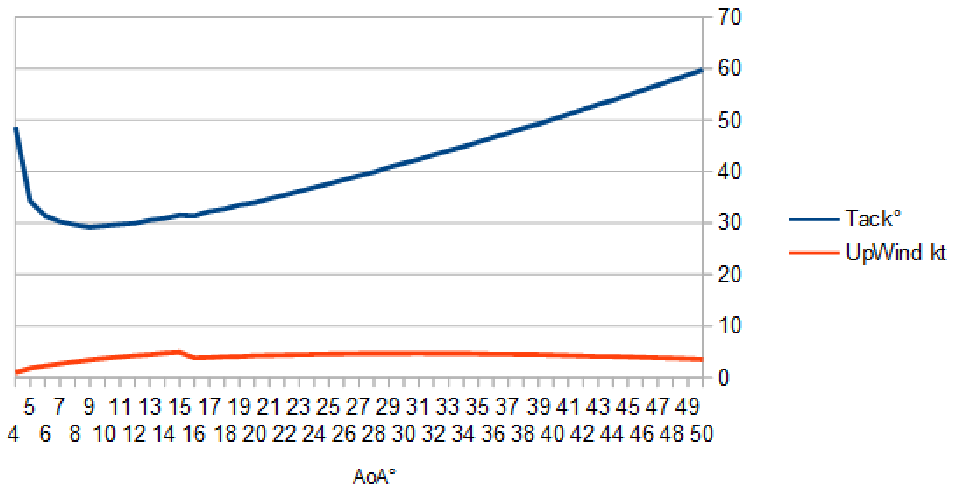


Figure 12: Tack angle (blue, [°]) and upwind speed over AoA (red, [kt]).

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° to *AoA* = 50°!

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

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

3.3.6 Example

In our example the ship is steering a heading of 270°. If we take an *AoA* of 10° at a wind direction of 260° and Bft6, we get a tack angle of about 29.4° and therefore and a course through the water of 299°. The speed made good is 4.2 [*kt*] and the upwind speed is 3.7 [*kt*]. This means, we make room in direction 260° with a speed of about 4 [*kt*].

If, alternatively, the wind comes still out of 260° and the *AoA* = 20° our heading will be 280° and the tack angle is 33.9°. So, the course through the water is 294°, the speed made good is 5.1[*kt*], and the upwind speed is 4.3[*kt*].

Given the same wind conditions, the best upwind speed of 4.7 [*kt*] is reached at an *AoA* of about 30° and a tack angle of 41.6°. Here, the heading is 290° and the speed made good is 6.2[*kt*] while the course through the water is 302°.

This demonstrates the wide tactical range for sailing decisions, where the strategic parameters don't change.

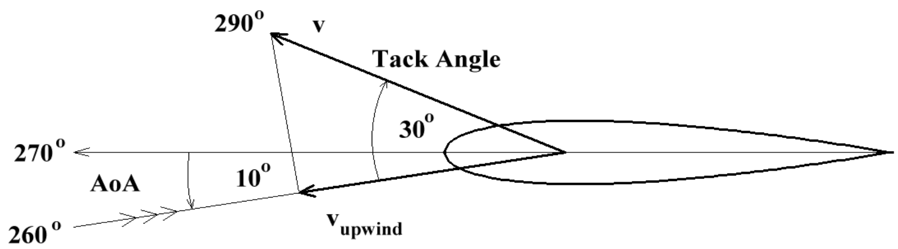


Figure 13: Tacking.

4 Summary

To study the VINDSKIP™ 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 fluiddynamical 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 demanding. 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™ 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™ looks like being a concept worth to be studied further and to be realized in a prototype.

5 Tests with a VINDSKIP™-Model

We performed crude trial runs with a simplified, small, not-to-scale model of the VINDSKIP™ and qualitatively evaluated the performance. Our testing site was a ditch beside a country road. The results are described in this version of the document.

The steerable model is made of plastic. No remote control is provided.

The size and technical data are:

```
Length ppl     46 cm
Breadth         7 cm
Design Height  20 cm
Design Draught  7 cm
Displacement    1 kg
Rudder      8 x 8 cm
Airfoil Section NACA0015
Ballast provided 2 kg Sand
```

Figure 14: Stb-Side view with midship rudder.

Figure 15: Starboard-Rudder.

Figure 16: Port-Rudder.

6 Test Results with the VINDSKIP™ Model

The test runs were performed on March 28th 2020 when good wind conditions were found in the countryside.

Steady winds out of 300° with 12 [*kt*] or 4 Bft.

Figure 17: Test canal alongside a country road.

Here the model was prepared. Due to the wind force, the overscaled height, and the low stability all the ballast sand had to be filled in. So, the real draught was double the design draught.

The rudder was fixed to port and a line was attached to retrieve the model ship in case it grounded at the far side.

The pictures on the next page show the model before and after the trials. Unfortunately it was a one-way-model. The hull developed leaks while the glue came of in the water. We had to discard it.

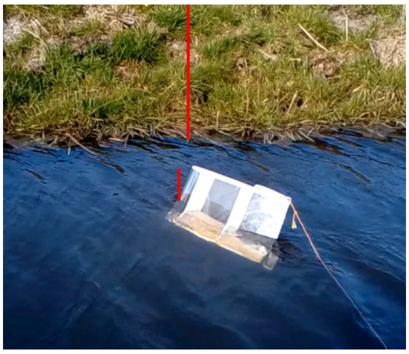
6.1 The Trials with the Model Ship

Figure 18: The model ship before the trials. Fixed-rudder to port, retrieving-line (orange) attached, ballast filled and trimmed.

Figure 19: The disintegrating model ship after the trials. The glue disolves, the hull shows leaks.

The following picture sequence reveals the slight upwind movement of the model ship. It is visible when we compare the landmark and the perpendicular. This test came with a gust (figure 5) that gave the model a final push.

1



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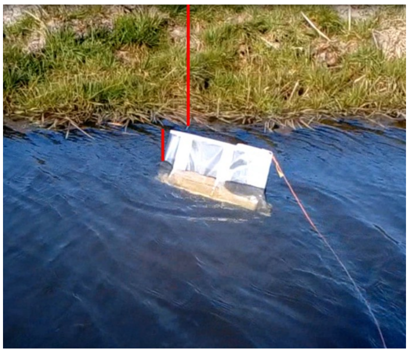

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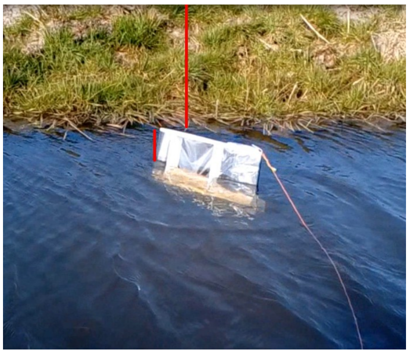

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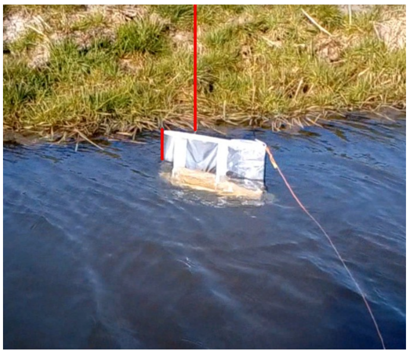

8

6.2 Conclusion

Because the model ship was in no way comparable by the Reynolds numbers with the full scale VINDSKIP™ it had an overscaled height. This caused severe instability which had to be countered by more ballast. The real draught was 14 cm while of the real height remained only 13 cm. Even than, to get better results the wind force could have been stronger.

The rudder was steerable but due to the lack of a remote control it had to be fixed before the tests. Therefore no trials with different *AoA* could be performed. The model ship fetched the proper *AoA* just by itself. In case of a remote control the rudder should have had a larger area.

In most test runs the model just traversed the canal with a drift angle and no visible upwind movement. But in stronger gusts it picked up speed and the small rudder turned it into the wind and an upwind motion occured.

We may conclude: Even this crude model ship was not just blown downwind but could, under ideal conditions, tack against the wind direction. A properly scaled model ship under controlled conditions may be doing much better. But, we see this concept confirmed!

It would be a great experience to see a full size commercial VINDSKIP™ sail.

7 Appendix

7.1 Program

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/s2 Erdbeschleunigung
rhoLuft = 1.25'kg/m^3
rhoWasser = 1025'kg/m^3
L = 200'm Schiffslaenge
b = 30'm Breite
H = 30'm Seitenhoehe
T = 10'm Tiefgang
Lr = b'm Antriebsruder Sehnenlaenge
Tr = 5'm Antriebsruder Blatt-Tiefe
W = 20000't Masse
A1 = L * H'm^2 Segelflaeche
A2 = L * T'Unterwasserflaeche
AR = 1 / 6.7'Segel Aspect Ratio Seitenverhaeltnis
cD0 = .02'Reibungswiderstandsbeiwert

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

'Hauptschleife: pruefe 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' Anstroemung (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; "m^2"
  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' Anstroemung (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; "m^2"

  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
```

7.2 Terje Lade's Answer

"Terje Lade"
An: "Wolf Scheuermann"
Datum: 30.12.2016 13:52:56

Dear Mr. Wolf Scheuermann

Further to above subject, thank you for your email with enclosure which is well received, and your interest in the Vindskip R-project.

Company Lade AS was established in 2010 to develop the Vindskip R-concept to a defined form and function and to license it through IPR to a Ship Owning company. It is holding both a national and international patent on the concept. A Ship Owning company is now being established, company Vindskip AS and we are now looking for opportunities to finance the project.

Extensive tests have been carried out since 2010, both in wind tunnel and CFD testing, also tests in model tank is completed. A CFD optimization study has been conducted over a period of almost one year regarding the aerodynamic performance and the balance between the aerodynamic forces and the hydrodynamic forces. Amongst other optimize the balance and thus to minimize the use of rudder and the production of drag forces.

Studies has also been carried out onboard a sailing reference ship.

Thus I believe that few ships project, if any, have undergone such extensive tests.

To realize a project like the Vindskip R-project, we need that all the good forces are working together in a team. We therefore thank you for your contribution.

I wish you a Happy New Year.

Best regards

Terje Lade
Manager Lade AS

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