A contribution to the discussion on speed sailing based on the mechanics of windsurfing.

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Sailing performance

In order to calculate the performance of a sailboat, a windsurfing board or a kite we have to look at the acting forces and moments and find the conditions where all forces and moments are in equilibrium (Newton's law). This condition is a so-called steady state of the system which allows us to identify the speed. Because the sail of a windsurfing board is connected to the board via a universal joint and the heeling moment is balanced by the weight of the sailor no heeling and pitching moments are transferred to the board as it is evident with sailboats and yachts.
So all the problems of the close coupling between sail and hull of a sailboat with heeling and pitch pointing do not exist and all the forces and moments can be calculated nearly independently for the sail and the board with the sailing speed as an independent variable. For the calculation, only the maximal sail force, the wind speed, and the course as well as the sail and fin lift/drag polar data has to be set.

Forces

The basics in aerodynamics and hydrodynamics allow us to calculate the acting forces and moments under wind conditions which are well known by theory and practical research on sailboats and yachts since long years.
Looking on a windsurfing system we have the aerodynamic sail force producing a heeling moment which is balanced by the sailors' weight (fig. 1). Because there is a negative heeling angle when the sailor leaning out with the sail some vertical lift \((F_v)\) is provided which reduces the total weight.

![Equilibrium of moments and forces](image)

**Figure 1:** Maximum sail force due to heeling moment compensation by sailor's weight

The heeling moment equation defines the maximum sail force which can be provided by the weight of the sailor and his distance from the board. Under typical dimensions of the distances, the maximal sail force is about 40% of the body weight. This force is absolutely limited under any wind, speed, sail size and course conditions. Because the mast is connected to the board by a universal joint there are no heeling moments transferred to the board. All forces are transferred via the mast and the sailors' feet to the board.

The total sail force could be divided into a component which is directed into the sailing direction (course), which is the driving force or **thrust** of the sail. In the thrust component lift and drag forces of the sail are considered. Low sail drag would turn the total sail force in direction of the course and would provide more thrust. Further, in a force component perpendicular to the sailing direction, the **side force** which must be balanced by the fin. The amount of the thrust and side force are only a function of the apparent wind angle which depends on the ratio of the sailing speed relative to the wind speed. Therefore, the apparent wind angle, the thrust, and the side force are not constant but vary with the sailing speed.

On the other hand, we have the hydrodynamic drag force of the board and the fin which solely depend on the board speed and which are in opposite to the thrust. When both forces are equal the maximal speed is reached, **fig. 2, fig. 3.** To get high speeds the thrust should be as high as possible and the board drag as low as possible.
Figure 2: Forces on a windsurfing board, side view

Figure 3: Aero- and hydrodynamic forces and angle definitions on a windsurfing board, top view, all forces in the horizontal plane, all moments $= 0$. 
Sail force limitations

Due to body weight

As mentioned above the maximal sail force is limited to about 40% of the body weight of the sailor. For maximal speed calculation, this sail force is used as a constant value versus the speed as an independent variable. This approach represents actual conditions where the sailor is controlling the angle of attack of his sail by shifting his weight as far as possible to get maximal sail force and speed. Weight shifting is like a throttle to provide the different amount of thrust and therefore speed.

Due to apparent wind angle

When sailing at a specific course and a specific amount of wind it is well known that the apparent wind angle will be reduced with increasing sailing speed, fig. 4.

![Apparent wind angle vs speed and wind speed, course 140 deg](image)

The apparent wind angle is a function of the speed (Vs) to the wind (Vt) ratio. The stronger the wind the larger the apparent wind angle and the larger the thrust. But the thrust reduction with speed at a constant sail force is an inevitable physical effect which could not be changed and which is valid for all vessels moving under wind conditions on the water, land, snow or ice. Therefore, to go fast the apparent wind angle must be as great as possible to produce more thrust which means that stronger wind is needed to get higher speeds.
Aerodynamic sail forces

The relevant sail forces for the horizontal and lateral movement of the board as a function of speed (apparent wind angle) are the thrust- and side forces versus speed for a constant sail force as shown in fig. 5. The thrust reduces with speed whilst the side force increases with speed.

![Figure 5: Thrust and side force relative to the total horizontal sail force vs speed, Wind 20 kts, Course 120 deg.](image)

Hydrodynamic drag of the board

Planing has a drag characteristic where the drag is nearly constant versus speed. Planing drag is at first directly proportional to the total weight of the windsurf gear and the angle of attack of the board independent of speed and wetted area. Secondly, we have to add some friction- and spray-drag proportional to the square of sailing speed. Due to the fact that with increasing speed the board is lifted the wetted surface area is automatically reduced in such a way that just the total weight is balanced. By this, the minimum drag is automatically provided at any time.

The maximal speed is reached when the sail thrust and the drag of the board are equal. This is given at the crossing point of both curves as shown in fig. 6. The figure makes it evident that higher speeds are possible when the thrust (thrust force includes the aerodynamic drag of the sail) is increased (curve shifted upwards) and or the drag is reduced (drag curve shifted downwards). The difference between the thrust force and the drag force divided by the mass of the gear represents the acceleration which is naturally zero when the steady speed condition is reached. Further, it is shown that at about 66 kts the thrust became zero. This would be the possible speed with zero drag of the board.
As a result, the sailing speed is defined by

1. the total sail force limitation due to sailor's weight (heeling balance),
2. the apparent wind angle (a function of sailing speed/wind speed), which reduces the thrust with increasing speed,
3. the course angle (more thrust at higher angles),
4. the drag of the board and fin and
5. the water surface conditions.

All aerodynamic drag components of the sail and sailor are part of the total sail force. The drag influences the angle of the total sail force to the course. More aerodynamical drag reduces the possible thrust.

It is very important to sail a higher downwind course when sailing in higher wind conditions as shown in fig. 7. The optimal course depends what the final ratio Vs/Vt will be. For Vs/Vt of 2 it is the well known 120 degrees. But when higher wind is needed due to the board drag the optimal course will change from 120 deg up to to 150 deg between 20 and 50 kts of wind.

All this could be calculated relatively easily and it comes out that the present world record of about 52 kts is just what we can get under consideration of typical sailor weight, sail size, fin size and wind conditions.

Fig. 8 shows the calculation of how fast we can go (Vs) at a course of 140 deg. downwind as a function of wind speed (Vt).
Also, if there are some uncertainties due to estimated data but the tendencies or relations are valid and allow us to draw the right conclusions.

Figure 7: Optimal course for maximal speed as a function of the $Vs/Vt$-ratio

Figure 8: Maximal sailing speed as a function wind speed at a course of 140 deg.
It turns out that the speed relative to the wind speed could be a factor of 2 at low speeds but nears 1 at over 50 kts. That means to go really faster much more wind force is needed. The gradient becomes very flat so that there is no much speed to gain.

Due to equilibrium requirement of thrust and drag for a steady state ride the hydrodynamic drag curve represents the required aerodynamic thrust curve. This equation allows us to calculate the total sail force which is required to provide exactly that thrust.

**Figure 9** shows that the sail force or the weight has to be exponentially increased for higher speeds. The maximal speed is indicated by the maximal sail force which is in balance with the sailor's weight.

![Figure 9: Required total sail force for steady state conditions at any speed. Sail force limit due to heeling stability. Wind 40 kts, Course 140 deg.](image)

**How can we go faster?**

In order to go faster, the thrust can be increased by more body weight and by sail drag reduction (better foil, optimized sail size) as well as by reducing all parasite drag (boom, sailor etc.). Further, by reducing the board drag by minimizing the spray drag (tear-off edge).

**The influence of body weight**

The body weight of the sailor defines the possible thrust. The more weight the more thrust but on the other hand the more weight the more drag from the board which must lift the additional weight which is connected to more drag. As a result, it can be calculated that 100 N more weight leads to about 2 kts more speed, **fig.10**.
Figure 10: Influence of body weight on maximal sailing speed. Body weight 700N and 1100 N.

If we look at the drag distribution of the windsurf components at about 52 kts as it is shown in Fig. 11 we can estimate how much speed we can gain if we could reduce the drag on some components.

Figure 11: Distribution of the amount of drag for windsurfing components at 52 kts

For instance reducing the drag of a fin by 10 % gives a total reduction in drag of about 1,1%. 1,1% drag reduction means 0,5 % speed improvement. That would be 52,26 kts instead of 52 kts also
0.26 kts more.
If we could reduce the body drag by 50% gives us a total drag improvement of 5.5%.
In speed, we would gain 0.26% that's 53.4 kts instead of 52 kts.
Only a small amount of improvements can be reached on existing windsurf boards by avoiding all adverse drag components at the sail by smoothing the sail leading edge, the boom, lines and the sailor itself.
At the board may be the spray drag could be reduced by a specific outline and other edges.
But in general, no big steps are possible.

**What about hydrofoils?**

The hope to use hydrofoils in order to get higher speeds is not very promising.

The foil is like a wing of an airplane. The foil must provide the total weight of the gear and the drag of a wing increases with the square of speed.

This is a big disadvantage compared to a planing surface where the drag is nearly independent of speed. See fig. 12.

On the other hand when foiling the gear is out of the water and no waves will reduce the speed which is a big advantage because no flat water conditions have to be used.

But the drag behavior limits the application of foils for high-speed windsurfing either we make the foil area very small.

Therefore foiling is working very well at speeds below 30 kts. There we have an advantage on drag compared to a planing board because the drag is less. This allows us to use a smaller sail in lighter winds. For higher speed, the foiling area must be reduced which shift the lifting speed to higher values.

For very high speeds, the foil area has to be drag optimized for the required speed, for 50 kts e.g. it means about 100 cm² in area. Such a small wing would lift the board out of the water, not before 20 kts.
Figure 12: Comparison of the drag curves of a planing and a foiling windsurf board and maximal sailing speeds. Wind 20 kts, course 120 deg.

A comparison of maximal speeds versus wind speed which can be gained for different windsurf configurations is shown in fig. 13.

Figure 13: Maximal sailing speed as a function of wind speed. Comparison of zero drag (windsurf on ice), windsurf (planing) and windsurf (foiling) and different foil sizes (m2). Calculated with constant sail force from the heeling balance and for optimal course.

Assuming no hydrodynamical drag as it is nearly given by a windsurfer sailing on ice (the world record is 54 kts at 20 to 30 knots of wind), then we have the windsurfer where the board is planing and finally, a windsurfer foiling with different sizes of the wing. It can be seen that planing is much more effective than foiling except the wing area of the foil is adapted to the target speed. Only with a foil with an area of about 100 cm² a speed of 54 kts at a wind speed of 40 kts seems to be possible.

Controlling a hydrofoil is very difficult especially the attitude and altitude control is not easy and needs a lot of skill. It is very unstable and like balancing on a needle. A touch of the board on the water surface at very high speed would result in a catapult.

Who is willing and able to balance on an unstable hydrofoil at over 50 kts? Up to now no speeds over 30 kts were sailed.

As a result for existing windsurf boards, much more speed could not be reached due to physical limitations mentioned above. Only little improvements at better conditions are possible: more wind and
more flat water is what is needed.

In case that the equipment is optimized and the sailor has the required skill the world record depends mainly in finding the right conditions in wind speed, flat water and the right course.

In Lüderitz e.g. due to the fixed channel the possible course angle depends solely on wind direction. It can't be changed by the sailor. This is not optimal. So that means you have to wait for the highest wind speed and the right angle there.

All that was mentioned above is also valid for a kite. A kiter can hold much more force because the moment arms of the heeling moment are different but the aerodynamic efficiency of a kite is much worse (more drag) than that of a windsurfing sail.

That's why the kite speed record is only just a little above than that of the windsurfing record.