

ENGINEERING 90 PROPOSAL

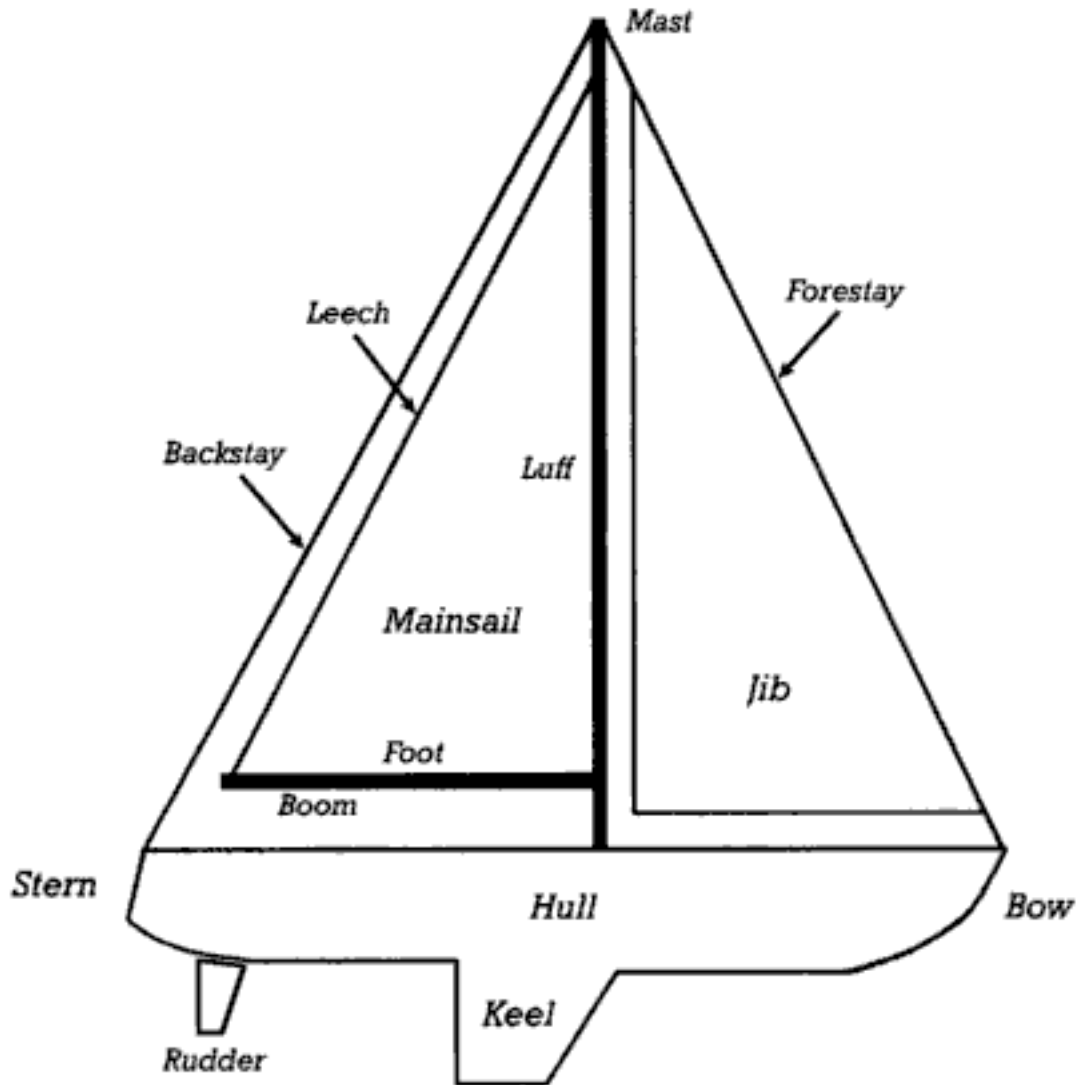
Mainsheet Tender



Jonathan Harris
Fall 2007

ENGINEERING 90 PROPOSAL

Mainsheet Tender



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Fall 2007

Abstract

This paper outlines my proposal for my Engineering 90 senior design project. This proposal will focus on the specific tasks that I plan to undertake and include their organization into the Critical Path Model which will project my estimation of completion based on time allocation. I intend to build a mainsheet tender for a sailing vessel. The bulk of my time will be divided between two main tasks: creating the physical manifestation of the mainsheet tender and creating the measuring devices for the inputs off of which I will optimize. After testing the mainsheet tender in the lab, it will be field tested using a variety of vessels (with availability) to ensure that it is able to withstand various amounts of force, moment and impulse, and that it is easily configurable for a variety of boats and sails. I hope to create a device that is both universal and durable.

Introduction

The mainsheet tender is a device that directly controls the angle of the sail on a sailboat. The angle of the sail is important in that it determines both the shape of the sail, and the amount of wind that can fill the sail. Given a trajectory for the sailboat, there exists an optimal angle that the sail can be kept at which allows for optimal sailing conditions. Using a variety of inputs we will seek to automate the process of setting the mainsheet at that angle and allow for simpler sailing conditions. There are two many possible situations to optimize for. In the case of this proposal, we will seek to optimize for two situations, which are not entirely independent of one another.

1. Maximum Velocity
2. Heel Angle

In both situations we will be looking to optimize a single variable, in the first the velocity of the sailboat (or scalar speed) and in the second, the angle of the boat (the heel of the boat) which generally relates back to the velocity of the boat. One universal idea that will fall under categories is finding the perfect sail shape for any given direction given a constant wind.

The proposal will begin by exploring the technical aspects of sailboat physics. It will then go into the project plan which will further examine the necessary inputs and the construction of them in order to set the variable mainsheet length. Here we will examine the objective, approach and output of each task individually. This section will also include a timeline and a Critical Path Analysis or Management tool to efficiently and logically arrange the tasks. Finally, it will outline a time budget of required hours per week to complete the project. In the section following, I will discuss my expertise in the area including my sailing experience, and engineering background. The Project Cost's are discussed in the section fol-

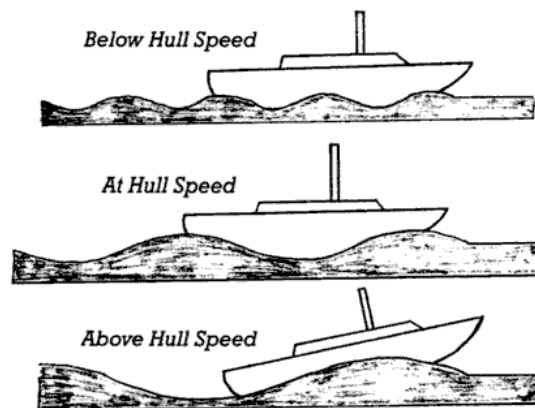
lowing. The final section will outline my journaling method of project reporting which will be explained at depth below.

Technical Discussion

My proposal seeks to optimize a sailing vessel, and so to begin, we must first examine the physics behind sailing vessels. Having examined the physics behind the way sailing vessels work, we will discuss the machines

A sailing vessel is comprised of three pieces which interest us: the Hull, the Keel and the Sail. We will begin by exploring the hull as it is the hull which determines the maximum speed that a sailboat can achieve in addition to it's ability to accelerate and it's available speed in low wind conditions. There are two types of water vessels, those that plane or skip across the water and those that displace and move through the water. Our analysis will only deal with the latter type. It so happens that the maximum speed of any vessel moving through liquid is determined by the length of the hull. The shape of the hull is also important in that it determines the friction or resistance that the vessel experiences during movement through the liquid. Finally, the hull - along with the keel - determine the stability of the boat, which is a crucial aspect of the performance of the boat.

We begin our discussion of hull speed by acknowledging the simple fact that hulls moving through water generates a wave. Smaller velocities generate smaller waves, and larger velocities generate larger waves. The maximum length of the generated wave - the maximum wavelength so to speak - occurs when a single wave stretches from the bow to the stern of the boat.



Bow Wave and Boat Speed ("Hull" speed occurs when there is just one wave along the side of the vessel.)

Image courtesy of Bryon D. Anderson.

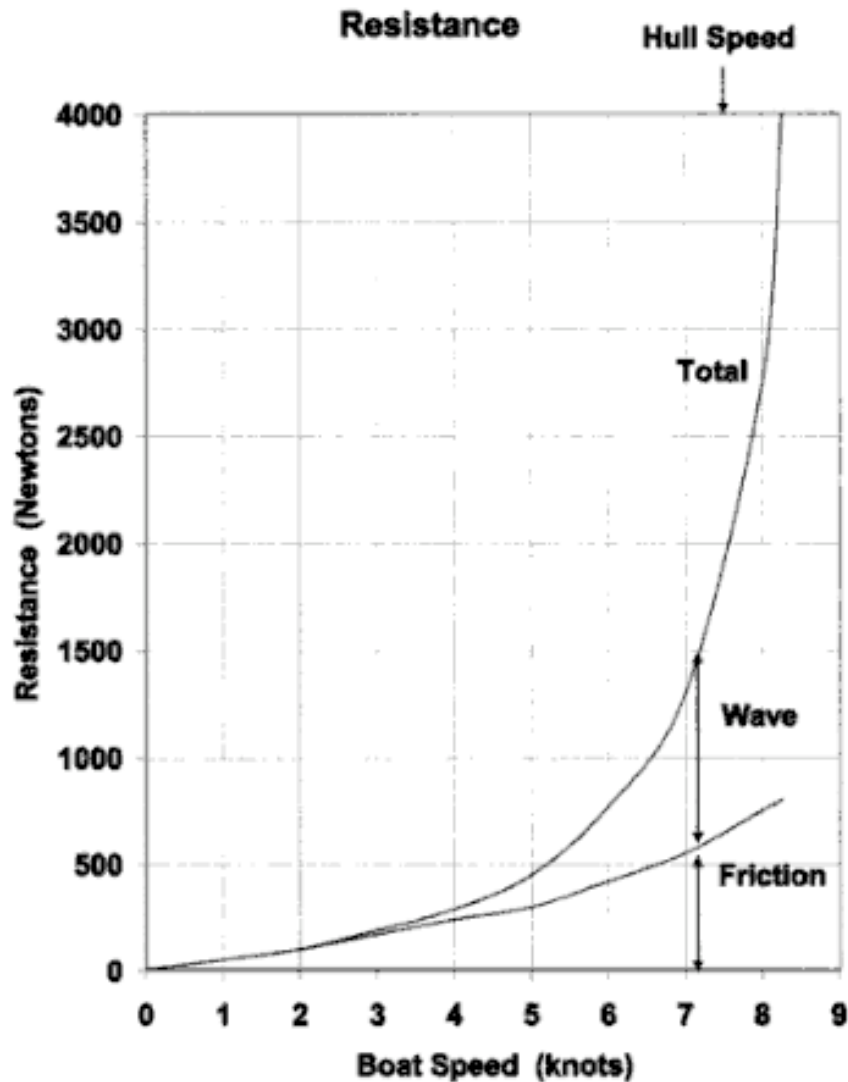
There is a crest at the bow and the stern with a trough between in the center of the boat. If we consider the friction of the boat and the resistance of the vessel in the liquid, this is the velocity at which during steady state the boat is at it's maximum. If the vessel were to go any faster, the stern would drop into the trough of the wave and the resistance would increase dramatically forcing the boat to slow down. Thus, we have reached the conclusion that there exists a relationship between speed and length. The speed of the vessel will be limited to the speed of the wave that has a wavelength equal to the length along the waterline of the boat. This "hull speed" effectively limits the speed of most sailboats to less than 10 knots and of most naval vessels to less than 30 knots.¹

Wavelength (feet)	(ft/sec)	Speed Mph	Knots (1knot= 1.15 mph)
1	2.3	1.6	1.4
5	5.0	3.4	3.0
10	7.1	4.8	4.2
20	10.1	6.9	6.0
30	12.4	8.5	7.4
50	16.0	10.0	9.5
75	19.5	13.3	11.6
100	22.6	15.4	13.4
200	31.9	21.8	18.9
300	39.1	26.7	23.2

Wave / Hull Speeds image courtesy of Bryon D. Anderson.

The table above shows the speed as it relates to wavelength, thus giving the maximum velocity of any vessel (without considering the possibility of planing). The table below gives the resistance experienced by a typical sailing vessel having a waterline of approximately 30 ft or 10 meters. The asymptotic nature of the curve suggests that the resistance goes high enough that little can be done regardless of power input via sails or engines.

¹ Anderson, Bryon D., The Physics of Sailing Explained. 2003

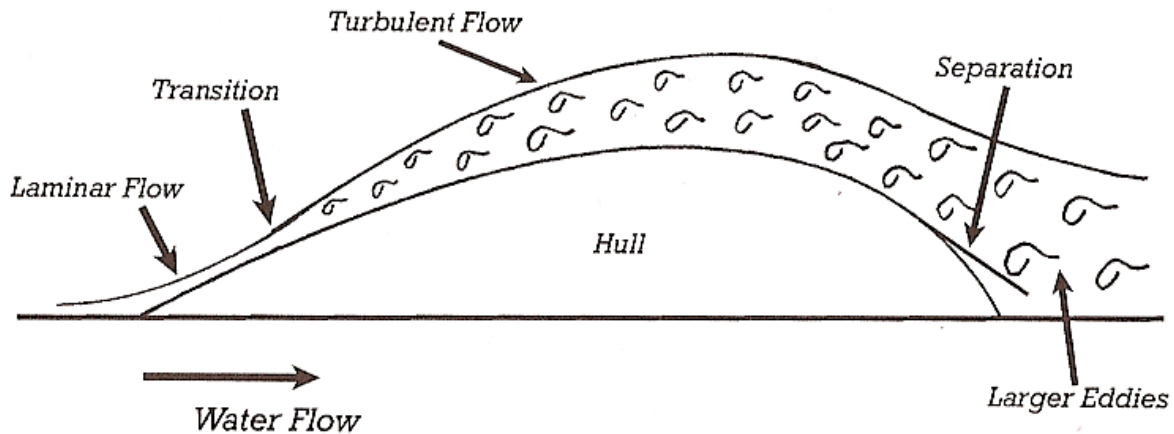


The graph above shows drag components and hull speed for a typical sailing vessel with a waterline of approximately 10 meters. Image courtesy of Bryon D. Anderson.

Everything experiences resistance as it moves through a liquid or gas. In fluid mechanics we are aware that the smallest layer of liquid surrounding an object doesn't move. The classic analogous example is that of a dust particle remaining on the hood of rapidly moving automobile. However, only the closest molecules remain (due to intermolecular forces). The remaining particles experience a shear force from the resistance, but do not necessarily move, especially as the distance from the hull increases. The perturbations in the water require energy which is taken from the sails of the vessel (on a sailing vessel, we will assume these are the only inputs of energy into the vessel, as is the normal case) thus limiting the amount of energy available to propel the vessel.

The second type of resistance comes from the shape of the hull. Clearly, a streamlined hull will create less resistance than the wider barge shaped hull. This is due to the amount of water deflected. The accepted design is that of a narrow bow and wider keel to allow for room beneath the deck. However, engineers must be wary of the affects of a wider keel which can create backward pulling eddies. These will be discussed in the following section, induced resistance.

The movement of the boat also induces resistance with the creation of small eddies which flow down the side of the vessel and behind the vessel. Larger eddies can actually have the strength to pull the vessel backwards as it moves through the water, and occurs with a wider stern. This turbulence is obviously related to the Reynolds number. Reynolds suggests that when we divide the product of the velocity and length of the vessel by the ratio of the viscosity to the density of the fluid, we begin to see turbulence around 1,000,000.



Fluid transiting to turbulent flow and formation of eddies image courtesy of Bryon D. Anderson.

The figure above shows how flow alongside the hull begins as laminar or smooth flow, and depending on the width of the hull will evolve into turbulent flow, separation and even possibly larger eddies which will drag the boat against the intended velocity. Of course, a smooth hull is extremely important in minimizing this resistance. It has been suggested that no bumps above 0.05 mm (0.002 in) can be considered “smooth.”

It should be noted that the numbers presented above are not absolute limits. The winner in the 2001 - 2002 Volvo Ocean Race, Illbruck, with a tapered hull shape was able to travel at approximately two times the theoretical maximum using planing for prolonged periods of time. Most mono hulled sailboats are incapable of performing at this level.

At this point we will continue our discussion, remaining bellow the water line, with the physics behind the fluid mechanics involved in keels.

Keels are very similar to sails, and so we will be able to apply many of the same principles we explore below in our later discussion of sails which serve as the “motors” or sources of en-



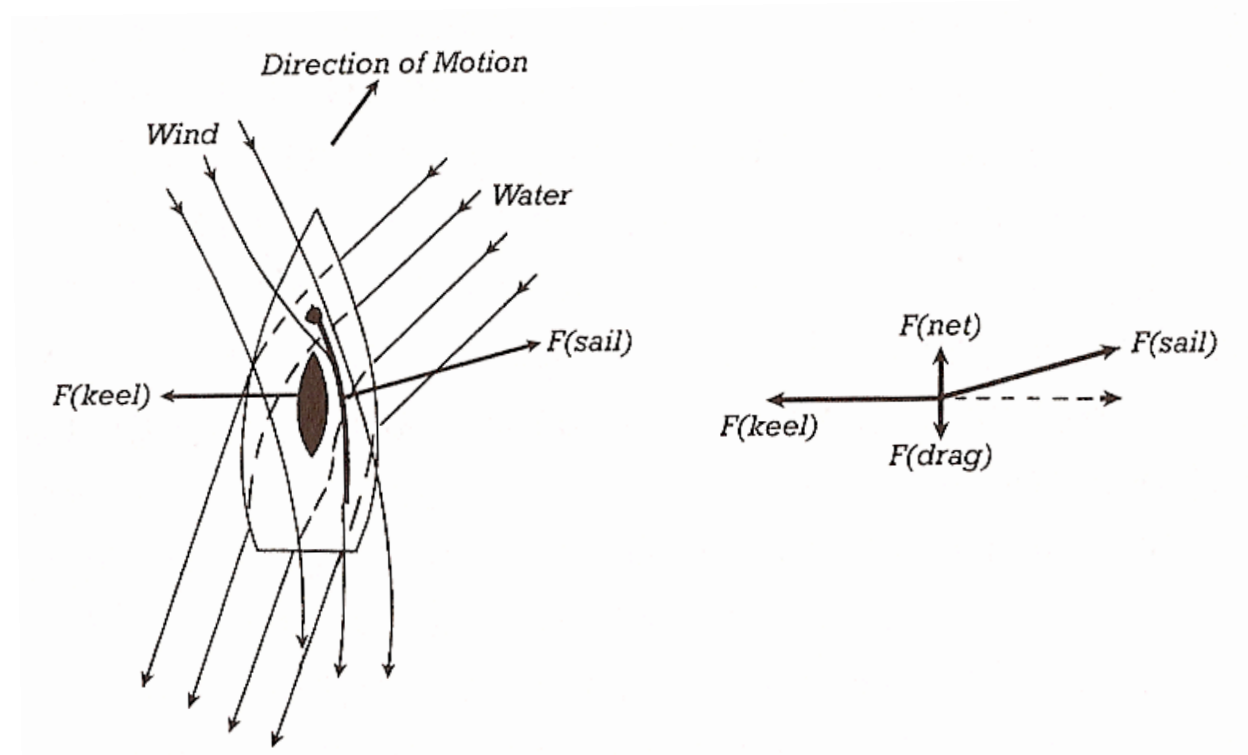
Photo by Daniel Forster, 2001 - 2002 Volvo Ocean Race

ergy that propel the boat through the fluid.

A keel can be anything that extends below the hull of the boat. On the modern sailing vessel, this is generally a long narrow piece extending well below the hull, however, a ridge line along the hull is also considered a keel.

Keels serve two purposes on a sailing vessel. First, they serve to prevent the vessel from “side slipping” in conditions when the wind approaches from the side. Secondly, they serve to offset the angle of the boat when it is heeling over in stronger wind. Two approaches exist: the first, a “full” keel runs from bow to stern, the second and more modern is the “fin” keel which can be a centerboard or dagger board or “fins” attached to the hull of the vessel. It was actually with the advancements in aerospace engineering that the keel can not only maintain the boat right side up, it can also provide a force into the direction of the wind. This is of course a reflection of Bernoulli’s principle.

The difference between the airplane wing as we normally conceptualize it which uses the work-energy theorem and asymmetry to maintain lift and the keel on a vessel going into the wind is that a keel does not require the asymmetry. As long as the angle of attack is not directly into the wind, the same affect occurs, as the wind races around the angled fin and creates a pressure difference causing a pressure difference. The forces are shown in the figure below of a sail boat traveling at about 30 degrees off of the wind direction. The picture shows the direction of the vessel slightly off from where the boat is pointing. This is called leeway or sidling. It is this motion to the side that causes the keel or fin to have an angle of attack and thus create the pressure situation described with the Bernoulli equation.



Net force on the Vessel as a summation of Forces of Keel, Drag and Sail. Image courtesy of Bryon D. Anderson, The Physics of Sailing explained

One concern of course is loss of energy in the keel. After all, a keel with more surface area will create more resistance. And further, a keel will leave vortices as it moves through the fluid, areas of spinning turbulence from where the upward moving and downward moving fluid meet up. The optimal shape for generating lift and minimizing vortices has been shown to be elliptical in distribution moving out to a zero width towards the stern of the vessel. This shape reduces the magnitude of the vortex. One might also place a vane - called a wing on a vortex (and winglet on a wing of an aircraft). Current racing vessels tend to use long keels that can be likened to the wings of a glider (sometimes as long as ten feet!) with a bulb attached at the bottom to control the turbulence experienced at the tips of wings.

Resistance from the boat's surface area remains the dominant resisting force to forward movement of the vessel. Thus, for maximum speed, the vessel should have the least amount of "vessel" below water. This is accomplished because of the narrower hull than deck when the vessel is upright. However, when the wind blows, the vessel will heel over to the leeward (downwind) side which increases form and surface resistance. Heeling over also causes a second undesirable side affect in that it can reduce speed by creating "weather helm." In this scenario, the leeward side of the boat dips into the water causing more resistance and

creating a virtual rudder board and aims the boat more into the wind. The helmsman (individual in charge of steering) must right the boat by turning the rudder so as to compensate. However, the rudder is now dragging and creating additional friction.

It so happens that there is an optimal heel angle for any given wind speed and point of sail that balances the negative affects of healing against the positive effects of carrying more sail.² This is one of the variables we will be working to maintain by tending the mainsheet.

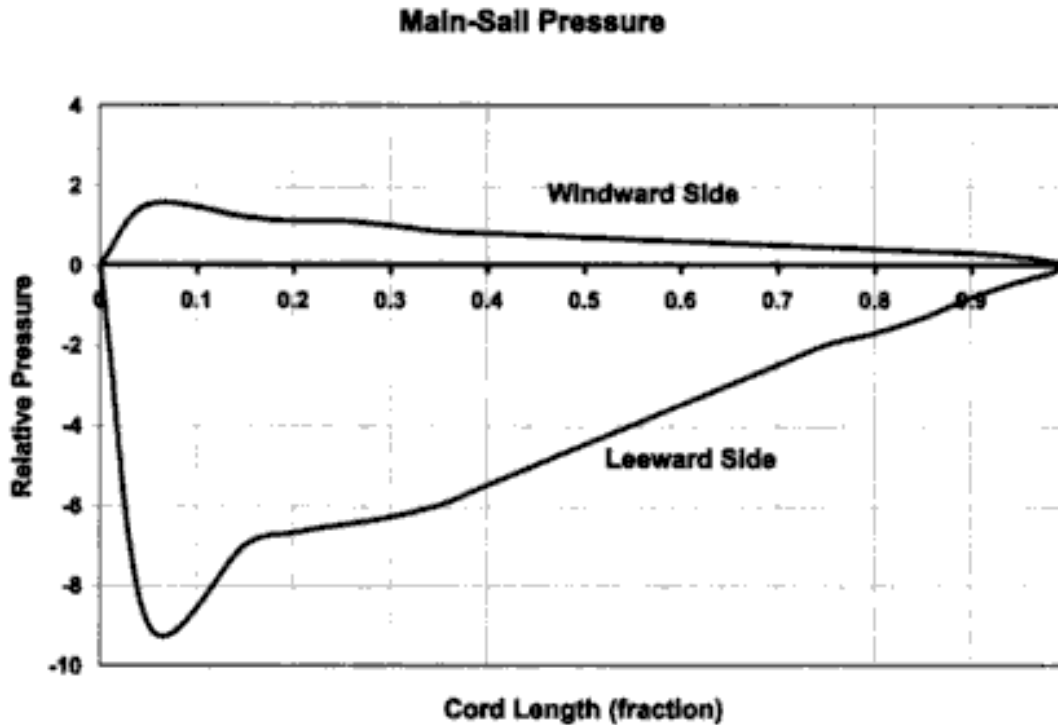
Of course, there are added benefits to having a heavier keel in it's righting ability. As the boat begins to heel, the heavier keel will bring the center of mass back by creating a moment. A weighted keel can often a right a boat that is lying at more than ninety degrees from upright.

Having looked at the various forms of resistance, we can weight them using the chart provided in The Physics of Sailing Explained (Figure 2.14, pg. 67), where friction comprises approximately 34% of the total resistance, Wave about 35% of the total resistance, Induced drag about 10% of the total resistance and Parasitic for the remaining 21% percent of the total resistance. With this knowledge in hand, one can understand the design choices made by sailing vessel designers. These values are calculated at a velocity somewhat below that of hull speed.

Having discussed at some length the relevant ideas behind hulls and keels, we now will turn our attention to sails which are the most relevant aspect of this report. This final aspect of the sailing vessel serves as the motor from which almost all forward motion occurs.

Sails operate in the same way that modern keels operate, by exploiting Bernoulli's principle, they create a pressure difference, and push forward. According to Bernoulli, the faster moving air traveling around the longer edge of the sail will have lower pressure. A wing, like a sail, must present an angle to the oncoming air flow. The sailing vessels we are dealing with, such as a sloop, are incapable of sailing dead into the wind. However, unlike aircraft wings, the net force also includes the pressure of the wind pushing up against the sail. The suction force on the outer edge of the sail is often a larger force than the pushing force of the wind. The pressure curves are dependent on sail shape, one of the variables we will be looking to control, and reading. It is important when examining the forces to consider both the fluid dynamics of Bernoulli and the intermolecular forces as presented in the Van der Waals equation. Typically, the vessel will travel between 30 and 180 degrees of the wind direction.

² Anderson, Bryon D., The Physics of Sailing Explained. 2003 pg. 61



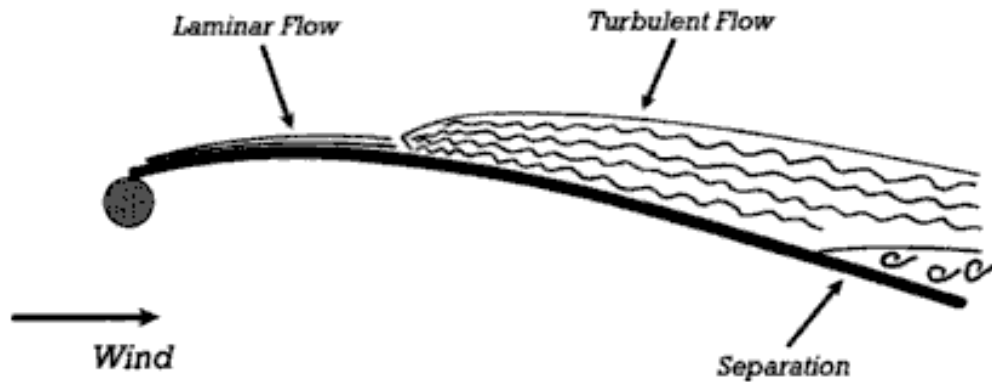
Pressure Distribution experienced by the sail. adapted from Yacht Design by Larsson and Eliasson.

The figure above shows the distribution of pressure experienced by the sail. The total area between the curves is the overall force produced by the sail acting on the boat. Obviously this force travels through the mast which needs to be sturdy enough to take the high pressures, but we will assume here that this is not an issue.

In acknowledging the similarities between the keel and sails, we need to address some of the impediments to movement that both share: resistance and energy loss. Like the keel, the sails create vortex's. Because the air meets at the back of the sail at different angles, there is a twisting effect as the air leaves. Energy is dissipated into the air to make this happen according the laws of conservation of energy. To illustrate the nature of this loss, we can look at the photograph of racing vessels moving through low lying fog, as shown below.

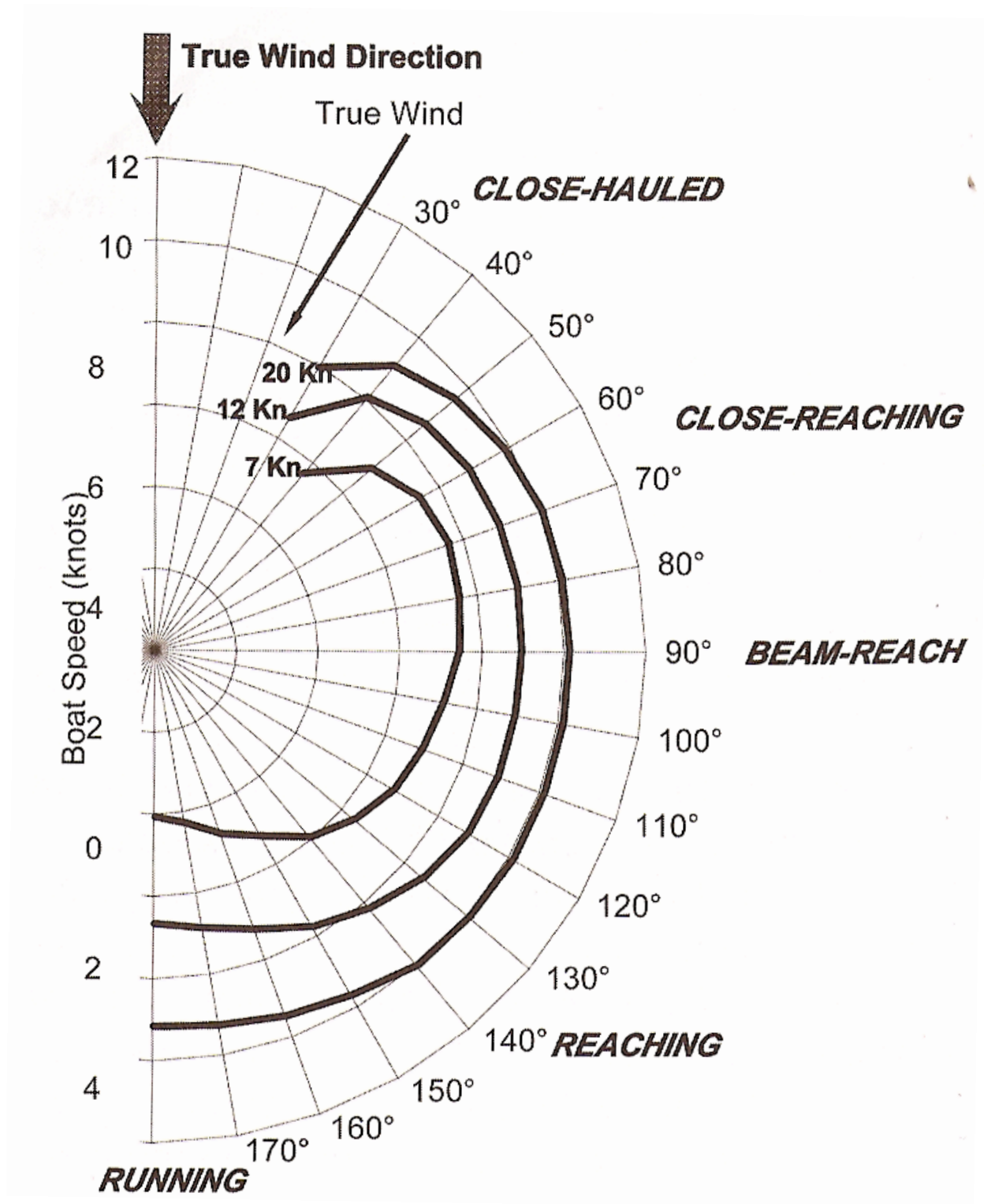
Wind moving along the sail in the same way that the fluid moving along the keel and hull of the boat produced turbulence will experience a shearing stress. Similarly, the no-slip condition of the molecules on the sail will remain in effect, however, these will interact with other causing the shear stress. Similarly, we can predict the point on the sails at which the laminar flow will become turbulent using the reynolds number. For typical wind speed of 10 knots, the switch will occur about 10 meters in. For higher wind speeds, the turbulence may occur closer to the luff of the sail. Laminar flow is possible in lower wind speeds. One of

the situations that sailors tend to avoid is the flapping of the leech, and or the flapping of the telltales which are thin pieces of streamer that used to indicate turbulent flow. For maximum power, you want smooth laminar flow on as much of the sail as possible. This stalling of the telltales, and the flapping of the leech is often due to the separation. We can see that separation in the diagram below.



Air Flow along a sail, drawing courtesy of Bryon D. Anderson.

Of course, we will ultimately be optimizing for gaining the fastest possible route to our destination. We can see the maximum boat speed in knots with respect to the wind direction on the chart below:



Sail Trims for various angles of attack image courtesy of Bryon D. Anderson.

The Physics of Sailing Explained

As we have been discussing, the sails are the predominant “motor” force of a sailing vessel, and the fuel for this is the wind. But what is meant by wind? After all, when moving in any vehicle open to the atmosphere one experiences “wind” directly against the direction of the moving vehicle. Consider sticking a hand out of a window of a moving automobile. This is the apparent wind. The wind measured on a moving boat will be the net wind. The wind of the air opposing direction and the wind with respect to the water surface, or atmosphere. Being able to measure the universal wind, that is, the wind not created by the boats movement will be important in our optimization. The wind produced from the boat movement cannot also push the boat forwards.

Having briefly explored the physics behind how sails work, we can now look into the theory behind the trimming of sails. First, we define the different terms for sailing directions with respect to the wind. Running is sailing downwind. Reaching is when the wind is coming from the side. If the wind is from behind - but not directly behind - it is a broad reach. A close reach is when the wind comes from between sideways and directly towards the boat. Close hauled is the term used when sailing as directly into the wind as possible, usually about forty five degrees.

Trimming is the art of making the sail flat or curvaceous. It is commonly understood in the sailing community that when going from downwind to pointing upwind, one needs to angle the sails closer to the centerline of the boat. In a downward sailing situation, one attempts to create a bulbous shape to catch the wind with the sail stretched out at approximately 90 degrees, or perpendicular to the horizontal line of the vessel. This bulbous shape also helps create suction in addition to “catching” the most air.

In a beam reach situation with the wind coming from the side, the sail needs to be oriented at approximately 45 degrees to the horizontal of the boat. The shape of the sail must be slightly less bulbous as a large bulb shape will not allow the wind to remain attached all the way to the leech. As we mentioned above, separation is not a good thing. Higher wind speeds require more flattening of the sail. Part of the program will be messages to the helmsman to adjust the outhaul accordingly. And of course, when traveling upwind, one must have an almost entirely flat sail pulled almost parallel to the centerline of the sailing vessel. The general rule appears to be that the sail moves from perpendicular to the centerline of the boat to nearly parallel as you go from pointing downwind to pointing upwind. And, as wind speed increases for given angle, the sails must be tightened (flattened) to stop separation from occurring. In terms of acceleration such as after tacking, it is generally best to start out with a bulbous sail and flatten it out as the vessel’s speed increases. This process of flattening the sail generally happens quickly, within a minute of tacking or even less time.

The physics behind sails, hulls and keels are relatively simple and very related with the equations paralleling one another. These three components of the sailboat however are each necessary and each have an effect on the speed of the sailboat. The actual process of trimming sails however (the only aspect of sailing that is really controllable once the boat is in the water) remains an art more than a science. Still, while fine tuning can only be accomplished well with a weathered hand, the calculations set forth in the discussion above show that to a large degree approximations will place the sailing vessel at a competitive edge based on the parameters presented. In the end, it is so much more that cannot be accounted for in physics that controls the performance of the vessels such as crew communication, smooth operation of equipment, and smart decisions. We hope however that with the creation of the mainsheet tender that a single individual will be capable of competitively sailing a larger vessel singlehandedly focusing solely on the rudder and enjoying the wind on his or her face.

Project Plan

In this section I will describe the necessary tasks that I plan to accomplish over the course of this project. The listing will be followed with a critical path analysis of the presented list of tasks.

- 1. Obtain Machine-shop certification** In order to make the main sheet feeder and create the various inputs, I will need to be allowed to use the machine shop. I have already taken the class once through, but would like to brush up on my usage of the machines. This will be very important for the feeder which will be completely customized.
- 2. Decide on and design the inputs** I intend on having a variety of inputs which will feed into a processor of some sort. Choosing this processor or micro controller will be a part of the input process as I decide how many inputs to have and the extent of the calculations I intend on performing. My objective is to select a few reliable inputs that will be durable and give accurate information off of which I can make key decisions such as maintaining the angle of the sail, or changing the angle. I will also be outputting visual (and possibly verbal) commands to tighten or release the outhaul. The definite measures will be the heel of the boat, the actual wind velocity which will be found by measuring the relative velocity from the top of the mast and subtracting from this vector the induced velocity taken from a short pipe at the front of the boat. I will measure the velocity of the boat using a variety of features, and averaging the response. My primary method will be using a GPS device. I will of course be measuring the angle of the sail to provide negative feedback for the sail angle relative to the horizontal line of the boat. Finally, I will be measuring the sail shape. This will be the most interesting. I intend to run a very thin line across the sail a few feet above the boom. It will run entirely around the sail and have lines running at set intervals to

the sail on sliders. They will report back to the main controller. The specifics I am still working out, but I hope to be able to recreate the sail shape and angle and wind direction along with speed in a visual program in Matlab which will allow for better insight on the helmsman's part in making the decisions on how to approach any direction of sailing. Previous methods involved tiny barometers which give readings at various locations and allow for a visual representation of what is going on with respect to the fluid mechanics of the system as the vessel moves through water.

3. Test Inputs I will need to design a test process for measure how accurate the inputs are. Having this accuracy will allow me to weight them prior to the optimization and calibration. I would ideally like to use a wind tunnel (such as exists in Hicks for the fluids labs) for the testing of the devices to make sure that they concur in their readings. Failing this, or perhaps in addition, I will measure in the field against tested instruments already mounted on a vessel. I can also test on a land vehicle such as a car for things such as the absolute wind direction and velocity measurement device.

4. Design Mainsheet Feeder Under the direction of Professor Orthlieb, I will work on a design for a compact, waterproof durable mainsheet feeder. Because I don't have information on the torques, impulses, moments, and forces experienced by the mainsheet, I don't have the specifications necessary to build this as of yet. It will however have a motor controlled by a chip. In order to lock the device, the rope will be cinched down from either side as it passes through a loop. The entire device will swivel so that the main sheet feeds directly out of the motor to the boom. There will be a winch to wind it in for close hauls, and an emergency release for when the boat has heeled beyond a reliable amount. The rigging will remain in the boat so that the boat can be returned to land in the case of malfunction. There will also be automatic controls for slight adjustments to be made which will remain in affect unless there is drastic change in one of the input variables.

5. Motor Selection I will have a working knowledge of the types of impulse I will require to select a motor that will be able to provide the torque (using a pulley system if necessary) to change the length of the mainsheet during sailing operation. I will also be looking for something that can be quickly recharged, is silent, small, and lasts for long periods of time.

6. Battery Selection to control the motor, and input devices, a battery will be required. I will select a rechargeable battery capable of powering my motor. Considerations will be weight, and characteristics such as voltage, current, etc.

7. Build Mainsheet Feeder I will work in the shop to construct the actual feeder designed prior to battery selection. Prior to this I will need to order materials which will be determined during the design period. The device will be created in Solidworks.

8. Test Mainsheet Feeder before continuing, I will require a bit of testing on the feeder to ensure that it is properly responding to my input controls. The serve motors will need to be timed to compress or release at the same time, and the device must spin approximately 180 degrees freely.

9. Create Optimization Program I will begin working on the program which will read in the inputs, and place them into the calibration curves. The output will be messages to a crew man such as the helmsman and instructions to the motor. It will calculate the fastest possible velocity for a given direction based on the inputs, ask the user what speed they would like to travel at (leisurely or racer) and trim the sails accordingly. Testing of this will require a test device.

10. Build Water Proof Container Because electronics don't like the wet or the cold, and we will be on the sea, I will develop or find a waterproof box that allows for wires to come in and out. This box will hold the battery and winch and be attached via a locking device to the boat itself.

11. Build Test Device Once each aspect is working I will design a test device that will be a makeshift model sized sail attached to a mast locked in the ground. I will use a fan to simulate a wind tunnel pushing air over the device and optimize variable by variable. This will be the final phase of land testing, and the only time prior to mounting on the boat that the

12. Final Testing on a Boat Professor Orthlieb has suggested that we might be able to gain access to a vessel in the spring for some testing on the open water to see if the mainsheet controller does in fact function as expected.

The following three items are self explanatory.

13. Prepare and Deliver mid-semester presentation

14. Prepare a final project report

15. Prepare and deliver final project presentation

The table below shows each task described above along with an estimate of the duration of time necessary to work on it. It will be the basis for the critical path diagram included in this report.

#	Task	Duration (Days)	Effective (hours)	Needs	Feeds
1	Obtain Machine-shop certification	Done	Done		2, 7, 11
2	Decide on and design the inputs	5	25	1,	3,
3	Test Inputs	5	25	2,	
4	Design Mainsheet Feeder	3	15		5, 6, 7, 8
5	Motor Selection	.5	2.5	4,	6, 7, 8,
6	Battery Selection	.5	2.5	4, 5,	7, 8,
7	Build Mainsheet Feeder	3	15	1, 4, 5, 6,	8
8	Test Mainsheet Feeder	1	5	4, 5, 6, 7	
9	Create Optimization Program	7	35		
10	Build Waterproof Container	.5	2.5		
11	Build Test Device	2	10	1, 2 - 8	12
12	Final Testing on a Boat	5	40	1 - 11	
13	Prepare and Deliver mid-semester presentation	3.5	17.5	Depends	Depends
14	Prepare a final project report	8	40	1 - 12	15
15	Prepare and deliver final project presentation	8	40	1 – 12, 15	
Totals	--	50	250	--	--

I come onto this job qualified in both regards. First, and foremost, I have grown up a sailor attending sailing camp when I was younger, and sailing with my cousins at the beach during the summer. For the past few summers I have competed in the Georgica pond races. I bring a passion to this project to learn and explore and optimize.

Equally important in my preparation for taking on this project is that I approach this after the iterative and recursive process of three and half years of engineering classes taken at

Swarthmore. While my experience to date has mostly been in electrical, my dynamics class taken in the fall of 2007 has strengthened my analytic mechanical skills and I feel comfortable with the math. Most importantly I feel comfortable with my abilities as an engineer to ask questions, find help, and persevere both as an individual and as a team backed by the support of the Engineering department at Swarthmore College.

Project Cost's

#	Item	Expected Cost	Funding Source
1	Microcontroller		
2	Input Devices		
3	Wiring		
4	Building materials for mainsheet feeder		
5	Motor		
6	Battery		
7	Building Materials for test set		
8	Boat usage fees		
9	Travel Costs to testing site		
10	Waterproof Container		