An Introduction to the Physics of Windsurfing

Jim Drake -- 2005

All sailboats including windsurfers use the wind for propulsion. Windsurfers differ greatly from all other sailboats, however, in three respects. First, the forces that are captured by the sail and that drive the board forward **all** go through the sailor -- literally. Second, the weight of the hull, the sail, the mast and everything else is far less than the weight of the sailor who controls it. And finally, even in zero wind the sailor can make substantial headway by "pumping" the sail from side to side, using it as an "air oar" or, more accurately, like a bird's wing. The first two features are explained in this paper. The last, "pumping", will not be further be treated except to note that current Olympic competitors use this technique extensively in the often light wind conditions that seem to plague the Games.

In **Figure 1** Kevin Pritchard, the 2004 World Champion, demonstrates the first of the features described above. He literally holds the wind in his hands and directs the sail's power to the board through his arms and legs. He controls the force and direction -- throttle and steering wheel -- with his grip on the boom. In this way he is both motor and pilot.

This paper will discuss the physics of windsurfing in two parts**. Part I** summarizes the forces and moments that act on the board and rig as a whole. This section is intended for a general audience and is not as complete or as careful as some might wish. It trades precision for what I hope is improved clarity. **Part II** translates the forces described in Part I into velocity vectors. This necessarily requires additional background for its understanding in the field of fluid dynamics. Thus it's not for everyone though the figures in this section can give a degree of insight even if the theory behind them is likely to be opaque to the general reader.

Part I – Forces and Moments

Kevin is back again on **Figure 2**. It shows the kinds of forces that nature confronts him with. His natural skills allow him to sense and react to these forces without really thinking about them. Most windsurfers are the same way but some, like myself and those to whom this paper is aimed, find that an analytical understanding is fun in itself and often helpful on the water.

The main forces can be grouped roughly into five categories:
1) Hydrodynamic **lift** acting upward on the bottom of the board,
2) Gravitational **weight** acting downward through the center-of-gravity (c.g.) of the combined mass of the board, rig and sailor,
3) Hydrodynamic **side** force acting sideways almost entirely on the fin (or fins in the case of a board with a centerboard) in reaction to sideways component of the
4) Aerodynamic **wind** force acting on the sail at its center-of-pressure (c.p.) and
5) Hydrodynamic **drag** on the board that balances the forward component of the wind on the sail.
The sideways component of the aerodynamic force on the sail is called **heel**; the forward component is referred to as **drive**.

A useful method for the analysis of forces on a body (in this case the body is the combination of board, rig and sailor) is that if the forces and moments acting on that body in two orthogonal (perpendicular) planes sum to zero, the body is moving at constant velocity. This is called steady-state and is by far the easiest case to analyse.

This method is applied to a vertical plane perpendicular to the direction of travel in **Figure 3**. This is also called the **lateral plane**. The forces pictured on figure 2 that Kevin has to cope with and which have a component in the lateral plane are those shown. Note that the sail's heel force has a slight vertical component. The lever arm between the heel force and the force on the fin – 106 inches – can be measured directly from the equipment sitting on the beach. The c.p. of the sail is about 40% up the mast and about 35% of the distance from the mast to the trailing edge of the sail.

The lever arm between weight and lift varies, of course, with the strength of the wind, the size of the sail and other factors. However, it can be measured for a particular condition from a photograph taken from the rear such as **Figure 4**.

This isn't Kevin but one of his colleagues and it gives a really dramatic view of how the sail and sailor combine to drive the board forward. Knowing the width of the board allows an estimate of the horizontal distance between the centerline of the board (i.e., the lateral center of lift on the bottom of the board) and the c.g. of the board-rig-sailor combination, namely 29 inches.[1]

The next step in the analysis is to make an estimate of the total weight and the breakdown between major components. An example of this is **Figure 5**. This is helpful in estimating the c.g. position needed on Figure 4 but crucial, as we will see, on the figure to follow.

The weights of each component can vary depending on many factors but lie generally within the range given for each component. Data like this can be obtained from manufacturer's specifications and brochures, easily found on the web.

Note the dramatic difference between the Formula windsurfer (the one pictured in Figures 1,2 and 4) and another very fast and exciting boat, the Hobie 14. The equipment – so called dead weight – of the Hobie 14 is **seven** times that for the Formula. (And that doesn't even include the trailer for the Hobie 14.) The leverage this gives the sailor is the main reason why windsurfers have held and now again hold the world speed record under sail.

The weight estimate from Figure 5 lets us complete the balance of forces and moments introduced on Figure 3. **Figure 6** is the result. Knowing that the weight of everything is 233 lbs and equalizing the moments around the intersection of the lift force and the lateral fin force unlocks the puzzle by yielding a heel force of 63.7 lbs when the sail is angled from vertical to windward by 15°. The horizontal component of heel is 61.6 lbs and thus is the force on the fin. The vertical component relieves 16.5 lbs of weight and lowers the lift required from the board to 216.5 lbs. The purpose here is to illustrate the process. The numbers change, of course, with different circumstances.

Estimating the hydrodynamic forces -- lift and drag -- of marine bodies is an art more than a science. This is because the boundary between air and water, where most watercraft operate, is complicated by waves, chop, spray induced by the body, etc. And

[1] The locations of the each component's c.g. can be estimated by eye with adequate accuracy and then combined by the well-known method of summing moments and dividing by the total weight.

the task is quite a bit more difficult for a sailboard hull. Its small size magnifies the effects of waves and chop and its trajectory is in no sense "steady state." None-the-less, there is a happy feature to the drag of a planing hull, indicated in theory and born out in tests as illustrated in **Figure 7**. It is that the ratio of drag to lift, once planing occurs, is pretty much constant over a fairly large range of speeds provided that the board's angle of attack is trimmed to minimize drag for each speed. That's the job of the sailor. This feature of a planing board happens because, as speed increases, the board rises out of the water, reducing the size of the patch of water it rides on. This reduction in size more than offsets the increase in friction drag per unit area of that patch caused by the increase in speed. Other effects, spray, waves, etc., increase with speed, however. The net effect is that a well trimmed sailboard's drag/lift ratio is around 0.15 for speeds from about 6 knots to well over 20 knots. Of course, different designs and different conditions can change this by a lot, perhaps ±0.05, but the phenomena of relatively constant drag with speeds above planing is a reasonable assumption.

Figure 7 also shows the drag/lift ratio for the Hobie Cat mentioned above. At low speeds -- below the windsurfer's planing speed of about 6 knots -- the Hobie has the advantage. Its long slender hulls part the water gently and leave very little wake. This reduces energy dissipated in the wake, minimizing what is known as "wave making drag". However, its hulls are not designed to plane and thus, as speed increases, "wetted area" stays the same and friction drag increases dramatically.

This flat drag/lift feature of planing hulls eases the next step in the analysis shown on **Figure 8**. This is another vertical plane but now parallel to the direction of travel, referred to as the **longitudinal plane**. The weight and lift forces and the vertical component of heel are taken from Figure 6. Knowing that drag/lift is 0.15 over a wide speed range tells us that Drag is about 32.5 lbs. And the figure also shows that Drive is 32.5 lbs and that by equalizing moments around the sail's c.p. the center of lift applied to the bottom of the board is 13 inches forward of the c.g.

To repeat the cautionary remarks from above, these estimates are only illustrative and can change with circumstances. Perhaps the most important of these is the sailor's trimming of the board's angle of attack relative to the water's surface to minimize drag. The sailor does this by adjusting the longitudinal position of 1) his c.g. and 2) the sail's c.p. while keeping all the forces illustrated in Figures 6 and 8 in balance. No small trick, as any beginner will tell you.

Figure 9 completes the three dimensional description of the steady state forces by viewing them on the horizontal plane of the combined board-rig-sailor body (omitting the sailor and rig for clarity). The interesting feature of this perspective is that all the horizontal forces interact at or behind the tail of the board. This feature is also unique to windsurfers as compared to all other sailing craft.

<u>Part II – Velocity Vectors</u>

Until this point there has been no need to specify the strength or the direction of the wind relative to the board or the speed of the board itself or the size of the sail. It's been possible to ignore them in estimating heel and drive forces -- 63.7 lbs and 32.5 lbs, respectively -- because 1) heel forces are a reaction to the leverage produced by the sailor, whose weight and lever arm are known and 2) drive forces are equal and opposite to drag forces which, in turn, are assumed constant over the speed range of interest.

These forces are generated by what physicists call momentum transfer, that is, energy transfer between the air and the water. The agent of this transfer is the board, rig and sailor combination acting as a whole. A less precise but more understandable way of saying this, however, is that the sail and sailor "lean" against the approaching wind as the board and fin "lean" against the oncoming water. This process slows the wind and accelerates the water.

There are three speeds of interest in the analysis to follow: 1) the **true wind speed** as felt by someone just floating in the water 2) the **board speed** as felt by the wet parts of the board and the fin and 3) the **apparent wind speed** as felt by the sail and the sailor. These three form a triangle or a "closed" vector system. If two are known, the third is also.[2]

Taking up the apparent wind first**, Figure 10** combines the heel and drive forces in their common plane, which, recalling Figures 6 and 8, is canted at 15° to the horizontal. The result is an aerodynamic force vector of 71.5 lbs at an angle of 64.7° to the direction of progress.[3]

This force is the net of all aerodynamic forces on the sail, the board and -- importantly -- the sailor. The combined force can also be estimated in another way using established aerodynamic formulae. This can be used as a check on the "Force and Moments" method of Part I and as a guide in equipment selection and/or sailing technique. And I think it's interesting in its own right. It needs information on wind strength and direction, sail size and trim angle, namely, the same factors the sailor deals with. These aerodynamic formulae can also be used to calculate, say, the sail and board trim parameters needed to generate the combined force estimated by the "Force and Moments" method as a function of true wind direction, and along the way calculate the three speeds defined above. The next steps use this approach.

It is the convention in aerodynamics to divide forces into 1) forces perpendicular to the apparent or "local" wind but perpendicular also to the plane of the sail and 2) forces parallel to the direction of the apparent wind. The first is called the **normal force** because it is normal to the airflow, (normal being another word for perpendicular in fluid dynamics.) It is analogous to the **lift force** on an airplane's wing. The second is called the **drag force**. These two force vectors form a right triangle and add together with the familiar square root of the sum of the squares.

To illustrate, take a case where the true wind speed is 15 knots and where the sailor (a better than intermediate one) selects a sail size of 8 sq. meters to suit. Out on the water **Figure 11** shows the resulting relations between heel, drive, aero drag and aero lift.

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[2] More correctly: a triangle has six properties, three sides and three angles between them. If any three of the properties are known, the other three are determined, though some cases are ambiguous and others are impossible.

[3] The magnitude and direction of this combined force is, in the real world, under the control of the sailor up to a limit placed by the strength of the wind. Before going out he will choose the size of sail on the basis of the wind's strength and the contents of his sail quiver. On the water he controls the sail's force through the trim (rotation) of the sail with his hands and harness lines, adjusting it to balance against his degree of windward hike and gain what he perceives is the maximum drive he can in the direction he has chosen.

The aerodynamic drag force is seen to be 10.7 lbs and normal force is 70.7 lbs. These vectors combine to provide the 71.5 lbs that the above Force and Moments analysis say is required to generate the required heel and drive.

The aerodynamic drag in this example consists of about 4.5 lbs of drag on the sailor with the remaining 6.2 lbs divided between what is known to aerodynamicists as "induced" and "profile" drag. This is illustrated in an expanded scale in the lower left. Note that the sailor is, so to speak, a real drag on the system. Note also that the direction of the apparent wind is now known since, by definition, it is perpendicular to the normal force – aero lift -- and parallel to drag, namely 36.1° from the direction of travel.

The relation between aero drag and aero lift is considerably more complex than shown but the general relevance of the estimates pictured here is aided by the fact that the ratio of the aero drag to aero lift is always small for most points of sail and in any event doesn't vary very much. Thus the estimate of angle between the apparent wind and the direction of travel doesn't change much either.

Figure 12 completes a typical velocity vector diagram for the case of the board on a beam reach, namely with the true wind of 15 knots at 90° to the direction of travel. Solving the vector triangle results in a board speed of 20.3 knots. This board speed is well within the range where the assumption of constant drag/lift ratio applies. Also, the apparent wind is increased from the true wind speed to 25.2 knots by the board's forward motion.

The equations shown on Figure 12 are simplified versions of more complex relations used in fluid dynamics. The first says that the normal force on the sail (L_{sail}) is the product of a lift coefficient (C_L -- a function of sail trim and shape)[4], sail area (S) and a group of terms that represents the "dynamic pressure" of the air[5], i.e., air density (ρ_a), over twice the gravitational constant (2g) times the speed of the apparent wind squared (V_a^2).

The second equation says that the lift force on the bottom of the board is the product of another lift coefficient (C_{Lb})[6], the square of the board's width (b^2) and the dynamic pressure of the water flowing past the board, i.e., water density (ρ_w), over twice the gravitational constant (2g) times the square of board speed (V_w^2).

But, of course, the wind isn't always perpendicular to the course. Another important case is when the desired course is upwind. That case is shown on **Figure 13** where the course is 60° off the wind. This reduces the apparent wind slightly to 22 knots but reduces board speed by about half to 10.3 knots, still enough to plane, however. Also speed-made-good-to-

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4 The optimum lift coefficient, $(C_L)_{opt}$, is that associated with a well designed (and rigged) sail that is trimmed properly for the direction of sail and strength of the wind. It can vary up to over 1.0 for downwind sailing. It is proportional to the angle of trim -- β -- in this case 6.8°

5 Dynamic pressure is the kind of pressure you feel on your hand when you stick it out a car window when traveling at high speed. The pressure increases as speed increases by the square of speed.

6 This lift coefficient contains terms for static lift and dynamic lift and is a function of the angle of attack (trim angle), the width of the board, the length of the patch of water the board planes on and board speed. It can vary from around 0.01 for a short wide board at high speed to 0.6 for a long narrow board at low speed.

windward reduces that by half again to 5.15 knots, still a great deal better than almost any other sailboat in a 15-knot wind. The sailor in this case has to sheet in another 2.1° from a beam reach to maintain the 71.5 lbs required force in the slightly less apparent wind.

The last case, sailing well off the wind while still maintaining efficient airflow on the low-pressure side of the sail, is illustrated on **Figure 14**. By this estimate, board speed increases to 24.2 knots even though the apparent wind reduces to 15 knots but still at 36.1° from the direction of travel. This reduction requires the sailor to sheet in 12.4° from that required on a beam reach. The resulting lift coefficient (C_L) of 1.1 is close to the maximum a sail can generate without stalling and causing a large increase in aero drag.

The case illustrated on Figure 14 is probably optimistic in the levels assumed for both board drag and aero drag but not by much. It is a good illustration, however, of the changes that occur as the board heads well off the wind. The most interesting observation in this case is that the board travels down wind faster than the wind itself. That is, the speed-made-good-downwind is 16.2 knots compared to the true wind speed of 15 knots. Tacking downwind has been the preferred tactic for many high performance sailboat designs but the above property of a windsurfer is rare among sailing machines except those that sail on solid water, i.e., iceboats.

It's clear that the Physics of Windsurfing is a three-dimensional puzzle a lot like Rubik's Cube. The difference is the scale is larger, the moves are more complicated and it's better exercise – physically and mentally.

References

For those readers interested in a more professional (and lengthy) explanation of the fluid dynamics involved, I would suggest two highly regarded sources: **Fluid-Dynamic Drag** by Sighard F. Hoerner, Library of Congress Catalog Card Number 64-19666 and **Fluid-Dynamic Lift**, by Sighard F. Hoerner and Henry V. Borst, Library of Congress Catalog Card Number 75-17441.

The fundamentals of forces and moments on the movement of bodies and the manipulation of vectors are well explained in any elementary level physics text. A request by email to the author, olliedrake@aol.com, for a suggestion will be promptly honored.