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Feasibility Study of Building a Human Powered Hydrofoil Vessel

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ABSTRACT: In this paper, a feasibility study of building a Human Powered Hydrofoil (HPH) vessel is reported. Hydrofoil vessels are a well-known class of high-speed crafts. In addition to high-speed operation, the hydrofoils have a reliable maneuvering capability, good stability and proper operation in waves. Also, a human powered vehicle, nowadays is an advancing idea. Different aspects of the design and construction of a HPH is explained. Some ideas are principles and others are ideas, set forth and should be further analyzed and validated theoretically and experimentally.

Keywords: *human powered hydrofoil; feasibility study; design and construction.*

INTRODUCTION

Not very long ago, human moved only by one's own power. Such a limitation gradually vanished by the development of energy extraction, conversion and transfer methods and today the quality and quantity of the motivating power has an incredible distance from the power of human muscles. However, using human power to move vehicles is still reasonable in many cases. In addition to advantages such as: low cost, providing physical and mental health, no environmental damage, simplicity, etc., human powered vehicle has a very important role in the advanced engineering effort.

The limited human power forces the designer to optimize the design. Direct human manipulation of the vehicle, forces the designer to increase efficiency, safety, comfort and beauty of the vehicle, otherwise the restricted available power will be wasted and the vehicle effectiveness falls dramatically.

In a human powered watercraft, the three main methods of collecting human power are directly from the hands or feet, through the hands with oars, paddles, or poles or through the feet with pedals and a crank or treadle (Wikipedia, 2011). After the 1970s the hydrofoil vessels' application gradually rose. The human powered type of these vessels developed in different countries contemporaneously. Designers and constructors of the Human Powered Hydrofoils (HPH) have been mostly the student groups and since enough financial benefit has not been assumed, the industry has had less interest and seriousness in the subject. Two major introducer and sponsors of the HPHs, are the International Human Powered Vehicle Association (IHPVA) and the International Hydrofoil Society (IHS). Moreover, there is an international competition for HPHs the criterion of which is the maximum speed in a 100-yard course. As of today, the Decavitator HPH from MIT with an 18.5 knots record is the pioneer (IHPVA, 2011).

According to the great difference between the density of water and air, a basic idea in designing high-speed vessels is to reduce the draft and consequently the wetted surface. But by the draft reduction, the buoyancy force will decrease as well, and it must be compensated by another force. The lift which is exerted to the hull in planing vessels, the lift of hydrofoils in hydrofoil vessels and the pressure of air layer in hovercrafts are the main compensators and many innovations in high speed craft technology are due to these main ideas. Efficiency of each of them varies according to the vessel's dimensions, service speed, environmental

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conditions and mission of the vessel. In comparison hydrofoils have some prominent properties: adequate stability, low resistance, good mechanical strength, good performance in waves (seakeeping), maneuverability, less pounding than planings. These characteristics cause the hydrofoils to be a good choice for special performances as military high-speed vessels.

Designing the hull of a hydrofoil is a sensitive step, since maximum resistance occurs in the hull-borne state, and after the maximum value, the hull starts to rise out of the water; during rise, resistance should decrease with an accelerating rate. This process can be seen in Fig. 1. The resistance of the bare hull of a planning vessel is shown for comparison.

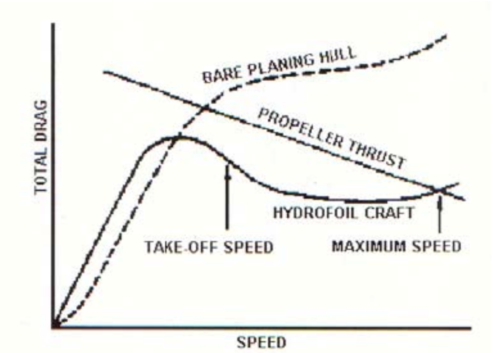

Fig. 1: Resistance vs. speed comparison (IHPVA, 2011)

On the other hand the propulsion system must be designed with regard to the hull-borne state, for the maximum resistance occurs at this state. The straight line in Fig. 1 illustrates the propulsion force. At maximum speed, the thrust line crosses the resistance diagram.

One of the hydrofoil privileges is the controllable lift. The lift force and so the rise speed can be changed by changing angle of attack of the foils or using flaps. Moreover, using ladder type arrangement for the aft foils smoothens the rise and provides the ability to control the drag. Fig. 2 shows the two main types of the foils. Appropriate design of the foils can provide necessary stability for the vessel.

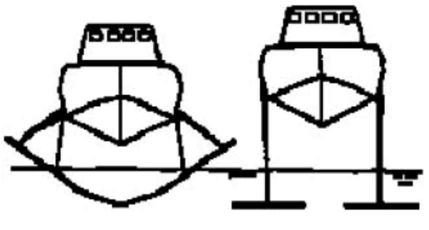

Fig. 2: Surface piercing & fully submerged hydrofoils (IHPVA, 2011)

Surface piercing foils provide transverse stability by the self-controlling property. In fully-submerged foils, the stability can be obtained by increasing the span of the aft foils. However, fully-submerged foils are less susceptible to the surface waves, thus cause less resistance, and their construction is easier as well, and therefore they are usually preferred.

Longitudinal arrangement of the foils depends on the location of gravity center. Three types of longitudinal arrangement, as shown in Fig. 3, can be generally named, though many minor changes are possible.

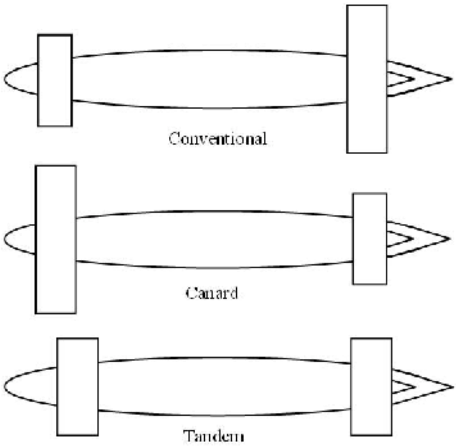

Fig. 3: Longitudinal arrangement of hydrofoils

Canard arrangement by which approximately 65% of the total weight is sustained by the aft foils can be more adequate because of less pounding and better seakeeping. Having these basics in mind, principles of the Human Powered Hydrofoil design will be outlined.

MATERIALS AND METHODS

Our goal is to attain the maximum speed with a HPH. The design must be accomplished with the least weight, minimum resistance, maximum power output and adequate strength. All of these, more or less depend on the constructing material as well. To begin we must decide on the entirety of all parts and limit the work to reasonable bounds - i.e. before any detailed calculations, we must make choices reference to the statistical information from similar projects (Decavitator, Cetan and Phyxius) and our general knowledge.

1. Number of Riders

HPH vessels are usually designed for one or two riders. The two-rider vessel should be bigger, therefore its design and construction is more complicated and expensive. The resistance of the two-rider vessel, which is bigger, will be larger albeit the power output is more; however, the order of increase of each (resistance and power) is not known. To exclude such intricacies, the one-rider vessel is chosen.

2. Number of Hulls

Total resistance exerted to the bare hull of a marine vehicle in calm water, can be decomposed as follows:

$$R_{\text{total-barehull}} = R_f + R_r \qquad (1)$$

where R_f is the frictional resistance, and R_r represents the rest of resistance which is mainly due to the wave-making effect. In fact, the pressure field generated by a body moving through the water has intense gradients near the sharp edges of the body. These sharp edges include the fore and aft ends, which are stagnation points, and shoulders. At shoulders, the fore or aft body of the vessel has a sharp turn to join to the parallel middle body.

In small, high-speed crafts the body shape has a smooth gradient and the major pressure gradients occur at fore and aft ends only. Thus there will be two potential fields and consequently two wave regimes in accordance to fore and aft end pressure gradients. The superposition of these two wave regimes results the total wave-making resistance. Of course, the magnitude of the superposition will oscillate between a maximum and a minimum, with respect to the phase difference of the two sources.

Additionally, the more the body is slender, the less will be the pressure gradients and the wave-making resistance. Therefore the wave-making resistance R_w of one hull can be reduced by increasing the vehicle's length-to-breadth ratio L/B. But in the case of twin-hull, R_w depends on many factors, which are still not studied accurately. For example, distance of the hulls from each other will affect the overall hydrodynamic performance.

Frictional resistance is directly proportional to the wetted surface of the vehicle. To tolerate a definite weight, the underwater volume is definite and thus the total wetted surface is almost constant, that is, one hull must have bigger breadth and draft to provide the same buoyancy as two hulls. Hence frictional resistance does not differ so much. On the other hand, to provide transverse stability, it is a good idea to have two hulls but the construction of one hull conceivably, is simpler and less costing. Although more accurate comparison is needed, the one hull vessel is a better choice.

3. Vehicle Stability

Lateral (roll) and longitudinal (pitch) stabilizers can maintain the stability. Two roll stabilizers, in the sides of the vessel, can be arranged several meters apart and out of water when the boat is upright namely in zero heel angle. Rolling to each side enters one of these stabilizers to water, which will generate a righting moment.

Longitudinally as well as transversely, center of buoyancy and center of gravity should be aligned accurately, otherwise the vessel will have an inherent trend to loll, which will result in an undesired list angle in the roll direction or a trim angle in the pitch direction.

4. Human Power

Human power is the main factor in determining vessel dimensions, its weight, propulsion system and power transmission system. An estimate can be obtained by some simple tests. Obviously the power of legs is more than arms, and using legs and arms simultaneously is rather impossible, so the test will be similar to biking. We need to reach the maximum speed so the rider must provide the maximum power in a short time interval.

The rider’s position is important as well. In semi-recumbent position, center of gravity comes down i.e. GM increases; hence the lateral stability of the vessel is improved. In fact the position of G, center of gravity, depends on the weight distribution, but the position of M, metacenteric point, depends on the geometrical characteristics of the vessel and will not change significantly by the change of weight distribution. The aerodynamic shape of the vessel in semi-recumbent position will be better also. The test results according to reference (KTH, 2002), in semi-recumbent position, are shown in Table 1. Extrapolating the results, one can deduce that an ordinary, somehow athlete, man can provide approximately 650 w in 15 s with 150 rpm. A first-class athlete will generate 600 w in 1 minuet and 730 w in 30 seconds (KTH, 2002).

Table 1: Ordinary Human Power Test Results

t= 30 s	t= 60 s
n= 130 rpm	n= 90 rpm
P= 620 w	P= 500 w

5. Propulsion Systems

The main choice for propulsion system is the pitch propeller i.e. a propeller that generates thrust perpendicular to its rotation disk and its axis is in the surge direction. However, other systems such as Pelton wheel may be worthy studying, though with a little wave its efficiency decreases greatly.

Propeller can be established in three different positions: under water, in air and in the surface of water. In the latter position we will need a surface-piercing propeller. For a surface piercing propeller power transmission can be done simply (because propeller and pedal are in the same attitude), but a permanent airflow will be generated (ventilation) which can cause side forces that are able to stray the vessel from its path in the horizontal plane. On the other hand, it seems that some energy will dissipate as impulse and thermal exchanges due to the continuous impact of the propeller blades to the water surface. Moreover, surface piercing propellers have good efficiency in high rotation speeds but the rpm of the propeller of HPH will not be high. With regard to these flaws this option is not reasonable.

A comparison between air-propeller and water-propeller demonstrates almost equal efficiencies. Presence of the propeller and its appendages in water will increase the resistance intensely. However, air-propeller should have a big diameter to produce necessary power and is also susceptible to wind. Manufacturing process is complicated in either case and the final weight doesn't differ so much, since material and dimension effects in overall weight, cancel out each other. For example air-propeller can be constructed by balsa and strengthened by carbon fiber, but the water-propeller generally is constructed by a metallic alloy, thus the bigger dimension of the air-propeller is compensated by its light materials.

Eventually taking a decision is difficult and available equipment must be considered. The air-propeller was experienced more successfully, and is chosen in this stage of design.

6. Power Transmission System

For this part, we have some choices in sequence with the propulsion system. If we use Pelton wheel as the propulsion system, power-transmission will be the simplest, for the pedal and the wheel are co-axe. If we use surface piercing propeller, power-transmission will involve a 90-deg gearbox and a longitudinal shaft. The gearbox will be set beside pedal; input shaft is the pedal's shaft and the output shaft that has turned by 90-deg is attached to the propeller. To omit the side forces that are generated by the ventilation, we can use a ball coupling, which attaches output shaft of the gearbox to a distinct shaft (Fig. 4). The latter shaft, which bears the propeller, can turn in horizontal plane; therefore side forces will not influence the vessel, albeit the effective thrust will be less.

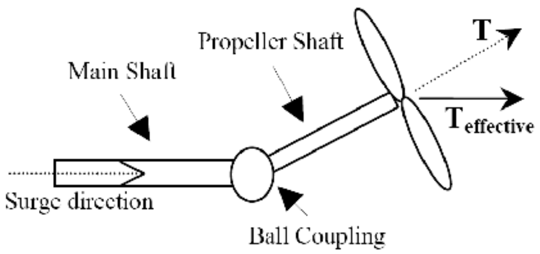

Fig. 4: Power transmission (surface piercing propeller)

For the air-propeller that was our first choice there are two possible power transmission systems:

a) Chain and Gearbox

A chain can transmit the power from pedal to the propeller location, and then a bevel gearbox can turn it 90-deg (since there is a 90-deg angle between the shaft of pedal and propeller). The long chain, hanged diagonally in air results in intense increase of weight, reduction of architectural grace and some problems in arrangement, maintenance and even lubrication. Also the chain and its wheel are relatively expensive. On the other hand, using 90-deg bevel gearbox decreases power transmission efficiency.

b) Tortuous Time-Belt

This one responds much better. Four pulleys are necessary: one pulley for the pedal, one pulley for the propeller and two others as mediators to provide the 90 degrees needed twist (Wall et al., 2011). Hence, by a single loop of belt and four pulleys we can transmit the power. If the material and the module of belt and pulleys are chosen accurately, slip probability will decrease and very high efficiency will be achieved.

7. Hydrofoils` Geometry and Arrangement

There is no need to evaluate and sketch foils' geometry. Actually, several profiles have been tested by persons or institutes (Eppler, NASA, Wortmann…) having high-tech facilities. They have done theoretical calculations beside empirical measurements, and have published the results as professional books, reports or web pages. The canard arrangement in which the aft foils are bigger is preferred for the longitudinal arrangement of foils, since the center of gravity is toward stern. Additionally, little fore foils will cause less pounding (Speer, 2001).

Two little fore-foils some meters apart and a ladder type aft-foil will be an adequate composition. Ladder configuration improves the performance of vessel in rising, and this way drag can be controlled as well. In fact, according to the relation of lift and drag with the second power of velocity, using a single foil makes the task intricate. When the velocity reaches the rise limit V_r the lift is almost equal to the weight so more increase of lift is unnecessary, however, V_max is about two times V_r, thus the lift and consequently drag will be very greater than needed. According to the formula:

$$F = 1/2\ \rho V^2 \times A \times C_L \qquad (2)$$

where ρ is water density, V the relative velocity of the hydrofoil and water, C_L the lift force coefficient of the hydrofoils, and A the hydrofoil planform area; the best way to solve this problem is to reduce A. By the ladder configuration, such a reduction will occur spontaneously i.e. the upper big aft wing by the increase of speed will come out of water. Better performance of the HPH necessitates using flaps or controllable angle of attack as well. The design should fulfill the essential demands with the least complexity.

8. The Frame

The frame should be a metallic structure, which in the middle of the vessel fixes the seat, and pedal, in stem attaches to two fore foils, under the seat by the struts keeps the aft foils. According to the single hull design, lateral stabilizers seem to be helpful. The frame must hold the stabilizers bilaterally in two sides of the seat. It is not mandatory that the structure be contiguous. However, it should be constructed by the least possible material.

9. Approximate Dimensions & Primary Sketch of the Vessel

The best way to estimate dimensions is to evaluate the total weight. An estimate can be made as in Table 2. From the table the average estimated weight of the HPH will be 25 kg, and with a 65 kg rider the total weight will be about 95 kg. Thus an underwater volume of about 0.095 m3 is required. Neglecting the buoyancy of hydrofoils, the hull dimensions can be approximated as in the first row of Table 3.

A primary knowledge about the lift needed in the foil-borne state, the dynamic stability condition and general arrangement, gives an estimate for the dimensions of the hydrofoils. Also an approximation of characteristics of the air propeller is made in Table 3. As the summary of the mentioned ideas, a schematic sketch of the HPH is shown in Fig. 5.

Table 2: Weight Estimation [kg]

Part	Weight
Rider	65-70
Bare Hull	15-19
Propulsion System	1-3
Hydrofoils and struts	1-2
Other parts	3-6

Table 3: Dimension Estimation [m]

Hull	$L_{ov} \approx 3.5$	$B \approx 0.5$	$T \approx 0.12$
Aft Big Wing	$b \approx 0.6$	$c \approx 0.07$	$t \approx 0.012$
Aft Small Wing	$b \approx 0.4$	$c \approx 0.05$	$t \approx 0.01$
Fore Wings	$b \approx 0.1$	$c \approx 0.04$	$t \approx 0.01$
Air Propeller	$h_c \approx 1.2$	$D \approx 1.5$	$P/D \approx 1.1$

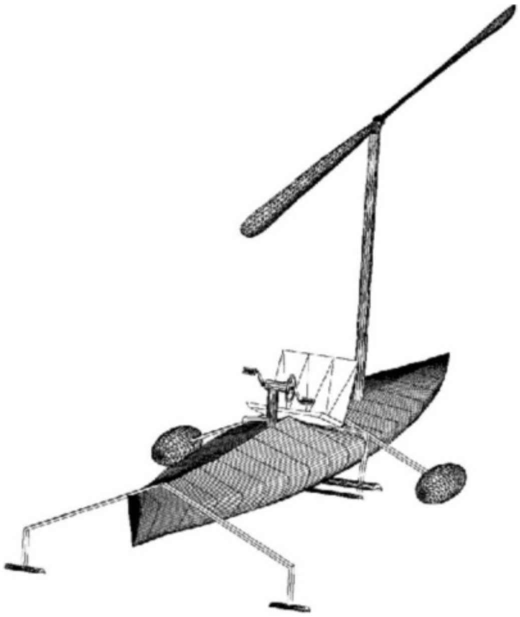

Fig. 5: A schematic sketch of the proposed HPH

RESULTS AND DISCISSION

As mentioned, the proposed design for the HPH has a single hull, which will be similar to small high-speed boats. The two main types are Kayak and Canoe. To analyze a hull of the form Kayak and to investigate if the HPH with such a hull can come out of water with human power, a computer model and a physical model of the hull has been constructed. In this section, model test results and the analysis of the bare hull according to that, will be explained.

The model is a Kayak (Schade, 2011). The computer model with 19 sections with length 3.5 m, breadth 0.5 m and draft of about 12 cm is shown in Fig. 6. The righting arm (GZ) versus heel angle is shown in Fig. 7. The vessel is stable up to 53 degree and after then the righting arm will be negative.

With regard to the available test facilities and manufacturing capabilities, the scale of the physical model was decided to be 1/3.5. Table 4 includes model and prototype dimensions.

Model test was run several times and after minimizing flaws and errors, the data according to 10 runs were stored and processed for final analysis. In Figs. 8 (a) and (b) sample test diagrams are shown for the towing speeds of respectively 2.58 and 3.2 m/s. Total resistance of the model versus speed is shown in Fig. 9. The steady region of test results (i.e. after about 6 meters in Fig. 8) is used to produce Fig. 9.

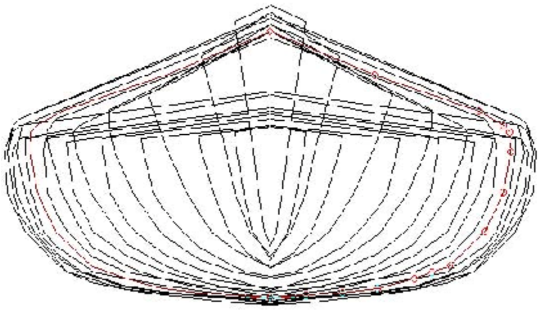

Fig. 6: The hull lines-plan

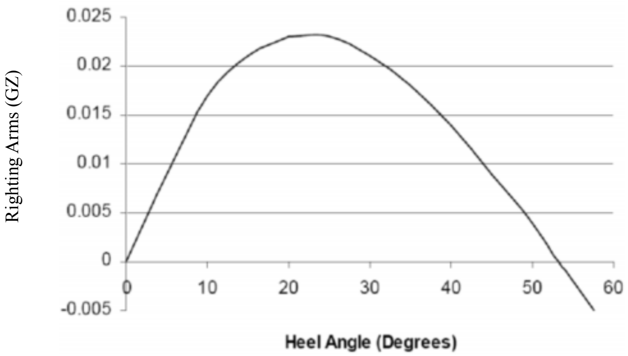

Fig. 7: Righting Arm (GZ) versus Heel Angle

Table 4: Model and main hull dimensions (meters)

Scale: 3.5	HPH	Model
L	3.5	1
B	0.5	0.143
T	0.12	0.034

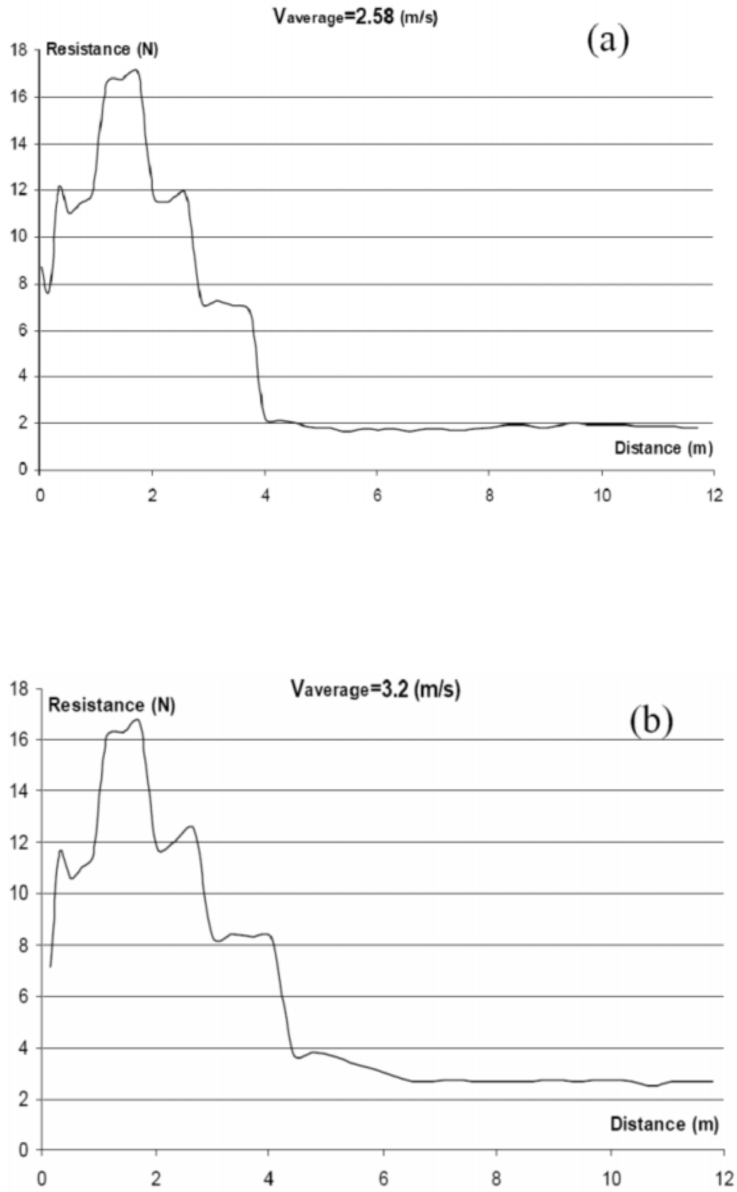

Fig. 8: Model Total Resistance vs. Towing Distance (a) towing speed= 2.58 m/s (b) towing speed= 3.2 m/s

The fluctuations in the curve of Fig. 9 are due to the water spray, test errors and wave-making resistance, which cause hollows and humps. Fig. 10 shows the model during test with a high speed (about 3 m/s). The hull has a planning behavior and water spray can be seen in stem. Of course the wings will have a deterministic role in this stage.

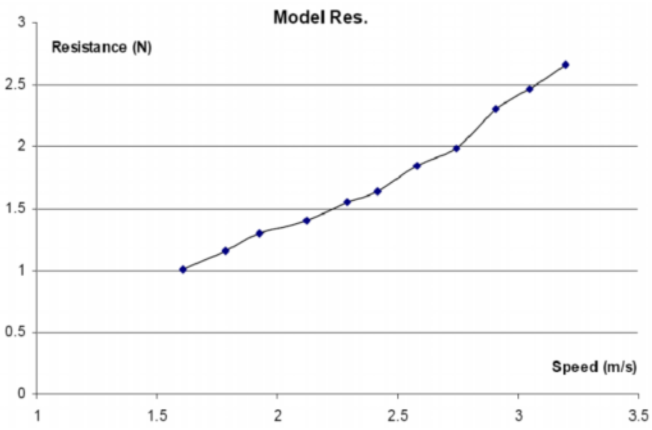

Fig. 9: Model Total Resistance vs. Speed

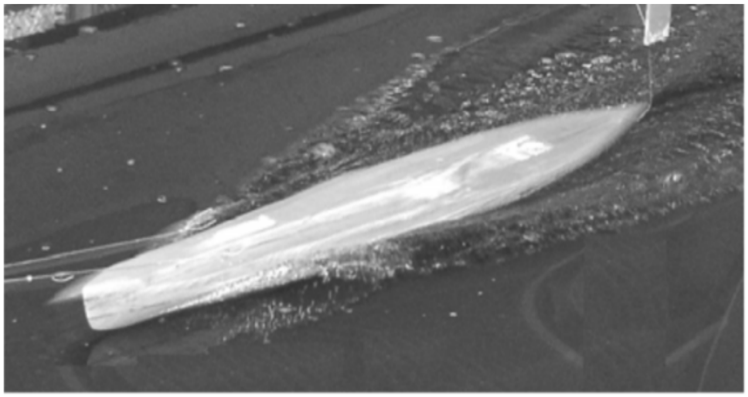

Fig. 10: Model test/ Spray of water in stem

There is a well-known algorithm for derivation of the total resistance of the prototype from test results. Fig. 11 shows the total resistance of the hull of the main HPH. The oscillations are seen again. Fig. 12 shows the effective power versus speed.

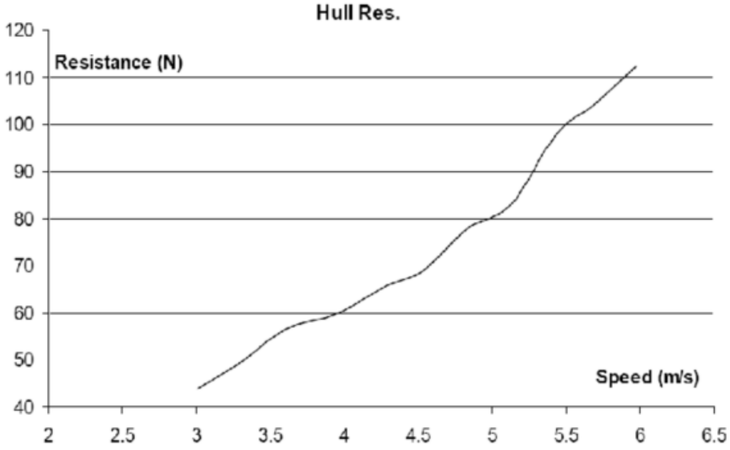

Fig. 11: Total Resistance of Main Hull vs. Speed

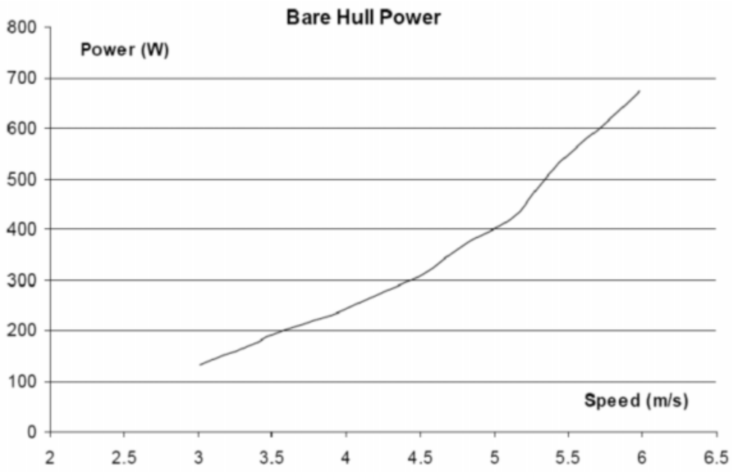

Fig. 12: Total Resistance of Main Hull vs. Speed

The maximum speed in which the hull will move in water is the rise speed. The maximum speed, which will be reached in foil-borne state, is aimed to be 10 (m/s) so that to overtake the Decavitator. Thus the rise speed will be about 5 (m/s). From Figs. 11 and 12 in this speed we have:

$$R_{Ts}=80\text{ N},\quad P_E=400\text{ w} \qquad (3)$$

where R_Ts is the total resistance of the main hull (ship), and P_E is the effective power. The rider must provide a power that can be calculated as:

$$P_B=P_E/(\eta_G\times\eta_S\times\eta_P) \qquad (4)$$

η_G is the gearing efficiency, η_S is the shaft efficiency, and η_P is the propeller efficiency. The propeller efficiency for water propellers is written as:

$$\eta P=\eta_O\times\eta_S\times\eta_H \qquad (5)$$

As mentioned, an air propeller will be used for which, with adequate design, efficiencies as high as 85 percent is achievable i.e. η_P=0.85. The power transmission efficiency through the time-belt system, as was described, will be about η_G×η_S=0.93. Therefore the rider's power necessary for attaining take off is:

$$P_B=506\text{ w} \qquad (6)$$

According to the data of Table 1, this is an attainable amount of power. Lastly, the interested reader is urged to review (Ray, 2009), (Miller, 2010), (Faltinsen, 2005), (Bertram, 2000) and (Lewandowski, 2004) for more information on hydrofoil hydrodynamics and the concept of using hydrofoils in order to float above the waterline.

CONCLUSION

In this paper, first some reasons for the importance of enhancing science and technology related to the human powered vehicles was stated and hydrofoil vessels were briefly introduced. According to the characteristics of both human powered vehicles and Hydrofoil vessels, principle parts and steps of the design of a HPH vessel were discussed. As is conventional in the design of marine vehicles, descriptions to this extent is Conceptual Design and many revising stages and even major modifications will take place until the final design be obtained.

In the third section, weight and dimension estimation was done according to the ideas and statistical data and a sketch of the proposed HPH was shown. In the final section, the bare hull of the vessel was analyzed. Computer modeling and physical model test were the tools of analysis. The results were satisfying and the project can be continued by completing the physical as well as the computer model. This way, the HPH vessel can be simulated completely and after eliminating deficiencies the desired HPH will be identified and constructed.

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