Old Habits die Hard: Theory of Sail Operation Revisited

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Motivation

I believe that everyone who sails, and specially those involved in competitive sailing, can obtain a great benefit from knowing the physics behind sail operation. The experienced sailor, for instance, would understand better why she or he do what they have been doing for years; while the novice sailor can focus more on aspects that would contribute to fast learning. You may wonder why an article on sail operation now. Is there anything new about it? Well, you'll see.

Almost 20 years have passed since Arvel Gentry published his original work giving a scientific explanation of the principles of sail operation—see [1]. In his articles, Gentry used scientific research and experiments to investigate some aspects of sail operation, and challenged the classical views on the topic at the time. However, even though 20 years seems a long time, yet there are myths in our sailing community on how sails work, how sails interact with each other and how sails interact with the hull. Unfortunately, these misconceptions on the principles behind sail work are being carried forth to new generations of sailors—"old habits die hard." I believe that this happens mainly because up-to-date references on this topic (that has been known for a long time in fluid dynamics and aeronautics) are relatively new within the sailing literature. And also due to the involved manner in which the concepts are presented in those references. Therefore, since the topic is related to my research, and motivated by trying to help a friend to present the concepts in his sailing course notes, I decided to wrote this brief article. I have reviewed some of the literature, which includes Gentry's articles and some other contemporary authors of the sailing literature like Marchaj ([5], [6]), and write these notes with two purposes in mind:

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- To motivate the keen sailor, who wishes to understand the complexity of this exciting sport, to consult up-to-date references.
- To attempt to close the gap between science and sailing by describing from a "simple" and "intuitive" perspective the complex physics of sailing and sail operation.

In this first set of notes, I concentrate on the basic principles of sails when they work aerodynamically. Who knows, you may be in for a few surprises!

1 Two dimensional flow: Lift generation

In this section, I will describe what happens when a sail works aerodynamically. I will start by explaining what this means.

Sails work "basically" in two conditions that can be classified according to the way the air flowing close to them behaves:

- With attached flow (usually referred to as aerodynamical condition)
- With separated flow (usually referred to as stalled condition.)

In the first case, most of the air flows following closely the sail contour. The sails operate in this condition when we sail close hauled and close reach courses. In the second case, most of the air separates from the sail and there exists a severe turbulence on the leeward side of the sail. The sails operate in this condition when we reach or run down wind. There is a smooth transition from one working condition to the other; and therefore, there exist intermediate stages in which the flow is neither completely attached nor completely separated— that is why I say "basically."

When the sail is immersed in wind at a small angle, say α, with respect to the wind direction (see figure 1), the wind remains attached. This condition prevails for different angles as long these angles are smaller than a critical angle called stall angle. The stall angle depends on wind speed, shape of the sail and several other factors—see [2]. For angles bigger than the stall angle, the air around the sail starts separating.

When the angle between the sail and the wind is smaller than the stall angle, there exists a difference in the velocities of the wind going on either side of the sail: the wind travels slower on the side facing the on-coming wind (windward side) and faster on the other side (leeward side). This distribution [1] of velocities on both sides along the sail, produces a distribution of pressure, and this can be explained using Bernoulli's principle: *at low speed, high pressure and at high speed, low pressure*. Therefore, we have high pressure on the side

[1] It is called a distribution because the velocities are different at each point in the sail.

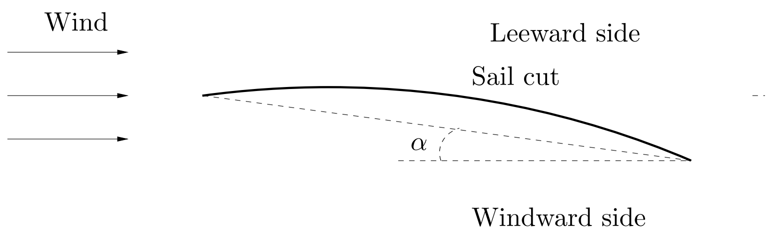

Figure 1: Sail and wind relative position.

facing the wind and low pressure on the other side; and this differential pressure distribution "in principle" multiplied by the area of the sail gives us a resultant force (Remember that Force = Area x Pressure) that is the resultant of all the force components distributed over the sail—see figure 2. That resultant force is usually called lift (term that has been taken from aerodynamics where these effects were first studied for plane wings) and acts perpendicular to the direction the wind had before reaching the sail at a point called Center of Pressure (CP). As stated in references [1], [5] and [6], the above explanation is the correct way to describe how the sail gives lift in steady flow (*i.e.,* flow characteristics do not change in time.)

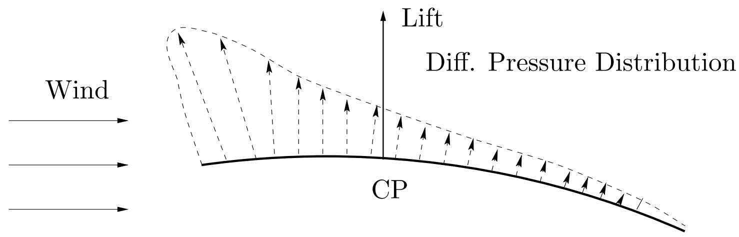

Figure 2: Differential pressure distribution and lift force generated over the sail by a two-dimensional flow.

The direction, as well as intensity of the lift force (for a given wind speed condition and angle between the sail and the wind) is affected by the depth of the sail called camber and the position of the maximum depth called draft. These are aspects of sail trimming that are not in the scope of this introductory notes. However, I encourage the reader to consult references [1] and [5] for a thorough coverage of this topic.

Fine, but why does this happen? Why are the velocities on either side of the sail different? Well, this is not as simple to understand, and here is where the classic explanation which says that "the wind travels faster on the leeward side because it has farther to go" fails. This neither happens in sails, which have small thickness, nor in wings which have considerable thickness —for a discussion on this see [7] and [6]. To answer the question, it is necessary to study fluid dynamics—which is a science in itself. However, we can still intuitively get the concept!

Let us note that in the boundary of the sail on the trailing edge (the leech) the wind leaves the sail with the same speed and pressure on both sides. This is easy to see, since there is no sail cloth separating the sides; and therefore, there cannot be difference in pressure and thus (by Bernoulli) in velocities. This condition is known as the Kutta condition—see [6]. Consequently, the difference in velocities on either side of the sail can be explained as follows:

The velocity of the air in the total region around the sail simply adjusts itself so as to satisfy the condition that on the leech the wind leaves the sail with the same speed and pressure on both sides, i.e., the Kutta condition.

You can leave it here and save yourself some trouble; with this simple explanation the concept is well stated. However, for those who wish to further pursue this, we can see how the Kutta condition is satisfied in the following.

The flow around the sail can be "thought" to be made up of two components[2]. The fist component is called a non-circulation flow and the second component is called a circulating flow—see figure 3. The circulation flow rotates around the sail such that it goes in the same direction as the non-circulating flow on leeward side and in opposite direction in the windward side. Therefore, the circulation flow adds up to the non-circulating flow increasing the speed on the leeward side and subtracts to the non-circulating flow reducing the speed on the windward side. For each condition (wind speed and angle between the wind and the sail) the amount of circulation flow generated is unique and it is the necessary to satisfy the Kutta condition. This last statement is known as Kutta-Joukowski hypothesis— see for example [8], [7] and [6].

Before proceeding with the rest of the notes, it is worth making a comment on the use of the word "lift." Unfortunately, the word "lift" have another use in the sailing jargon. Lift is also a favorable wind shift that allows the yacht to sail a course closer to the objective (this could be a mark on a race course.)

2 Three dimensional flow: Induced drag

Our discussion so far is just part of the whole story. It should be noted that there was no comment on the actual shape of the sail except for that it has a sharp

[2]This serves the purpose of explanation; the only flow is the real flow on the sail. This way of thinking about the flow is similar to that of a force being a resultant of different components.

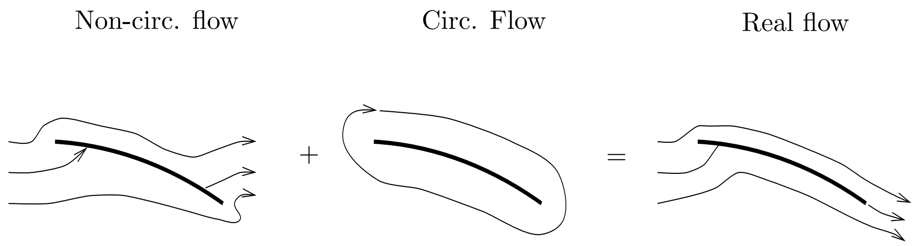

Figure 3: Flow components representation of the real flow around the sail.

trailing edge. Therefore, could, for instance, a door produce lift? The answer to this question is "yes". Then, what is the difference between a sail and a door?

So far we have only discussed about lift; but sails, as well as doors, also produce drag. And the difference between a sail and a door is that the sail, because of its shape, is more efficient than the door in the sense that the lift to drag ratio (*i.e.,* lift / drag) is bigger. But, what is drag anyway, and why does a sail produces drag?

Drag is a resultant force that acts in the direction the wind had before reaching the sail, and it is induced by the vortexes shed at the tip and foot of the sail—see figure 4. The sail has finite dimensions: span (height) and cord (width); and this makes the air velocity to have three-dimensional components instead of the two considered when we explained how lift was generated, *i.e.,* the air not only flows from the leading to the trailing edge (two-dimensional flow from the mast or forestay to the leech in the cross-section plane), but also from one side of the sail to the other at the top and at the foot. This three-dimensional flow produces concentrated trailing vortexes at the ends of the sail and the energy carried in these vortexes is reflected as a drag force component.

3 Sail interaction: the controversial "slot effect"

It was pointed out in references [1] and [5] that for long time there was a controversy on how the headsail and the mainsail interact to increase the performance. Therefore, it is not surprising that in many references in the sailing literature incorrect explanations appear. The slot effect or sail interaction can be simply summarized as follow:

The headsail and the mainsail interact in such a way that the performance of the headsail is increased and the the performance of the main sail deteriorates with respect to the performance of each sail alone. However, the overall performance is increased. This is produced because the air slows down where the sails start overlapping (mainsail luff) and then it accelerates at the end of the overlap (headsail leech). The region overlapping is referred to as "the slot".

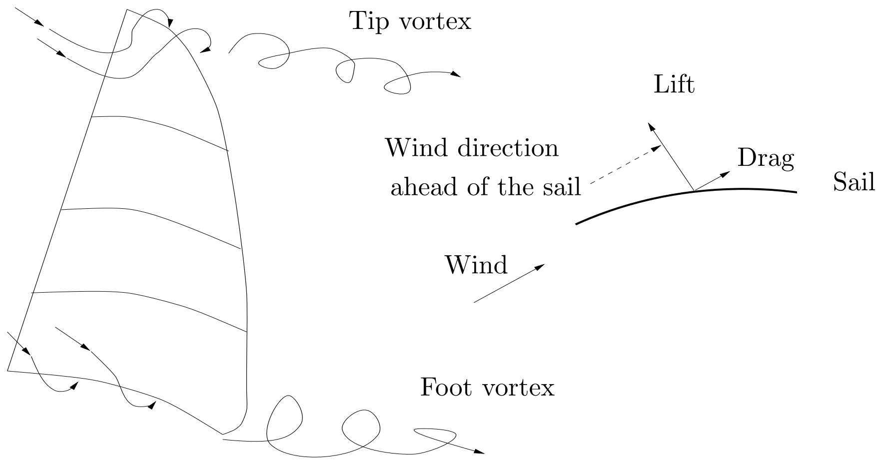

Figure 4: Schematic representation of tip and foot vortex due to the three-dimensional flow and the induced drag.

The fact that the air first decelerates and then accelerates is the most remarkable feature of the slot effect. Not recognizing this, seems to be most common mistake in the sailing literature as has been eloquently discussed in reference [1]. For example, it is common to find explanations saying that the slot acts like a Venturi tube[3]. However, this is not the case of the slot since in the Venturi tube, the air only accelerates; and therefore, it behaves in a different manner.

It is worthwhile making a comment on the use of *streamlines* to visualize the slot effect. Streamlines are curves with a precise mathematical definition: *The streamlines are those curves that are tangent to the velocity vector* [4] *at a particular time instant*. Because of this, there is no flow across the streamlines and therefore if we know the streamlines, we can apply Bernoulli's Principle. That is to say, if two streamlines separate, the speed of the air between them reduces, and if the streamlines get closer, the speed of the air increases. As discussed in reference [1], the problem with many references in the sailing literature is that the streamlines are not carefully drawn, and therefore incorrect explanations arise. Figure 5 shows an schematic of the streamlines that were experimentally obtained by Gentry using a analog field plotter–see [1]. We can see from figure 5 that at the beginning of the overlap between the headsail and the main, the

[3]The Venturi tube is a device utilized to measure flow in pipes based on Bernoulli's principle—see for example [9]

[4]There is a difference between velocity and speed. Velocity is a vectorial magnitude, *i.e.,* it has direction, sense and intensity. Speed refers to the intensity of the velocity. For example, we can describe a wind condition NE-20kts. This expresses the velocity: Direction NE-SW, Sense from NE to SW, and speed 20kts.

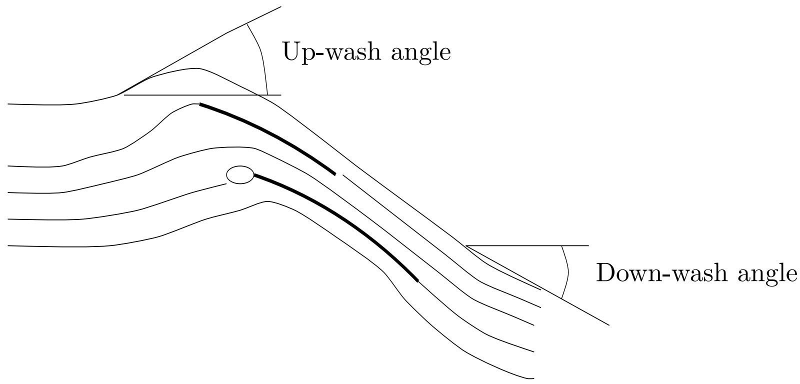

Figure 5: Slot effect

streamlines separate and they get closer at the headsail leech.

The major effects on the change in performance of both sails due to the slot effect can be summarized in following [1], [6]:

Effects on the head sail

- Because of the air acceleration at the end of the slot, the leech of the headsail is in a higher velocity zone; and then, the distribution of air velocity over the entire headsail on the leeward side is increased with respect to the distribution of the headsail alone (Remember the Kutta condition in section 2). Therefore, this makes the headsail more efficient when the main is present.
- Because of the main, there is a change in the relative angle between the air flow and the headsail. These effect is called up-wash and it is essentially, a shift in the wind direction—see figure 5. This up-wash allows the head sail to be able to operate at smaller angles of attack with respect to wind direction ahead of the sail. Therefore, the yacht can sail closer to the wind.

Effects on the main sail

- The velocity reduction at the beginning of the slot on the leeward side of the main reduces the lift produced by the main since the pressure on this side is increased (Remember Bernoulli.)
- The main, because of its triangular shape, is very sensitive to stall especially at the top 1/3, but since the differential pressure on the main is reduced stall is prevented and it can be operated a higher angles of attack without stalling.

We have seen how the slot effect produces a change in the performance of both head and main sail. The closer the two sails are and the bigger the overlapping between them, the grater the effect. However, there exist trade off's. If the slot is too narrow the pressure on the leeward side of the main equals the pressure on the windward side and the so-called back winding is produced on the mainsail luff. Therefore, for each sailing condition there is an optimal sheeting angle—see references [6], [5] and [4]. Also, wind tunnel tests seem to indicate that the amount of overlapping has an optimum value, and beyond that value the performance is not increased—see references [6] and [3].

It is evident from the discussion in this section that any change in one sail affects the other. Therefore, trimming should be always done on both sails.

4 Summary and discussion

In these notes, I have tried to explain in a simple manner the complex aspects of lift and drag generation of a single sail and how sails interact when the they work aerodynamically. To encourage the reader to consult up-to-date bibliography, I have made references to the sources from which I have taken each of the concepts throughout the notes. The concepts behind sail operation are complex but the underlying ideas are quite intuitive and can be summarized as follows:

- When the sail works aerodynamically (*i.e.,* with attached flow) it produces both lift and drag forces.
- The lift is a force which acts on a point called center of pressure and is perpendicular to the direction the wind had before reaching the sail.
- The presence of lift can be explained as follows: Because of the sharp leech, there exists a distribution of velocities of the wind on both sides of the sail (the air flows slower on the windward side and faster on the leeward side.) This distribution of velocities produces a distribution of pressure over the surface of the sail, which in turn produces a resultant lift force.
- The induced drag is a force acts on the center of pressure and in the direction the wind had before reaching the sail and on the center of pressure.
- The Drag is induced by the vortexes shed at the tip and foot of the sail. Since the sail has finite dimensions, there exist not only a flow from the leading to the trailing edge, but also a flow from windward side to the leeward side at the tip and foot of the sail. Therefore, there is a three-dimensional flow. This three-dimensional flow generates vortexes at the tip and foot of the sail and the energy carried in these vortexes is reflected as a drag force acting on the center of pressure.

- The most important characteristic of the slot effect is that the air first decelerates at the beginning of the overlapping (main luff) and then accelerates at the end of the overlapping (headsail leech.)
- Due to the slot effect the performance of the headsail is increased and the the performance of the main sail deteriorates with respect to the performance of each sail alone. However, the overall performance is increased.

I hope I have accomplished in some degree my two tasks: to motivate the reader to consult up-to-date references, and to introduce in an intuitively manner the complex physics of sail operation. Therefore, next time you hear someone explaining how sails work, I do hope you will be in a better position for a fair discussion. This way, you will be contributing to eliminate those classical and usually misleading explanations on how sails work.

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