Modeling the Forces on a Sailboat
OSS summary

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1 Introduction

My project aims to model the lift and drag forces on the sail and keel of a sailboat and calculate the sail set angle that maximizes forward motion. The boat modeled has the rough dimensions of a sunfish, with an eppler 379 airfoil modeling the sail and a naca 0006 airfoil modeling the keel.

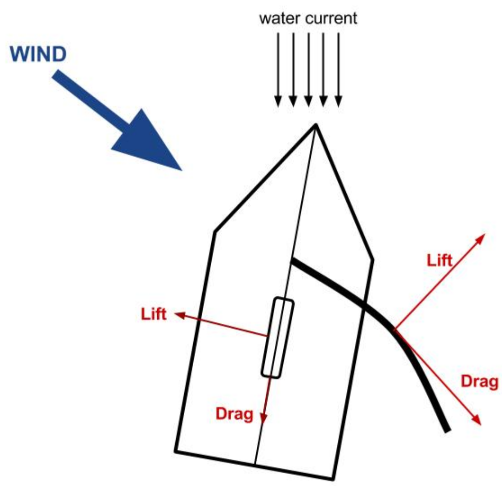

Figure 1: Forces on xy plane

A full-sized sailboat is extremely complicated. The boat is affected by the shape of the sails, keel, and hull, the angle of these three elements in relation to each other, the wind, and the current, drag forces on all parts of the boat due to both wind and water, and many other factors. In order to simplify this problem, I made several major assumptions. First, I ignored all forces on the hull. The sail, which in real life is an flexible, ever-changing surface, was modeled as solid airfoil. Additionally, the heel of the boat was not considered, leaving only forces in the xy plane. Further research into this topic would begin by modeling the effects of boat heel and the hull. A sail as a flexible surface, instead of a fixed airfoil requires focused pHd level knowledge and would be much more difficult to model.

2 Sail Forces

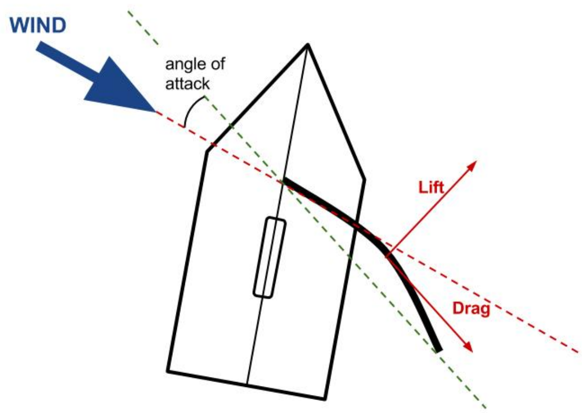

Figure 2: Forces on the sail

The equations of for lift: $F_l = \frac{1}{2}\rho S C_l v^2$ and drag: $F_d = \frac{1}{2}\rho S C_d v^2$ on and airfoil are relatively straightforward. For both equations, ρ is the air density, S is the surface of the sail, and v is the velocity of the air flowing over the sail. Lift always points perpendicular to the sail and drag is always parallel to the sail. The final variable, C is a complicated coefficient that encompasses sail shape, reynold's number, and other factors. It is difficult to calculate quantitatively so the sail in the simulation uses coefficients measured experimentally on a [airfoil] airfoil with [constants]. The coefficient used depends on the angle of attack of the sail (see figure 2).

Modeling the sail required determining the angle of attack, α given the current sail angle and the current wind direction relative to the boat, looking up the coefficient for lift and drag given α, calculating the magnitude of lift and drag, and setting the correct direction given sail angle.

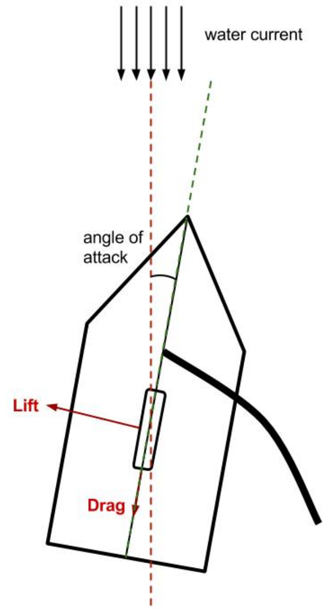

Figure 3: Forces on the keel

3 Keel Forces

The equations of lift: $F_l = \frac{1}{2}\rho S C_l v^2$ and drag: $F_d = \frac{1}{2}\rho S C_d v^2$ on the keel are identical to the equations for sails. In this case, ρ is water density, S is the total surface area of the keel, and v is the water velocity of the water over the keel. The coefficent C is taken from [source] with [constants] and is again dependent on angle of attack α (see figure 3).

Modeling the keel forces was more complicated than sail forces because of the way angle of attack is calculated. For sails, this depends on wind direction and sail angle, which are both independent features defined by the user. The angle of the boat relative to its heading is determined dynamically such that the forces on the sail and keel balance out, preventing sideways slippage of the boat. Adjusting the keel α changes the lift and drag forces on the keel, which affects the total forces on the boat. This slowed down the simulation significantly, as it ran through each boat angle and found the one that best balanced the total forces.

4 simulation

The simulator creates a boat object that saves state information such as the sail angle and the sail and keel coefficients. Given a wind angle and magnitude, the boat can calculate the net forward force currently acting on itself from the sail and the keel. From this, the simulator takes a given wind and finds the sail angle that maximizes the forward force. Figure 4 was produced by running this optimization for a range of wind angles, demonstrating that the optimal relationship between wind angle and sail angle is roughly linear.

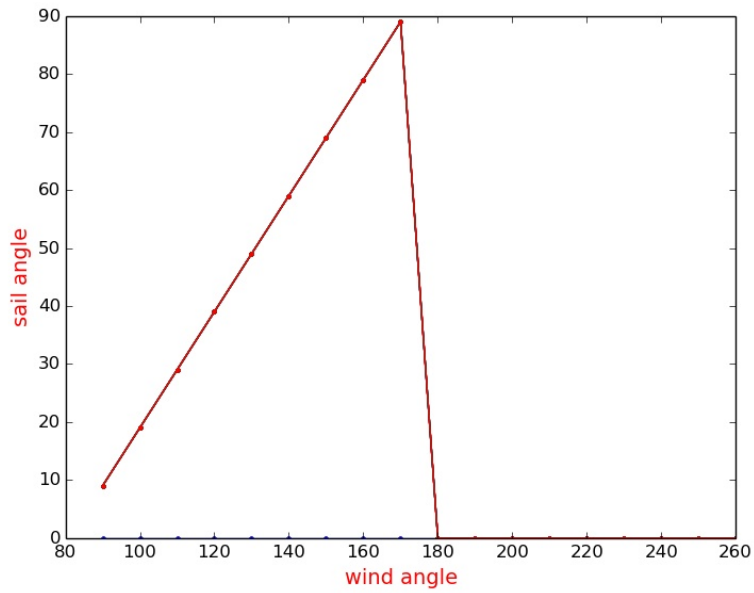

Figure 4: When the wind is coming over the bow, then the sail is close hauled. As the wind shifts to coming over the port side, the sail shifts to full out. After that point, the sail is no longer produces significant aerodynamic lift.

5 Conclusion

The discovery that optimal sail angle is directly proportional to wind direction is not a new observation. In fact, a sailor friend of mine recently pointed out that she has been trying to tell me this for several years now. I have, however, learned lessons along the way that aren't directly related to the results of the simulation:

1. Recognize when it's time to seek out help, and then act on that knowledge. Failing to do so will only prolong the inevitabale and result in a inferior final project.

2. If someone has a request that includes the words "math" and "sails", run. Quickly. Unless it is your PhD project. Otherwise, it is not worth your time and sanity.

3. The ORS software team greatly simplifies the mechanics of sailing. Whether or not this constitutes a problem remains to be seen.

4. Sailboats are very cool. I am tempted to continue this project next semester since increasing my understanding the minutae of sailing physics has greatly increased my intuitive understanding of how to control a sailboat.