Downwind faster than the wind.

Sailing explained by Newtonian physics and Galilean relativity.

Mr. Nicholas Landell-Mills MA CFA ACA

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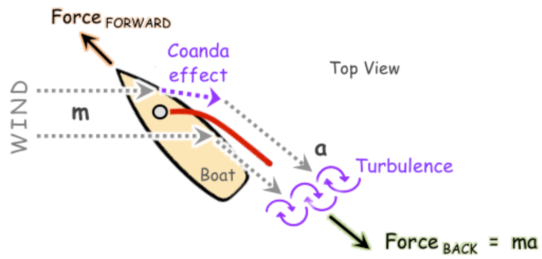

Fig. 1a. Newtonian forces sailing.

Abstract

New analysis shows how Newton and Galileo provide a straightforward and useful explanation of sailing.

The sail re-directs a mass of air (m) of the apparent headwind backwards, which decelerates (a) when it interacts with the undisturbed atmosphere to produce turbulence. This action creates a backward force (Force = ma). The reactive equal and opposite forward force pushes the sailboat ahead. Momentum is transferred from the apparent wind to the boat via the sail by slowing the wind down. See Fig. 1a.

This Newtonian analysis means that boats can sail faster than the wind because wind velocity is only one part of the equation for the force generated (Force = ma). For example, doubling the sail size will double the mass of air re-directed (2 x m), and therefore, double the force generated by the sail (2 x Force = 2ma). Also, the sail is pushing against the wind to generate the force, which is a moving mass and not a fixed or static point.

Then applying the ideas of Galileo, a boat can sail downwind faster than the wind for the same reasons that it can sail upwind faster than the wind. Each tack is simply the mirror image of the other one. This is because in both situations the sailboat experiences a headwind, and the true wind is moving backwards relative to the boat. That's it.

I. Introduction

A. Background.

The Newtonian approach is significant as it provides new and useful insights. It challenges the prevailing sailing solutions based on fluid mechanics and resolves long-running nautical conundrums, including how a boat can sail downwind faster than the wind.

The physics behind how boats sail into the wind is unresolved. No experiment on a sailboat in realistic conditions has proven any theory or equation to be true. Problematically, many people mistake mathematical proof (e.g., Navier-Stokes equations) and computer simulations (e.g., CFD) for scientific proof.

The failure to adequately explain sailing is puzzling given how long people have been sailing and how important sail-powered boats were to early global economic development. A number of different theories have been proposed. The prevailing theories rely on fluid mechanics, not Newtonian mechanics. [1][2][3][4]

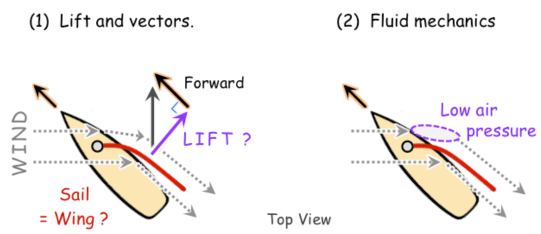

Fig. 1b. False vector-based solutions and fluid mechanics.

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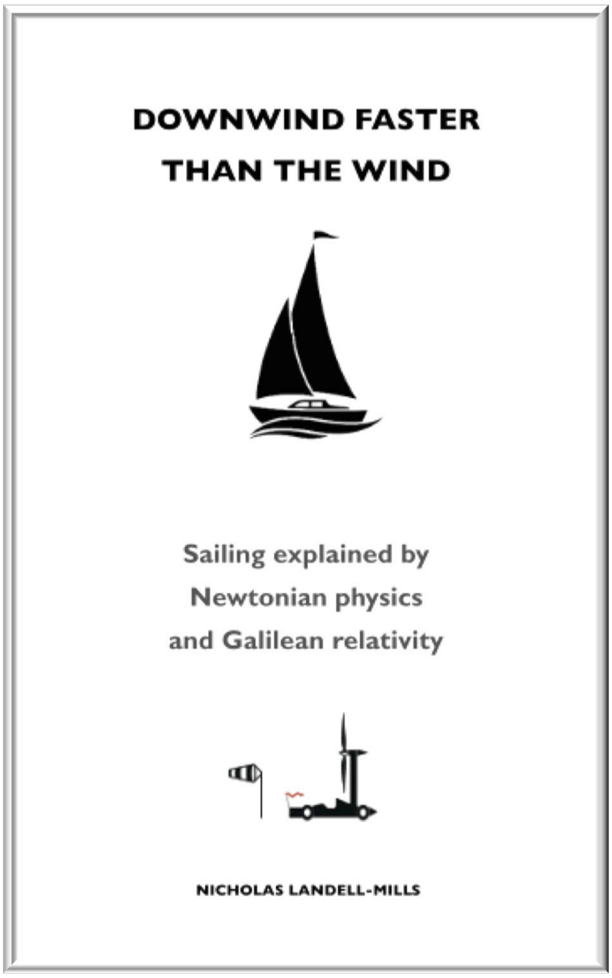
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II. Newtonian Argument Summarized

A. Newtonian mechanics explains sailing.

The generated forward force depends primarily on the amount and speed of air re-directed by the sail. Boats sailing into the wind on a close haul at a positive sail angle-of-attack (AOA) re-direct a moving mass of air each second (m/dt) from the apparent wind backwards at a velocity relative to the boat (dv), which is helped by the Coanda effect on the leeward side. As the re-directed air pushes against the undisturbed air from the apparent wind causing turbulence, this action creates a backwards force ($\text{Force}_{\text{BACK}}$ = ma = m/dt x dv).

The reaction generates an equal and opposite forward force that pushes the boat ahead. Momentum is transferred from the apparent wind to the boat via the sail by slowing the apparent wind down. See Fig. 2a.

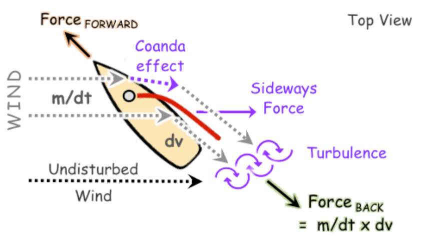

Fig. 2a. Newtonian forces acting on a sailboat.

B. Multiple sails.

The Newtonian approach can explain why multiple sails (e.g. jib and mainsheet) provide a greater forward force than a single, large sail with the same total sail area. Specifically, multiple sails increase the mass flow rate (m/dt) without significantly jeopardizing the relative acceleration of air (dv). A higher 'm/dt' increases the force generated (Force = m/dt x dv). See Fig. 2b-i and 2b-ii.

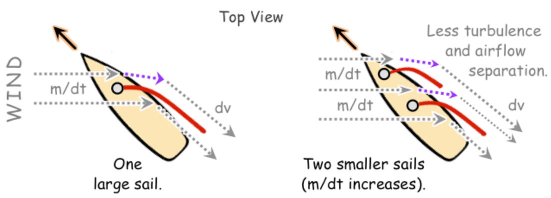

Fig. 2b-i. One large sail v. two smaller sails with the same total sail area.

Fig. 2b-ii. Ships with multiple sails. [33][34]

C. Example calculation.

The example calculation below demonstrates the Newtonian approach applied to sailing.

It is assumed that: See Fig. 2c-i.

- Apparent wind is 10 m/s.
- Air density is 1.2 kg/m^3.
- Sail 12 m high.
- Sail reach of 1 m; which means the wind is re-directed 0.5 m on either side of the sail.

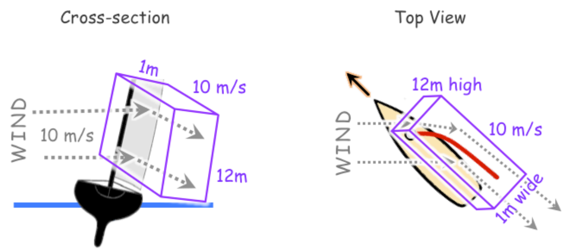

Fig. 2c-i. Volume of air re-directed by the sail.

The sail displaces a volume of air each second of 120 m^3/s:

Volume/dt = 12m x 1m x 10 m/s = 120 m^3/s

The displaced volume of air equals a mass of 144 kg/s of air:

m/dt = Volume/dt x Air Density
= 120 m^3/s x 1.2 kg/m^3 = 144 kg/s

If the apparent wind is re-directed by the sail at 8 m/s (dv), then according to Newtonian mechanics this creates a backward force of 1,152 N. The reaction generates a forward force of 1,152 N. See Fig. 2c-ii.

$\text{Force}_{\text{BACK}}$ = m/dt x dv
= 144 kg/s x 8 m/s
= 1,152 N
= $\text{Force}_{\text{FORWARD}}$

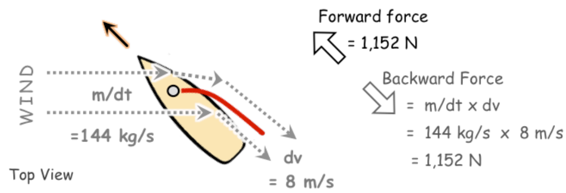

Fig. 2c-ii. Example calculation of Newtonian forces.

D. Sailing into the wind.

According to Newtonian mechanics the closer the boat sails into the wind, the greater the 'm/dt' and 'dv.' Therefore, the greater the forces generated (Force = m/dt x dv), and the higher the boat's speed. This feat occurs because the force generated by the sail is not limited to the speed of the wind. In addition, closer into wind a positive feedback loop develops, accelerating the sailboat.

The Newtonian explanation in more detail is due to:

- The force generated by the sail pushes against the turbulence behind the sail, and not directly against the sail as commonly believed. See Fig. 2d-i.

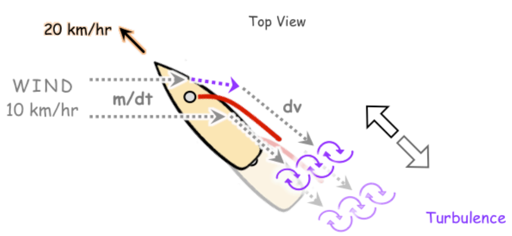

Fig. 2d-i. Sailing into the wind.

- The force (Force = m/dt x dv) generated by the sail depends on the mass of air re-directed each second (m/dt) from the wind and its relative velocity (dv) compared to the boat.
- When sailing into the wind, a significantly greater airflow (m/dt) is re-directed due to the Coanda effect on the leeward side of the sail at a higher velocity (dv). This generates a greater force (Force = m/dt x dv). See Fig. 2d-ii and 2d-iii.

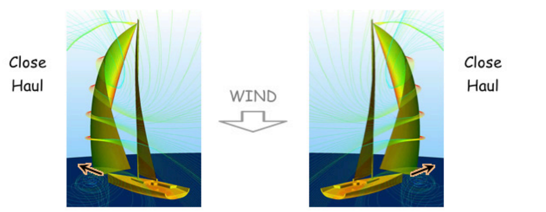

Fig. 2d-ii. Computer simulations of the Coanda effect. [28]

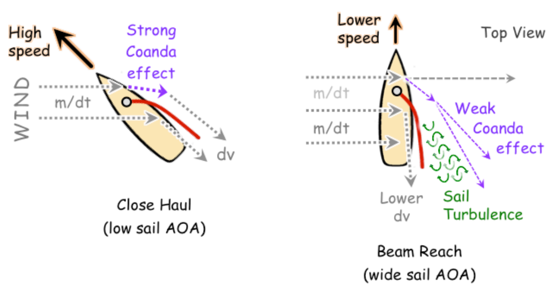

Fig. 2d-iii. Coanda effect is stronger on a close haul.

- **A positive feedback loop arises as the boat sails closer into the wind.**, As the boat's speed increases sailing into the wind, this causes an increases the 'm/dt' and 'dv' of the apparent wind, and therefore the forward force generated (Force = m/dt x dv). In turn, this causes the boat's speed to increase further.

E. *Conundrum: Sailing into the wind v. with the wind.*

A nautical conundrum exists: A sailboat on a close haul can sail into the wind faster than the wind itself, but a boat sailing with the wind cannot sail faster than the wind. For example, a boat can sail at 20 km/hr into a 10 km/hr wind, but not faster than 10 km/hr with the wind. See Fig. 2e-i.

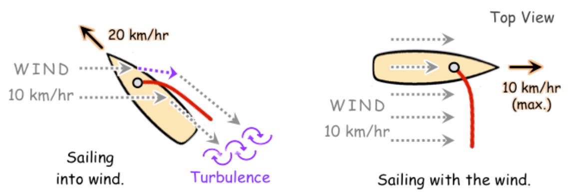

Fig. 2e-i. Example of sailing speeds relative to the wind.

This is a conundrum for several reasons:

- At first glance it appears illogical for a boat to be able to sail into the wind and to do so faster than the wind. Surely, the wind should blow the boat in the direction of the wind. How then does the sailboat use the wind to create a forward force in the opposite direction to the wind, which is greater than the wind itself?
- Compared to running with the wind on a close haul, relatively little sail is exposed to the wind. Surely, the sail would generate less power.

Newtonian mechanics and the Coanda effect provide a simple solution to this conundrum:

(i) As explained above, a boat can sail upwind faster than the wind because (i) the force generated by the sail pushes against the turbulence behind the sail, and (ii) the force generated by the sail depends on the mass of air re-directed each second (m/dt) from the wind and its relative velocity (dv) compared to the boat.

(ii) When running with the wind, a sail has nothing to push against and cannot re-direct the wind. Therefore, no 'dv' and no equal and opposite forces are possible. The boat's speed is then limited to the speed of the wind. In addition, no Coanda effect is possible on the leeward part of the sail, limiting the amount of wind being re-directed. Only the windward side of the sail is providing any forward force. See Fig. 2e-ii.

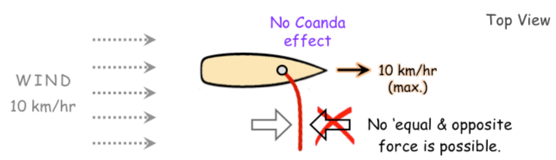

Fig. 2e-ii. Sailing with the wind.

F. *Apparent wind sailing downwind faster than the wind.*

New technologies have produced high-performance sailboats that can sail on almost any tack at speeds many multiples (e.g. 3 - 6 times) faster than the true wind, both downwind and upwind. This is called apparent wind sailing. See Fig. 2f-i.

Fig. 2f-i. Apparent wind sailing. [46]

Apparent wind sailing downwind faster than the wind has eluded explanation until now. It is argued that the same physics that explain sailing into the wind faster than the wind also explain sailing downwind faster than the wind.

The conundrum is that in apparent wind sailing boats sail downwind several times faster than the wind. It is counter intuitive for a boat to sail downwind faster than the wind, when powered by the wind. For example, a boat can sail downwind on a broad reach at a boat speed of 30 km/hr, with a 10 km/hr tailwind. See Fig. 2f-ii.

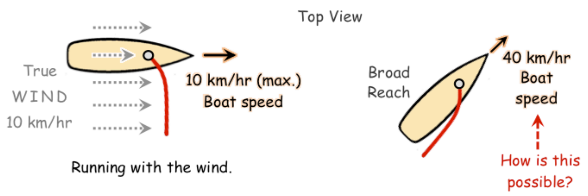

Fig. 2f-ii. Sailing downwind faster than the wind.

G. *Solution to sailing downwind faster than the wind.*

Key issues for apparent wind sailing downwind faster than the wind include:

1) **A sailboat maintains the apparent wind in front of it,** regardless of whether it is sailing upwind or downwind.

2) A boat sails downwind faster than the wind, which is explained by combining Newtonian mechanics with Galileo's assertion that all motion is relative.

When sailing upwind and downwind, the sails re-direct the relative airflow (headwind) backwards toward the stern of the boat to create a force (Force = m/dt x dv) that propels the boat ahead.

From the perspective of a sailor standing on the boat, the wind pushes against the boat sailing upwind, and pulls (sucks) against the boat sailing downwind. However, the sailor and the boat cannot tell the difference between being pulled or pushed, because these forces are indistinguishable.

Nonetheless, to avoid confusion in this analysis, a boat sailing upwind the wind is described as being pushed backwards against the boat. Conversely, for a boat sailing downwind faster than the wind, the wind is described as being pulled backwards relative to the boat.

For example, if two boats have the same boat speed of 3 times the true wind (i.e. 30 km/hr) travelling upwind and downwind; with a true wind of 10 km/hr, then the boats have different ground speeds. See Fig. 2g-i.

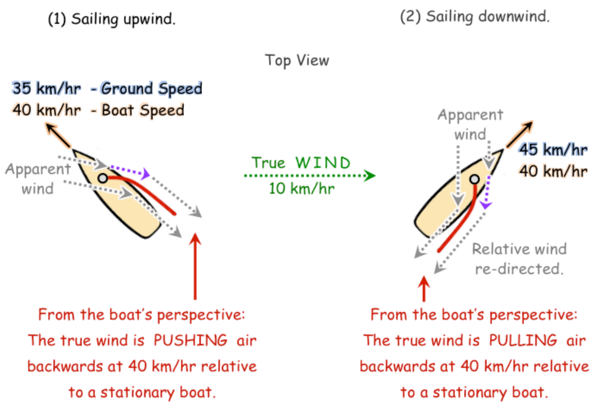

Fig. 2g-i. Relative movement of the wind and boat. 1

This example can be illustrated in a different way with the same boats side-by-side and true wind blowing in opposite directions. The relative action (pushing / pulling) of the wind is also opposite. See Fig. 2g-ii.

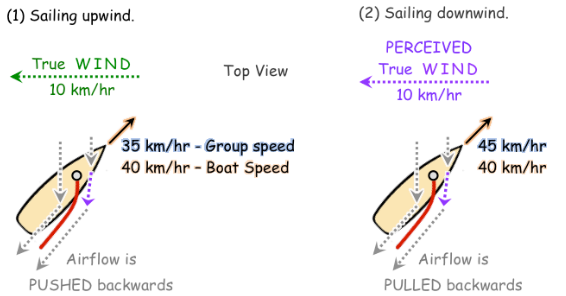

Fig. 2g-ii. Relative movement of the wind and boat. 2

From the perspective of the boat sailing downwind, the true wind is perceived as travelling in the opposite direction.

This aspect of the argument is confusing at first, as it is counter intuitive. Yet it breaks no laws of physic and fits with what is observed in practice. It is hard to reason that a tailwind is pulling air backwards relative to the boat sailing downwind. The boat is outrunning its tailwind and accelerating further away. It is simply the reverse of sailing into the wind faster than the wind.

The different relative ground speeds and directions observed on the two different boats in this example are largely irrelevant to the forces generated by the sail.

3) **The transfer of momentum from wind to the sail.**

According to Newtonian mechanics, a force is created when the sail re-directs the relative airflow backwards against the undisturbed true wind, creating turbulence. The turbulence provides something for the re-directed wind to push against and generates the equal and opposite forward force. This process slows down the true wind, extracting momentum from it. The momentum is then transferred to the boat. See Fig. 2g-iii.

Therefore, the sail transfers momentum from the wind to the boat by slowing down the true wind, both during upwind and downwind sailing. The wind is the only source of power and energy for the sailboat.

This transfer of momentum helps explain how a boat can sail downwind faster than the wind.

4) Apparent wind sailing downwind.

The transition from running with the wind to apparent wind sailing downwind using example speeds is described as follows: See Fig. 2g-iii.

a) Drag from the water generally means running with the wind, which produces a speed below that of the wind.

b) Shifting to a broad reach alters the AOA of the apparent wind, which exposes the leeward side of the sail to the apparent wind. This change boosts the mass of air re-directed backwards each second (m/dt), which is helped by the Coanda effect. In turn, this increases the generated force (Force = m/dt x dv) by the sail, causing the boat to accelerate.

c) As the boat gains speed, the AOA of the apparent wind moves towards the front of the boat. The boat transitions to apparent wind sailing and the physics allow the boat to exceed the speed of the wind.

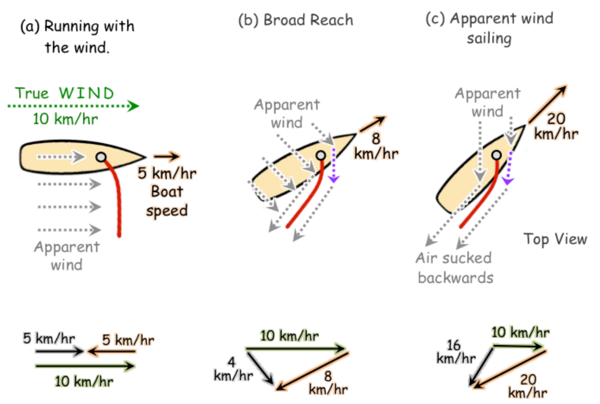

Fig. 2g-iii. Downwind sailing with example speeds.

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