Introduction

First Steps

I started thinking about electric propulsion for boats about seven years ago. At the time, I owned an O'Day 20 ft sailboat. Knowing that an efficient hull was needed to propel the boat with as little power as possible, I decided to use the O'Day sailing hull to test the idea. The simplest solution was to buy an electric trolling motor and to put the two 12 volt batteries in series to provide 24 volts of power. At 30 amps, the input power to the motor was 720 watts or nearly 1 hp. (1 hp equals 746 watts.)

The results were under-whelming: at full power the boat moved at possibly 2 or 3 mph and lost steerage whenever the wind picked up. To a retired engineer, who loves everything about boats and has time on his hands, the seed of a challenge had been planted. After all, 1 hp was the equivalent of 7 "manpower" and you would think that 7 rowers pulling hard could move a small boat fairly quickly while keeping it under control. So, the question was how much power was needed to move a small boat at hull speed and could that amount of power realistically be generated electrically?

The answer is that 1 to 2 hp is adequate to achieve hull speed in a small sailboat.

One way to prove this statement is to consider the power developed by the sails. In Thomas Firth Jones' book *Low Resistance Boats*, he quoted Bill Durham: "One thousand square feet of modern sails will reliably deliver 1 hp (running in a 10 knot breeze) to 9 hp (reaching in a 20 knot wind)." But, said Jones, "A thousand square feet of sails would have to be put on a 45 foot boat." Interpolating the 9 hp number for a 20 ft boat with 175 square feet of sails, we found that the sails generated about 1.5 hp in a very strong wind.

Another way to prove this important premise was to consider the actual power that an outboard motor generated to move the boat forward. My 20 footer had a 6 hp Johnson outboard mounted on a bracket. The specifications state that the motor delivered the 6 hp at the output shaft at 5000 to 6000 rpm. Although I never took actual measurements, I estimated that the 80% cruising rpm needed for a comfortable 6 mph hull speed was about 4000 rpm. As we will find out later, propeller speed versus power output is a cube function. This means that as the speed of the prop increased, the power output increased much faster. In fact, when the speed is doubled, the power output increases by a factor of eight. So, at 80% of maximum rpm, the shaft hp of this outboard was approximately 3.2 hp. When this number is multiplied by the efficiency of the propeller, which could be no more than 50% considering its high speed and small diameter, we found that the actual force pushing the boat was 1.6 hp.

A third way to test this important concept was to measure the pull of the sails with the boat tied to a mooring and to compare the answer with the pull produced by an electric motor. I tried this experiment and found that the biggest gust of wind on a day with 15 to 20 mph winds produced a pull of 105 lbs. I estimated that the average pull was 50 to 60 lbs. (Should someone want to try this maneuver, be sure to use a preventer on the boom because violent boat movements are likely to occur). I performed many such "static thrust" tests, where the transom of the boat was secured to a mooring and the pull of the motor was measured. One static thrust test performed with a golf cart motor powering an outboard motor leg produced 70 lbs of thrust with an input power of 1500 watts or about 2 hp, which was more thrust than the average pull of the sails on a very windy day.

The fallacy demonstrated in the trolling motor experiment was that the 720 watts was the input power. The output power, which actually pushes the boat along, was the input power multiplied by the efficiency of the motor and of the propeller. Assuming 60% efficiency for that particular motor and 50% efficiency for that particular propeller, we now have 720 X 0.6 X 5 = 216 watts or less than 0.3 hp pushing the boat. Almost three quarters of the input power was wasted in heat, friction and turbulence that did nothing to move the boat forward. In terms of "manpower," we only had 2 rowers pulling hard instead of 7. No wonder the boat moved at such a slow speed and lost maneuverability when the wind picked up.

The Need for Efficiency

A recurring theme in this book is the need for high efficiency. The three major components, the hull, the motor and the propeller, all have to be selected to provide the best possible performance within the framework of a practical vessel that is fun to use. We tried to pursue this search for high efficiency without going overboard...so to speak.

A long narrow hull, like that of a racing scull or a canoe, requires far less power to propel it through the water than today's best designed sailboat but it is not practical for pleasure boating. At the turn of the century, when gas engines were first installed in boats, they had a single cylinder and produced about 2 hp. To make up for the lack of power, their hulls had a very long waterline and were very narrow to the point, it was said, that the passengers had to part their hair in the middle to keep the boat balanced.

The type of motor used in electric boats today is the series-wound traction motor. It isn't all that different from the motors built 100 years ago. It is very reliable and in the 2 or 3 hp size, such as the ones found in golf carts, the efficiency is about 75%. It should be pointed out, however, that 75% is the full power efficiency; at less than full power, the efficiency diminishes rapidly. The performance of electric boats could be greatly improved with a more efficient electric motor for boating applications. We will see that a 3 phase AC (alternating current) motor is even more reliable and more efficient than the DC (direct current) traction motor and that with appropriate electronics it can be made to run on DC batteries.

The selection of an appropriate propeller is also vital to good overall performance. It is well known that a large, slow turning propeller is more efficient than a small propeller turning at high speed. The rule is that the efficiency of the propeller continues to improve up to the point where its diameter reaches 1/3 of the boat's beam measurement at the waterline and turns at a very slow speed of 300 to 400 rpm. But in small boats, there are simply too many restrictions impeding the use of such a large propeller. And today's high-speed motors, both gas and electric, make propeller speeds in the 400 rpm range very difficult to attain. But even if we can't achieve perfection, a lot can be done to maximize performance. For example, if the efficiency of each of the three main components--the hull, the motor and the drive--could be improved by 20%, the overall improvement in terms of range would be close to double. A worthwhile bonus comes from the battery when it is discharged at a slower rate.

Improving the efficiency of these components is the challenge. The rest of the book describes how to meet this challenge.

Electric Cars vs. Electric Boats

Many millions of dollars have been spent on the development of electric cars over the last few years without much success. The challenges are enormous: range, acceleration and hill climbing ability have to match what we've come to expect from a gas-powered car. With today's batteries, it can't be done. The reason is simple: to store the same amount of energy, the lead acid battery weighs about 50 times as much as gasoline (after the efficiency of the gasoline engine and that of the electric motor have been properly factored into the calculation). Accordingly, to obtain a range of 300 miles, the gas powered car would require about 80 lbs of fuel while the electric car would need 4000 lbs of batteries.

Fortunately, the challenges are far less demanding to electrify a boat. There are no hills to climb, acceleration is not a factor and power-robbing accessories such as heat and air conditioning units are not needed. Moreover, the weight of the batteries has a minimal effect on performance. In a sailboat, for instance, the weight of the batteries can replace all or part of the ballast, in which case there is no ill effect whatsoever on performance.

Types of Boats

Boats come in all sizes, shapes and prices. Their uses range from exercising in a rowboat, to fishing, to competitive sailing, to exploring. Most boats are used for fishing, day cruising or sailing in small craft (18 to 22 feet long). Unlike cars, boats receive very little use. On average, motorboats run less than 100 hours per season and sailboats are used less than one day per week. The boating that I do fits in this average category and so do the boats that I converted to electric power.

Expected Performance

The main characteristics of performance in the context of electric boats are speed and range. There are some electric racing boats where the hull is designed to plane, but for pleasure boating we are limited to hull speed. Hull speed is generally understood to equal the square root of the boat's waterline dimension times a factor as high as 1.3, depending on the boat. My experience is that the power required beyond the square root figure goes up so dramatically that it is best not to plan on it in an electric boat. For example, if the boat has an 18 ft waterline, the hull speed equals the square root of the waterline or 4.25 knots (4.9 mph). We should limit our expectations to a cruise speed of 5.5 mph to avoid being disappointed.

When it comes to range, unless the boat is a sailboat where the motor is used only to set the sails and to travel to the mooring or slip, the batteries should be selected to provide six hours of running time. For example, eight standard golf cart batteries, weighing about 510 lbs and costing about $600, will provide 48 volts for 220 ampere hours. If the motor draws 30 amps, which is the input power of a 2 hp motor, the range will be more than six hours. Of course, it takes an efficient hull and an efficient drive to obtain the desirable 5 knot hull speed. A bigger boat or a less efficient one would require more batteries or would have a shorter range; that's the trade-off.

Advantages of Electric Power

For people living near a body of water where restrictions forbid the use of gas-powered outboards, the use of electric power is an attractive alternative. Mort Ray, who owns the Ray Electric Outboard Co., told me he has a large concentration of sales near Baltimore where fishing is allowed in the reservoirs but only electrically powered boats are permitted.

Many people are environmentalists. They conserve energy, recycle materials and refuse to pollute the air or the waterways. For them, electric power is another way to protect the environment. If you've ever run a small outboard in a barrel of water and seen the scum that it leaves after a very short time, you will surely agree that it is the dirtiest internal combustion engine going.

Electric motors start instantly and the quiet, odorless and vibration-free power is a very pleasant experience. This is especially true for sailors who enjoy a quiet sail. Personally, I can't deny that engineering curiosity has a lot to do with my involvement with electric boats. However, I do like the instant and quiet power, and I am quite willing to put up with the shortcomings of limited power and the trouble of keeping the batteries charged. I hope that other technically interested, do-it-yourself boating buffs will gain some knowledge from the information that I present and will carry it to a higher level for the benefit of those who find that there is absolutely nothing in the world that beats messing about in boats.