Principles of Sailing

• This is a PowerPoint set of charts presented by Demetri Telionis on March 21, 2015 at the Yacht Club of Hilton Head Island.

• The aim of this presentation was to help the audience understand the physical principles of sail aerodynamics, and hull/centerboard fluid mechanics.

• Most of the graphs in this presentation were taken from “Sailing Theory and Practice” by C.A.Marchaj, published by Dodd, Mead & Company
Definition of basic components found on a sailboat.
Concentrated Forces

The action of two forces is equivalent to the action of their resultant.

The resultant is the diagonal of a rectangle.

Forces are “vectors”. They possess magnitude and direction.

Forces can be concentrated at a point.
Distributed Forces

Consider 10 lb of water in tank with 5”X6” base

The force is distributed over 30 square inches

The distributed load
10 lb/ 30 in$^2$ = 0.33 psi

Force distributed over an area we call “pressure”
Two basic laws of fluid mechanics

LAW 1. Continuity
\[ A_1 \cdot V_1 = A_2 \cdot V_2 = \text{constant} \]

Velocity (feet per second) TIMES area (square feet) = volume flow rate (cubic feet per second)

- This law indicates that if as we move into the tube the area decreases, then the velocity increases, so that the product stays the same
- This holds for flow through a pipe, or just between any two streamlines in the flow
Two basic laws of fluid mechanics

LAW 2. Bernoulli’s law

\[ P_1 + \rho V_1^2/2 = \text{constant} \]

(Here \( \rho \) is the density of the fluid)

Pressure plus...(almost) velocity squared = constant

This law indicates that if along a stream, the velocity increases, then the pressure decreases
Pressure and velocity vary when fluid moves over a solid surface.

The surface could be the hull of a boat, or a sail.

Here pressure can be measured by manometers.

Look for areas of low pressure over the solid surface.
Air Flow over a Wing at Incidence

The pressures that develop result in net forces in the vertical and horizontal direction:

- $F_L$: Lift
- $F_D$: Drag

Where the streamlines bunch together, the velocity increases, and then Bernoulli dictates that the pressure decreases. This generates suction on the upper surface and compression on the lower.
Flow over a Flat Plate

This could be the boat center board, the keel or the rudder

No incidence generates no side force (no lift)

As the incidence angle increases Lift is generated, but also drag.

As incidence increases, drag increases faster than lift.
Adjusting the shape of a wing or a sail affects the net aerodynamic force.

Mechanical devices can change the shape of a wing.

Adjustments can be made to change the shape of a sail.
Flaps increase lift and drag

Flaps increase lift (needed when landing at low speeds)

But flaps increase much more drag (also needed when landing)
Forces on Sails

The wind generates pressure over the sail. Pressure acts normal to a surface.

Negative pressure (suction) develops on the lee side of a sail.

Positive pressure develops on the windward side.

The “resultant “of all these pressures, $F_T$ exerted on the sail is transferred to the boat.

Gage pressure = local pressure – atmospheric pressure.
Add a "boat" to the sail

When the wind is on the port side:

PORT TACK

\[ F_H : \text{Healing Force} \]
\[ F_R : \text{Driving Force} \]
\[ F_T : \text{Total Force} \]
Forces on a sailboat

Forces on center board:

$F_D$ : Drag
$F_L$ : Lift

Forces on boat (sail and center board) balance each other
The boat is in “equilibrium”

In the situation depicted, the boat is moving at an angle of $\alpha_B$ with respect to its axis
Forces on the sail
Forces exerted on boat

Newton’s first law:
At constant body speed, all forces are balanced
Skipper is pointing North

- You see the mark dead North
- You are on a clean windward leg
- You decide to look only at your compass
- You keep your boat pointing North
- Where will you be at the end?
Skipper is pointing at mark

If you steer towards the mark, your boat does not move towards the mark.

If you keep steering towards the mark, then your trajectory is a curve.
If we increase the angle of incidence to the sail, the flow separates close to the luff of the sail. The sail stalls and the suction on its less side is reduced.
A well-trimmed sail should have the flow “hugging” the sail on both sides. At higher incidences, the flow separates on the lee side as detected by the flapping of the streamers. At low incidence the flow separates on the windward side, and the streamers on that side flap around. Trim the sail and steer the boat so that your jib is in condition 2.
Sail Interaction

The jib directs a stream on the lee side of the main. This increases velocity and thus lowers pressure, which further enhances the main’s performance.
Velocity distribution over an object

If a wind is approaching an object say at 60 mph, or equivalently if the object is moving at a speed of 60 mph with no atmospheric wind present, then the body distorts the flow around it. In other words, if you stick your hand through the sunroof, you will feel a speed much higher than 60 mph. (Just see the bunching up of the streamlines)
Apparent or Relative Wind

No head wind

Apparent wind is 60 mph

Head wind of 30 mph

Now apparent wind is 60 mph + 30 mph = 90 mph
Apparent wind

Boat velocity and wind velocity are not aligned.

The apparent wind strength and direction is what your telltales tell you and what you feel when you are in the sailboat.
POINTS OF SAIL

AR = Aspect Ratio:
Approximately:
Height over base:

\[
AR = \frac{h}{b}
\]
Aspect ratio of sails

High aspect ratio sails are more efficient close to the wind

Felucca on the Nile

My J22
Pointing to windward

Close-hauled a boat can sail at about 45 degrees upwind
The wind ladder

This is an imaginary ladder with its steps normal to the wind direction. If two boats are on the same step of a ladder, then their sailing distance to the mark is the same.

Direct distance versus “sailing distance”

- Direct distance:
  - A to Mark: 1,000
  - B to Mark: 1,400

- Sailing distance:
  - For both: 1,400
Different options of sailing to windward

No matter what courses are followed, the sailing distances of A to the mark and B are the same.

But each tack slows you done some.
Boats merge on lay line near the mark

The dashed lines drawn from the windward mark at an angle of 45 degrees to the wind are called the lay lines.

AVOID CROSSING THE LAY LINE !!!!! Because then your sailing distance is increased.
The starting line must be aligned with a ladder step.
If the wind direction changes, a boat may find itself on a higher or a lower step (the boats indicated on this graph were left over from the previous chart and are irrelevant to the above statement).

To observe this effect, go to the previous chart, touch the screen at a point say on step 200, and keep it there, then move on to this chart and see where your finger will find itself with the shift of the wind.
Starting line not along a ladder step

If the starting line is not aligned with a ladder step, then one side is more favorable than the other.

In the case depicted here, starting on the left, you will be on step 200, while a competitor starting on the right will be on step 100.
Dead Air Region

Downstream of a lifting surface at high incidence, or downstream of any object, like a building, a region develops with almost zero velocity. This is called the “dead-air or dead wind region”.

In sailing we sometimes refer to this region as the shadow of the boat to our windward.
Wind shadow

The dead wind region of a closed-hauled sail is limited. But a sail presenting its full shape to the wind, as is the case in a downwind leg is significant.
If you are astern of one or more boats, you should anticipate that you could find yourself in the dead-wind region of another boat, or in a region where the wind is deflected against you, and thus will require you to point lower than the competitor. Get out of there as soon as possible.
The sails disturb the flow all around

It is not only the wind shadow that hurts you. It is also the direction of the disturbed wind that will force you to point lower.
Wind tunnel measurements of disturbance expressed as a percentage of undisturbed-wind sailing.
Spinnaker Rigging

- Head
- Halliard
- Topping lift
- Spinnaker boom
- Spinnaker boom heel fitting
- Spinnaker sheet
- Fairlead
- Tack
- Fore guy
- Tweaker
- Clew
- After guy
Downwind

The aerodynamics of sails downwind
Entirely different principles

- A spinnaker is essentially a parachute
- A spinnaker/main wind shadow is much broader
Spinnaker in Reaching
Reaching with Spinnaker

Freeing the clew of the spinnaker will make it work like a big genoa, and thus increase the forward force generated by the spinnaker.
Jibing the spinnaker

The pole must be disconnected, and while the main is jibed, the pole must be connected on the other side, thus the “old” clew now becomes the tack