PERFORMANCE MODELING SPREADSHEET FOR ELECTRIC PROPULSION SYSTEMS IN DISPLACEMENT MONOHULL BOATS

USER'S GUIDE

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This is the first draft of a predictive performance model for planning electric boat installations in displacement monohull boats. I am an audio/video engineer used to working with complex mathematical models for room acoustics and performance predictions for sound systems and projection systems. Naval architecture and sailing are hobbies. I have been researching and playing with electric conversion calculations for a couple of years now. But most of the rule of thumb tables and simple equation sets for estimating performance under power are geared for IC engines and there has not been a simple coherent approach for modeling the power transfer characteristics of an electric propulsion system. The math involved in computational fluid dynamics of propulsion versus hull drag makes my brain go numb and my eyes glaze over after about an hour. This stuff can't be fully calculated in Excel and most people wouldn't have the required data for their hulls anyway. So I am hoping to come up with simplified rules of thumb calculations and data tables that will apply to most situations and get close enough results, say +/-10% or so that people can have some confidence when they plunk down the big bucks for the hardware.

Any predictive model is based on a set of underlying conditions to control the number of variables. This one is no different. The model parameters are as follows.

1. Hull performance data:
    a. Waterline length and displacement entries are used to calculate speed length ratios and estimated hull resistance.
    b. Beam and hull depth entries are used to calculate optimum prop size.
    c. Prismatic coefficient is not used directly in calculations at this point.
    d. The speed/length ratio calculations are well known. The actual limiting ratio for displacement hulls is as high as 1.54 depending on hull design. The classic 1.34 ratio is just a point on the curve, but a practical one for most small boats as the power curve goes almost vertical beyond that point. Most efficient cruising speeds are going to be below 1.10 for most common hull types. The model calculates speed in knots referenced to speed length ratios based on the LWL entry.
    e. Hull drag estimates are based on tables and equations in an article by Ted Brewer in the July 2004 edition of Good Old Boat. They apply only to modern sailboats with Prismatic coefficients between .54 and .58. Waterline lengths to beam ratios for such hulls are typically around 2.5-3:1. Older heavy displacement full keel hulls will have about 5% or so higher drag figures. These figures also assume a clean smooth hull.
    f. The horsepower calculation is for the actual minimum power required at the prop shaft for a 3 blade prop of about 55% efficiency. No allowances are included for reserve power, drive system losses or accessories. It is reasonably accurate according to my correspondence with prop manufacturers. The requirements are the same regardless of the power source driving them.
    g. There is a table for entering towing test results in Lbs. If you want accurate results I highly recommend measuring the actual drag of your hull at various speeds with a spring scale between your boat and the tow vessel. The estimated drag will at least suggest an appropriate range for the spring scale. Use a GPS set to read speed in Knots instead of onboard instruments.

2. Propeller Model and Data Entry
    a. The model suggests a close to optimally efficient prop size, shaft speed, and pitch based on the hull model data. It is included as a suggested starting point for selecting an appropriate propeller. Performance calculations are based on the data entry fields.
    b. The prop data fields allow entry of size and shaft speed.
    c. Valid shaft speed range for this model is 100-300rpm per knot of boat speed.
    d. For best efficiency one should fit as large a diameter propeller as possible. The limiting factors on diameter are usually available torque, maximum draft limits, and tip clearance to the hull or prop aperture. Optimum tip clearance is generally accepted as 1/3rd the diameter of the prop. Brewer's rule of thumb for minimum tip clearance is 10% of prop diameter plus one inch.
    e. Sailors may want to reduce prop size or blade area to minimize drag under sail. Small props turning at high speed will have much greater cavitation and turbulence losses resulting in prop efficiencies closer to the 35% range than the 55% range. This model will not predict those losses
    f. Pitch is automatically calculated for a 55% slip factor. This conforms to a basic law of Newtonian physics that for every action there is an equal and opposite reaction. At any given steady state cruising speed, the mass x velocity squared plus thermodynamic losses of water flowing aft in the slip stream is exactly equal to the mass x velocity squared plus thermodynamic losses of the water displaced by the boat moving forward, I.E. 50% slip. There is a 5% fudge factor for losses due to turbulence and prop cavitation.
    g. Determining the ultimate optimum pitch for a particular IC engine and boat at full power is a real black art. For a given throttle setting an IC engine produces constant torque. Engine speed and horse power vary with the load. Over pitch the prop and you lose RPMs and power. Under pitch the prop and you over rev the engine. Props may vary in thrust response by a few of inches of pitch one way or the other due to differences in foil design. The manufacturers use voodoo to figure this stuff out. This is not an issue with series wound electric motors because the power response is exactly the opposite. Apply a known voltage and the motor is going to turn at a constant RPM. Current demand will vary as needed to meet the actual torque load. Lock the motor shaft in a vise and the current demand and torque will rise toward infinity right up to the point where the weakest link in the system blows up (hopefully that will be a fuse). Since there is no significant change in available power with small changes in pitch response, compared to simply adjusting the motor speed, there is little reason to depart from the theoretical optimum. So the model balances prop diameter against shaft speed to meet the power requirements of a particular design. Pitch is maintained at theoretical optimum.
    h. If one absolutely can't find a practical combination of prop and reduction gear to meet the power requirements, the rule of thumb for pitch adjustment is 2 inches of pitch = 1 inch of diameter. Unfortunately the standard prop equations will not model the variation in thrust for pitch adjustments alone. You are on your own here.
    i. The shaft horsepower and thrust calculated from these fields should match or exceed the hull drag and estimated HP to achieve a given speed. These results are used to spec an appropriate motor, reduction gear, and system voltage to meet power requirements.

3. MOTOR AND DRIVE SPECIFICATION
    a. The motor variables used in the calculations are the torque constant in Ft. Lbs per Amp and the voltage constant in RPMs per Volt. These are usually listed in the motor specifications under no load and maximum load. They can also be derived from the motor data charts that plot RPM and Current at a constant voltage with varying torque loads.
    b. The voltage constant determines the speed of rotation for a specific voltage input. This speed will be maintained within a very narrow range for any torque load up to the maximum peak torque output of the motor.
    c. The torque constant in Lbs/Ft determines the current demand in amps for a given torque load applied to the motor shaft. The current required will be the same for a given torque load regardless of motor speed. Actual torque load is determined by the prop. If the torque specifications are listed in Newton meters (Nm) or lbs/inch there are conversion tables to change this to Lbs/Ft.
    d. The drive reduction ratio variable will determine specific RPM and torque demand on the motor for a given prop shaft speed. From this the required motor voltage and current are calculated. This is where you match your available maximum system voltage and current limits to the drive train.
    e. Power input to the drive system will always be greater than power output. The motor efficiency rating determines thermodynamic losses in the motor. An arbitrary 4% loss is added to estimate bearing losses in the drive train and thermodynamic losses in the controller. These numbers are used to calculate power demands on the controller and battery compared to actual power output at the prop.

4. CONTROLLER SPECIFICATION
    a. Controller specs are there for visual comparison with calculated data. They are not directly involved data calculations.
    b. Be sure to spec a controller with generous reserve current capacity for reliable operation at continuous cruising speeds.
    c. As a conservative designer I would want a controller with short term peak current capacity that matches or exceeds the motor's short term peak current capacity. If you plan on continuous run times longer than one hour, the current demand for long term cruising should be around 50-70% of the one hour rating of the controller.

5. BATTERY SPECIFICATION
    a. The individual battery voltage and Amp hour rating at the standard 20 hour discharge rate are used along with the Peukert factor to estimate run times in minutes for 50% depth of discharge, 80% depth of discharge and 100% depth of discharge.
    b. The string voltage is the maximum nominal system voltage available to the controller from individual batteries wired in series.
    c. The total number of batteries in the system must equal at minimum the number batteries in series to achieve string voltage. Batteries added in parallel to increase total amp hour capacity must be even multiples of the number in series.
    d. Peukerts factors can range from a low of around 1.08 for AGM batteries to a high of around 2 for some flooded cell batteries. I have entered a mid range number that should be reasonable for most high quality marine grade deep cycle batteries. If you can find out from the manufacturer what the Peukert number is for your battery, enter that number in the data table.
    e. String current calculations are derived from the system KW rating after losses.
    f. Battery current calculations show the actual current demand for individual batteries in the string and are used to calculate run times incorporating the Peukert factor.
    g. Runtime calculations assume new batteries in fully charged condition.

6. GENERAL ASSUMPTIONS OF THE MODEL
    a. The performance predictions are based on steady state cruising speeds for optimal displacement hulls in calm flat water conditions. No winds, no waves, no currents.
    b. There is no assumption that the results given will match the actual performance of any particular boat or propulsion system.
    c. This model assumes optimum conditions of the overall system: new components, proper installation, adequate wiring, etc.
    d. Performance predictions reflect absolute minimum requirements with generally accepted minimum allowances for overall system thermodynamic losses. There are no reserves built in.
    e. The user should regard this as a planning tool and allow for appropriate reserve capacities to meet changing conditions with respect to intended use.

I hope this will prove to be a generally useful design tool for planning electric installations in small boats. By reducing the design process to a coherent set of known basic requirements we will be free to explore range of possibilities available for our intended application with confidence that results will be what we intended. The first edition is a theoretical tool only and has not been tested or verified by comparison to existing real world installations. I would appreciate any feedback that will help further refine this model including testing against real world data from existing boat owners. If in using this spreadsheet you discover any errors or omissions or have suggestions for improvements please e-mail me so I can correct them

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