A Practical Theory of the Performance of Low Velocity Boat

Shigeyuki Minami [1], and Naoki Yamachika [2]

[1] *Department of Electrical Engineering, Osaka City University, minami@elec.eng.osaka-cu.ac.jp*
[2] *Department of Electrical Engineering, Osaka City University, yamachika@em.elec.eng.osaka-cu.ac.jp*

Abstract

Research was put into the shape of the hull with the objective of making the electric boat run efficiently. This project examined the practical power characteristics of a sightseeing boat of about 20 m in length that would travel at a velocity of 5-8 km/h. It is hoped that the obtained information will be applied to future hull designs. This paper reports result of comparisons between previously proposed characteristics that were tested using a 1:4 scale boat fabricated specifically for this research.

Keywords

electric boat performance, low-velocity

1. INTRODUCTION

The reduction of CO_2 emissions has become an important issue in recent years. The reasoning is not only to solve environmental problems related to global warming but more importantly to reduce humankind's mass-consumption of energy. In other words, a reduction in CO_2 emissions means to reduce the consumption of irreplaceable energy resources such as fossil fuels. As one possible solution, a modal shift was proposed that pictures land transportation being converted to marine transportation. Compared to means of land transportation, ships consume one order less fuel. If ships could be made to run on electric power, marine transportation would be even more efficient since electric motor efficiency is superior to the internal combustion engine. Boats that run on electricity would not emit gases nor pollute the water and would run quietly. An electric sightseeing boat has yet to be used in Japan. To test performance and feasibility, we designed a 20 m-long sightseeing boat that could be fabricated in Japan [Minami, 2003 a, b, c].

Though electric motors are efficient, they have one setback in that the electricity they use as fuel has a small energy storage capacity per unit volume compared to gasoline. For this reason, an efficient hull design is needed in order to develop an electric boat. A boat's energy consumption increases rapidly in regard to the increase in velocity. Looked at inversely, a large ship can be moved with a lower amount of energy at a low velocity. A sightseeing boat is an ideal application for an electric boat because it must travel at a slow velocity. Theoretical research into efficient hulls for low velocity travel has not progressed. There are equations for expressing the relationship of energy to velocity of a ship moving at high velocity, but until recently there has been little use for an equation that expresses the performance of a boat at low velocity. This paper elucidates equations for expressing the relationships between required energy and boat velocity in a low velocity range, through tests and comparisons. It can be considered the start of low velocity hull engineering that is needed for the society of the future.

2. THEORETICAL EQUATIONS

Table 1 List of principal symbols

C_{adm}, C_c, C_k = coefficient
K_1, K_2, K_3 = coefficient
L_1, L_2 = hull length, m
L = hull length, m
R_A = air resistance, N
R_E = eddy resistance, N
R_F = a boat encounters frictional resistance, N
R_R = residual resistance, N
R_T = total resistance, N
R_W = wave making resistance, N
S = surface area below the water's surface, m^2
IHP = indicated horsepower, W
W = displacement of the boat, kg
t = water temperature, ℃
v = boat velocity, m/s
v* = boat velocity, km/h
v_1, v_2 = boat velocity, m/s
γ = specific weight of water, kgf/m^3
μ = dynamic friction factor, 1 x 10^{-6} m^2/s at 20℃ seawater
ρ = density of water, 1,025 kg/m^3 at 20℃ seawater

2.1 Resistance

This section examines the suitability of equations for expressing the relationship of boat velocity, *v*, and energy consumption, in the low velocity range. When cruising, a boat encounters frictional resistance, R_F, wave making resistance, R_W, eddy resistance, R_E, and air resistance, R_A. The total of that is the total resistance, R_T. At low velocity, frictional resistance, R_F, is dominant. The sum of all other resistances is the residual resistance, R_R.

$$R_T = R_F + R_W + R_E + R_A = R_F + R_R \qquad (1)$$

R_T is a function of hull form, surface irregularity, fluid properties, velocity of the boat, length of the boat, configuration of the boat, etc.
R_F can be expressed with the following Froude's approximation [Gillmer and Johnson, 1982].

$$R_F = \lambda \cdot \gamma \ (1+0.0043[15\text{-}t])\ S \cdot v^{1.825} \qquad (2)$$

R_F is said to account for 70 to 80% of the total resistance of a boat traveling at low velocity. Velocity is expressed as Froude's Number, $\mathrm{Fn} = v/\sqrt{L \cdot g}$. Here, L is the hull length.
Wave resistance, R_W, is caused by surface waves formed by the bow and stern of the boat as it moves. When the bow and stern waves are of the same phase, resistance increases because of what is known as a "hump". When the waves are of the opposite phase and cancel each other out, resistance decreases, referred to as a "hollow". These conditions depend on boat velocity even with boats of the same hull shape.

2.2 Determination of resistance using a model and water tank

The following equation is used for velocities v_1 and v_2 and hull lengths L_1 and L_2 of two geometrically similar boats.

$$v_1/\sqrt{L_1 \cdot g} = v_2/\sqrt{L_2 \cdot g}$$

or

$$\frac{v_1}{\sqrt{L_1}} = \frac{v_2}{\sqrt{L_2}} = const \qquad (3)$$

In other words, the equation indicates that, if Froude's number is constant, the characteristics of an actual boat can be obtained with a model. By obtaining the frictional resistance with Eq. 2 and determining the residual resistance, R_R, (dependent on Froude's number) with a model, it is possible to determine the total resistance as the sum of the two.
The power required of an actual motor is obtained by dividing this total resistance by the propeller efficiency, η_P.
The propeller efficiency, η_P, is obtained with the following equation as the ratio of the required horsepower H_{PR} when the model is running and the required horsepower H_{PT} when the model is being towed.

$$\eta_P = H_{PT} / H_{PR} \times 100\ [\%] \qquad (4)$$

2.3 Calculation method of required horsepower

The following two approaches are available for calculating the required horsepower based on boat velocity.

a. Assume the mechanical efficiency and transmission efficiency based on the required horsepower of a model traveling at the required velocity, and then obtain the required horsepower.
b. Determine the coefficient C_{adm} from the actual measured values of a boat of a similar hull shape using the following equation, and then obtain the required horsepower, assuming that the following equation can express the velocity, v^*, and required horsepower, IHP, of the boat.

$$IHP = 750 \times \frac{(\frac{W}{10^3})^{\frac{2}{3}} \times (\frac{v^*}{1.85})^3}{C_{adm}}$$

$$= 750 \times \frac{1.58 \times 10^{-3} \times W^{\frac{2}{3}} \times v^{*3}}{C_{adm}} \qquad (5)$$

where, C_{adm}: Admiralty coefficient = 60-100.
Here, W [kg] is the displacement of the boat, and v^* is the boat velocity. C_{adm} is either Froude's Number (F_n) or a function of values known as the "velocity length ratio". In the data obtained so far, F_n has rarely been 1 or less. This is where more research is needed in low velocity hull engineering.

2.4 Effect of individual parameters

Let us look at the effect of individual parameters [Larsson and Eliasson, 1977].

a. Effect of displacement
   At an F_n of 0.5 or less, the residual resistance R_R is said to be mostly proportional to W. However, as W increases, so does R_R.
b. Effect of hull length/displacement
   A boat of a large ratio of hull length to displacement is light in the water, but it is said that the effect is felt only when traveling at high velocity.

At low velocity, frictional resistance is dominant. This can be determined from the Reynolds Number, R_n.

$$R_n = v \cdot L/\mu \qquad (6)$$

Here, μ is the dynamic friction factor (1×10^{-6} m^2/s at 20℃ seawater).
The frictional resistance, R_F in Eq.2, is expressed with the following equation.

$$R_F = C_F\, 0.5\, \rho\, v^2\, S \quad (7)$$

Here, ρ is the density of water (1,025 kg/m^3 at 20℃seawater), S is the wetted surface area. C_F is the coefficient of friction and expressed with the following equation.

$$C_F = 0.075/(\log R_n - 2)^2 \quad (8)$$

In this way, resistance at low velocity can be estimated.

2.5 Theoretical equation of boat velocity and required power

Followings are the theoretical equations for the estimation of boat velocity. [Geer, 1989; Little, 1994]

Gerr's Formula: $IHP = 0.0359 \times W \times \frac{v^{*3}}{L^{1.5}}$ [W] (9)

Yokoyama's Formula [Yokoyama, 1980]:

$$IHP = 750 \times \frac{v^{*3} W}{(1.85)^3 \times 10^5}\left(v^{*3} K_1 \frac{W^{\frac{1}{3}}}{(1.85)^3 10L^2} + 10K_2\sqrt{\frac{10L}{W}}\right)K_3$$

$$= 1.18\times10^{-3} \times v^{*3}\, W\left(0.0158 \times v^{*3} K_1 \frac{W^{\frac{1}{3}}}{L^2} + 31.6K_2\sqrt{\frac{L}{W}}\right)K_3 \quad (10)$$

where K_1, (Hull resisitance coefficient) 0.4-0.55

K_2: (Friction resistance coefficient) 2.2-2.7 for power boat, 2.4-3.2 for sailing boat

K_3: (Wave resistance coefficient) ≒ 1

Keith's Formula $IHP = 750 \times \frac{W}{10^3} \times \left(\frac{0.827 \times v^*}{1.85 \times C_K \times \sqrt{L}}\right)^3$:

$$= 0.75W\left(\frac{0.447 \times v^*}{C_K \times \sqrt{L}}\right)^3 \quad (11)$$

where C_k = 1.3-1.5

Crouch formula $IHP = 750 \times \frac{W}{10^3} \times \left(\frac{54.03 \times v^*}{1.85 \times C_C}\right)^2$:

$$= 0.75W\left(\frac{29.2v^*}{C_C}\right)^2 \quad (12)$$

where C_C = 180-200

3. RESULTS USING A TEST BOAT

3.1 Cruising test

Tests were performed using a catamaran hull of a total length of 4.4 m shown in Figure 1. The specifications of this boat are given in Table 2.

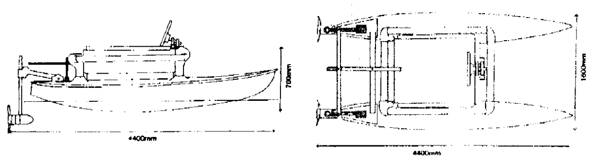

Fig. 1 Experimental model of catamaran

Table 2 The specification of the tested boat

Length	4.4 m
Width	1.6 m
Shape	Catamaran
Beam width	0.25m (each hull)
Electric motor	PM type 300W x 2
Propeller	2 Blades, 30 cm in diameter
Power supply	75AH lead-acid battery x 2 or 1.2KW fuel cell: NEXA (made by Ballard Co.)
Displacement	140kg

Figure 2 shows the relationship of the required horsepower as a product of the voltage and the current to the velocity, v, of this boat. The characteristics of several formulas are simultaneously shown.

By projecting Figure 2 as a logarithmic plot, the power (IHP)-to-velocity characteristics become clear (Figure 3).

The solid lines in the plot indicate the theoretical and measured power-to-velocity characteristics. In this velocity range, it can be seen that the measured power is almost proportional to the cube of the velocity. For an absolute value, Yokoyama's equation agrees best with the test results.

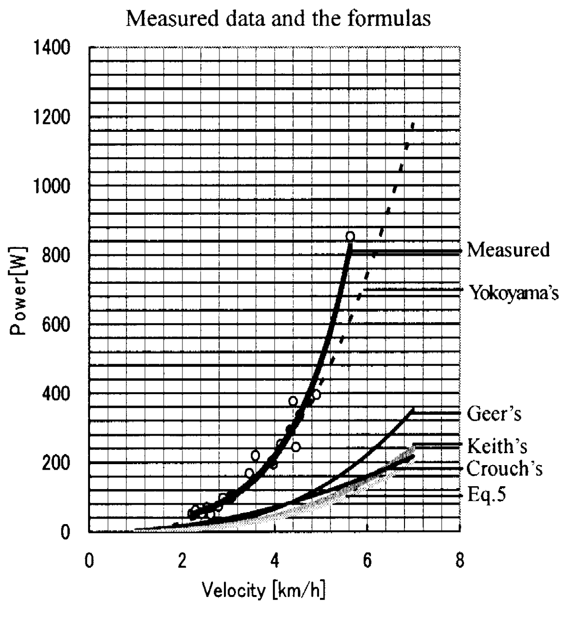

Fig. 2 Test results of horsepower (IHP) vs. boat velocity in a water tank

3.2 Propeller efficiency

The required horsepower at various velocities was obtained for this boat when being towed and when traveling by means of an onboard motor (Figure 4) [Minami, 2003a]. The propeller efficiency obtained with Eq. 4 is

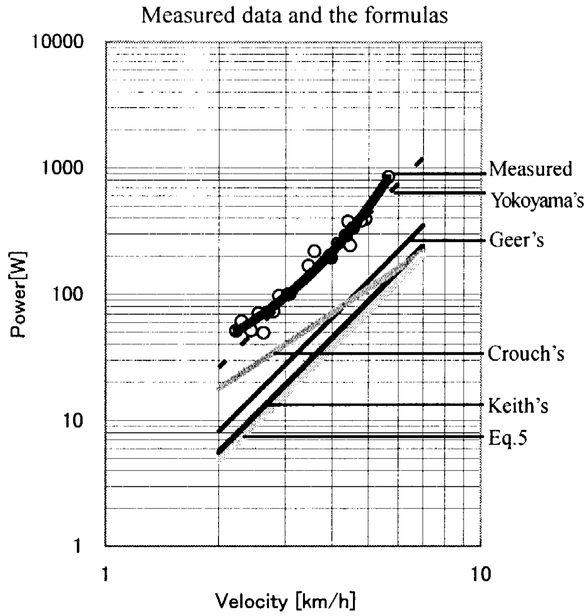

Fig. 3 Characteristics of Figure 2 as logarithmic plots

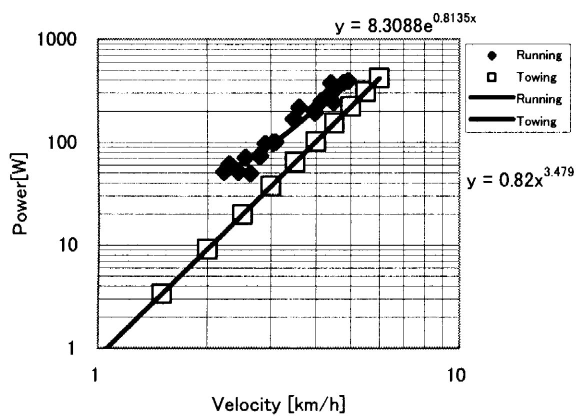

Fig. 4 Experimental relationship of required power and velocity in towing and running

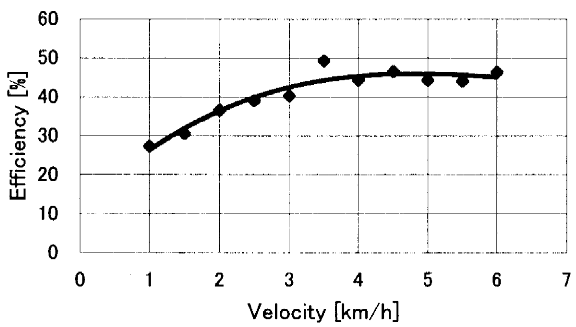

Fig. 5 Propeller efficiency deduced from the result shown in Figure 4

shown in Figure 5. A photograph of the propellers that were used is shown in Figure 6. A direct-drive electric motor is installed on the propeller shaft and the two propellers move in synch to the hand wheel. A photograph of the test boat is shown in Figure 7.

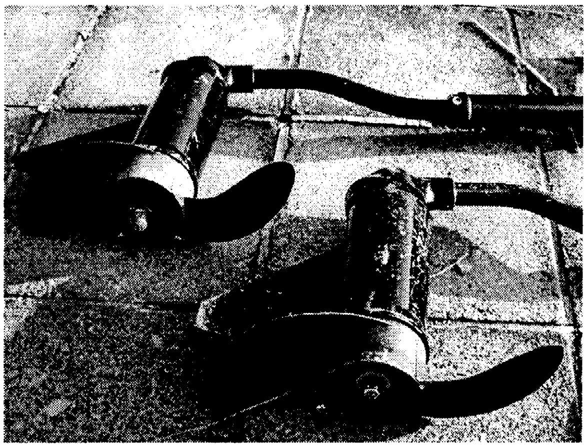

Fig. 6 A photograph of the propellers with electric motors of the test boat

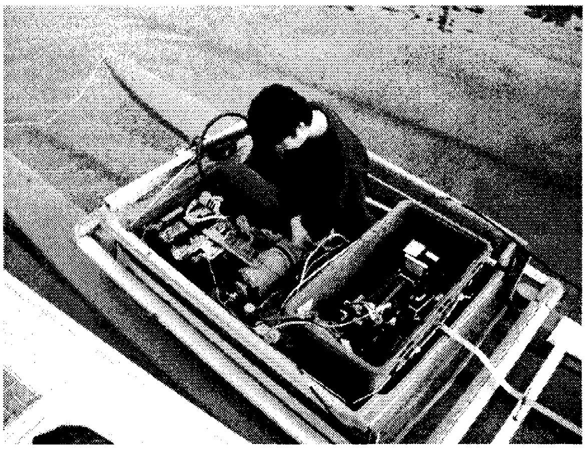

Fig. 7 The experimental boat using a fuel cell

4. CONCLUSIONS

For the purpose of developing a hull for a 20 m-long electric boat that travels efficiently, a 1:4 scale model was built and the relationship of velocity and required power at comparatively low velocity was investigated by comparing various velocity theories. As a result, Yokoyama's theory best agreed with measurements made using the test boat. It was also shown that propeller efficiency of the propellers used in the tests was a maximum of 50%.

It is believed that demand will grow in the future for boats that move at low velocity. On the opportunities presented by researching and developing a 20 m electric sightseeing boat, research should now be able to focus on reducing resistance against hulls of various shapes as a means for improving the cruising efficiency demanded of electric boats, or in other words, it is viewed possible to develop the field of low velocity hull engineering.

References

Geer, D., Propeller Handbook, *The Complete Reference for Choosing, Installing, and Understanding Boat Propellers*, pp. 152, International Marine, Maine, USA, 1989.

Gillmer, T. C., and B. Johnson, *Introduction to Naval Archtecture*, pp. 324, Naval Insitute Press, MD, USA, 1982.

Larsson, L., and R. Eliasson, Principles of Yacht Design, 352, *International Marine*, Maine, USA,, 1977.

Little, D., Electric Boats, *The Handbook of Clean, Quiet Boating*, pp. 150, International Marine Maine, McGraw-hill, USA, 1994.

Minami, S., and N. Yamachika, Experimental Performance of a River Cruising Electric Boat Electric-powered by a Fuel Cell, *Journal of Asian Electric Vehicles*, Vol. 1, No. 2, 475-477, 2003a.

Minami, S., Designing the River Cruise Electric Boat, *Journal of Asian. Electric Vehicles*, Vol. 1, No. 1, 131-138, 2003b.

Minami, S., New Opportunities for Electric Vehicle Researches, *Journal of Asian. Electric Vehicles*, Vol. 1, No. 2, 2003c.

Yokoyama, A., *Yacht Designing* (in Japanese), KAZI Co.,Ltd., pp. 210, 1980.

(Received April 3, 2004; accepted May 2, 2004)