COMPARISON FINAL VELOCITY FOR LAND YACHT WITH A RIGID WING AND CLOTH SAIL

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(Received: April 7, 2008 – Accepted in Revised Form: September 25, 2008)

Abstract The powering requirement of a land yacht is one of the most important aspects of its design. In this respect the wind tunnel testing is an effective design tool. In fact, changing the parameters of the vehicle and testing the changes in the wind tunnel will give us a better understanding of the most efficient vehicle, and yet it is time consuming, expensive, and has inherent scaling errors. Another set of design tools are Computational Fluid Dynamics and parametric prediction. Computational Fluid Dynamics (CFD) codes are not yet wholly proven in its accuracy. Parametric prediction is the starting point for most engineering studies. It will be used to calculate the land yacht's performance and provide a steady-state trim solution for the dynamic simulation. This tool is absolutely self validating. In present work, parametric prediction tool has been used for velocity prediction of a radio control land yacht with a rigid airfoil and cloth sail. The lift and drag coefficient of the rigid wing and cloth sail are obtained from the wind tunnel. The results show that the maximum velocity of the land yacht model with rigid wing is higher than cloth sail which occurs at 100 to 130 degree angle, courses.

Keywords Land yacht, Sail Craft, Velocity Prediction Program, Aerodynamic

چكيده قدرت مورد نياز يک خودروی بادی، از مهمترين پارامترهای مورد نظردر طراحی اين نوع از خودروها می‌باشد. تست تونل باد خودرو يکی از ابزار های موثر برای طراحی می‌باشد. در واقع تغيير پارامترهای مختلف خودرو و تست اين تغييرات در تونل باد، درک مناسبی از مفهوم خودروی بهينه را ارائه می‌دهد اما اين روش زمان بر بوده و بطور ذاتی داری خطای مقياسی است. روش‌های ديناميک سيالات محاسباتی (CFD) و تخمين پارامتری از ديگر ابزارهای طراحی می‌باشند. صحت و دقت کدهای ديناميک سيالات محاسباتی تاکنون بطور کامل اثبات نشده است. روش تخمين پارامتری نقطه شروعی برای اکثر مطالعات مهندسی می‌باشد. اين روش که برای محاسبه عملکرد خودروی بادی مورد استفاده قرار می‌گيرد و يک جواب صحيح و پايدار برای شبيه سازی ديناميکی خودرو ارائه می دهد، در اين تحقيق بطور کامل صحه گذاری شده است. در اين مقاله روش تخمين پارامتری برای تخمين سرعت يک مدل خودروی بادی کنترلی با يک ايرفول قائم همچنين بادبان بکار رفته است. ضرايب برآ و پسای اين ايرفويل قائم و بادبان از طريق تست تونل باد بدست آمده‌اند. نتايج نشان می دهند ماکزيمم سرعت خودروی بادی با ايرفويل قائم بيشتر از بادبان بوده و در زاويه باد طبيعی بين ۱۰۰ تا ۱۳۰ درجه اتفاق می‌افتد.

1. INTRODUCTION

For land yacht, high performance means high speed relative to the true wind speed and absolute high speed. Velocity Prediction Programs (VPPs), predict the performance of a land yacht. Recent results concerning the mathematical simulation of a land yacht is presented. This simulation is done by balancing the aerodynamic forces and moments, so that the vehicle is in equilibrium. Aerodynamic simulation is based on a simple equation and experimental lift and drag coefficients.

In this paper we consider the flow of downwind and upwind on the sail to keep the land yacht in motion. The forces on the sail are computed at each time step and by knowing the body's velocity, the parasitic drag is calculated. The acceleration is estimated by Newton's equation; hence the velocity is estimated from the acceleration.

In the next part of our project the rigid wing is used instead of cloth sail. We can design a rigid airfoil with high lift coefficient (up to 2), and therefore a high velocity of land yacht can be obtained. Another advantage of rigid wing is its longevity compared to cloth sail. In the present work, we have used a typical airfoil with maximum lift coefficient of about 1.3.

The velocity was used as the calculating method for this land yacht with cloth sail and rigid wing. This method is applicable to all sail crafts with appropriate substitutions with references to land [1]. The results show a reasonably good agreement with the experimental results which were obtained from the road test done with the land yacht. Finally the land yachts' rigid wing velocity was compared with cloth sail.

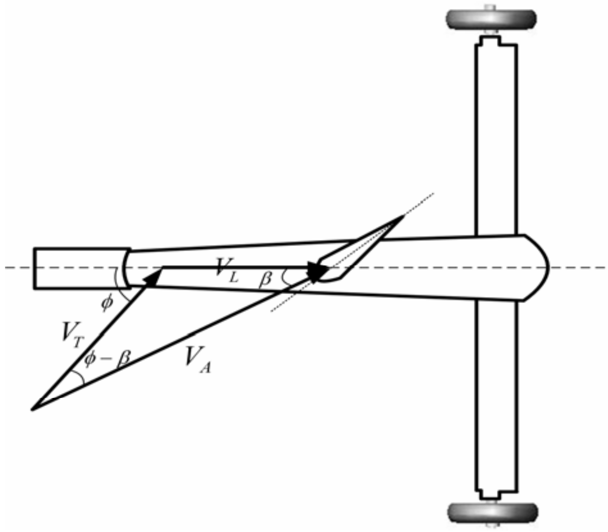


Figure 1. Velocity triangle in horizontal plane.

2. VELOCITY TRIANGLE

The velocity triangle showing the relationship between true wind speeds (V_T), land yacht speed (V_L), and apparent wind speed (V_A), is depicted in Figure 1.

From Figure 1, the apparent wind angle (β) and the apparent wind speed can be expressed algebraically by:

$$\beta = \arctan\left(\frac{V_T \sin\phi}{V_T \cos\phi + V_L}\right); \quad \beta \le \frac{\pi}{2} \tag{1}$$

$$\beta = \arctan\left(\frac{V_T \sin(\phi - \frac{\pi}{2}) - V_L}{V_T \cos(\phi - \frac{\pi}{2})}\right) + \frac{\pi}{2}; \quad \beta > \frac{\pi}{2} \tag{2}$$

$$V_A = \sqrt{V_T^2 + V_L^2 + 2V_L V_T \cos\phi} \tag{3}$$

Figure 2 shows the schematic variations of land yacht speed and apparent speed with respect to true wind angle at constant V_T and β.

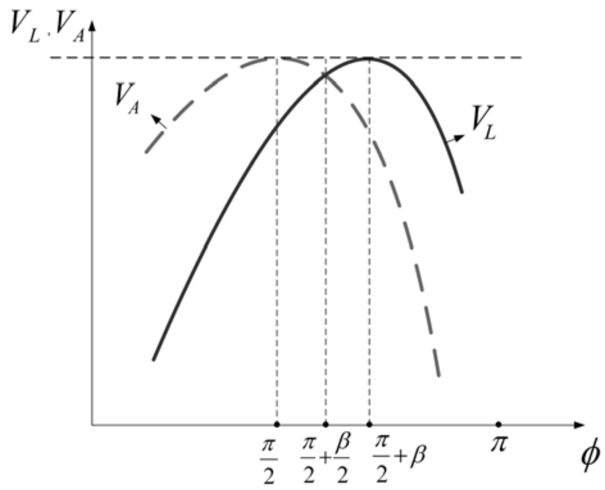


Figure 2. Schematic behaviour of V_A and V_L in different true wind angles (Constant V_T and β).

3. AERODYNAMIC CALCULATION

It is the apparent wind speed and direction that determines the forces experienced by the sail. Therefore the sail of the land yacht generates lift and drag forces from the apparent wind, much like an airplane. In the VPP code for aerodynamic calculating we have used of experimental lift and drag coefficient. Aerodynamic forces are depicted in Figure 3.

The lift and drag force of the sail, are calculated from Equation 4:

$$F_{aero} = \frac{1}{2}\rho V_A^2 C\ A_P \tag{4}$$

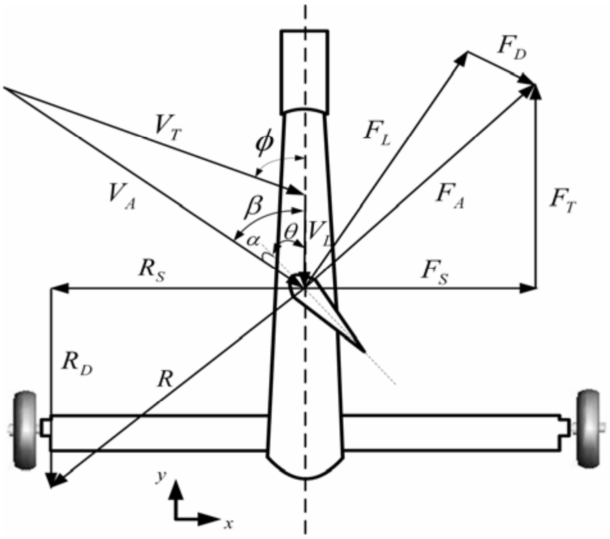


Figure 3. Aerodynamic force components.

Where,

C =	Lift or drag coefficient
ρ =	Air density
A_P =	Linear approximation to adjust effective sail area based on angle of attack

The coefficient of the lift (C_L) generated by a sail is assumed a function only of apparent wind angle [2]. The coefficient of drag (C_D) is the summation of three variables: parasitic drag, induced drag and windage (only for cloth sail). Parasitic drag (C_{DP}) is the friction associated with wind passing over a sail. Like lift, it is assumed also to be only a function of apparent wind angle [2]. Equation 5 shows the Induced drag (C_{DI}) which is the result of vortices created as the airflows sucked around the wind ward portion of the sail to the leeward side [3]. Induced drag is a result of pressure differential on the sail and the end condition at the top of the sail. Based on simple wing theory, it is a function of the square of the lift coefficient for a sail. Furthermore, the aspect ratio (AR) of a sail plays an important role in sail efficiency. A high aspect ratio sail will lessen the induced drag by effectively delaying the amount of vortices which can be created [4].

$$C_{Di} = \frac{{C_L}^2}{\pi AR} + 0.005 \tag{5}$$

The aspect ratio used in calculating induced drag is not of any particular sail, but of the entire sailing craft. For upwind sailing, the height of the deck above the ground (FBD) is assumed to have an effect on the induced drag of the land yacht. Therefore, there are two equations for the calculation of aspect ratio. Close-hauled, aspect ratio is a function of the freeboard (FBD), the effective height of the mast, and the nominal sail area (A_N) [3]:

$$AR_{upwind} = \frac{(1.1(EHM + FBD))^2}{A_N} \tag{6}$$

For any other sailing condition besides upwind (true wind angle > 45 degrees), the freeboard term is simply removed from the aspect ratio equation. According to Equation 7, windbag (C_{D0}) is a function of the characteristics of the land yacht, and is a crude method of determining the aerodynamic drag of the rigging and land yacht body [3].

$$C_{D0} = 1.13\frac{(B_{MAX}.FBD) + (EHM.MD)}{A_N} \tag{7}$$

Wind age is determined from the maximum longitudinal length of the land yacht (B_{MAX}), the average freeboard, the effective height of the mast (EHM), the diameter of the mast (MD), and the nominal area of the sails (A_N).

Figure 4 shows the characteristics of cloth sail that are obtained from the national open jet wind tunnel of Malek Ashtar University of Technology in Iran.

In this work a rigid wing with NACA0012 section and AR = 2.4 was used. Figure 5 shows the characteristics of this wing that are also obtained from the jet wind tunnel of Malek Ashtar University of Technology in Iran (Configuration 0) in comparison with published values up to stall point (Configuration 1) [5].

4. COUPLING METHOD

All forces acting on a land yacht are of two distinct classes: aerodynamic and downward. Aerodynamic forces are depicted in Figure 3. The component of the resulting aerodynamic force (F_A) in the direction

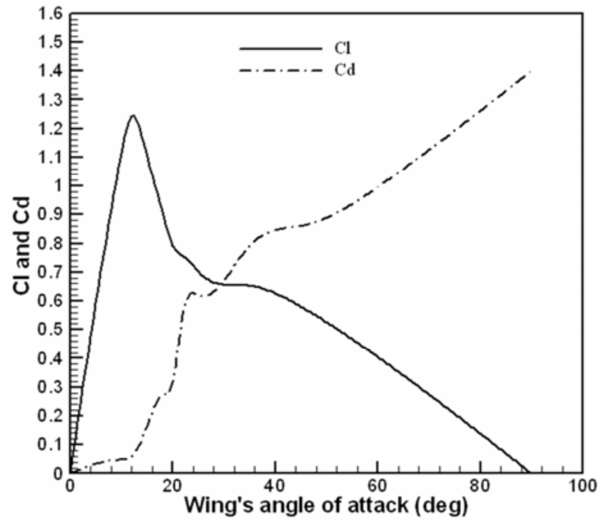


Figure 4. C_L and C_D versus Wing's angle of attack for cloth sail at Re = 3 × 10^5.

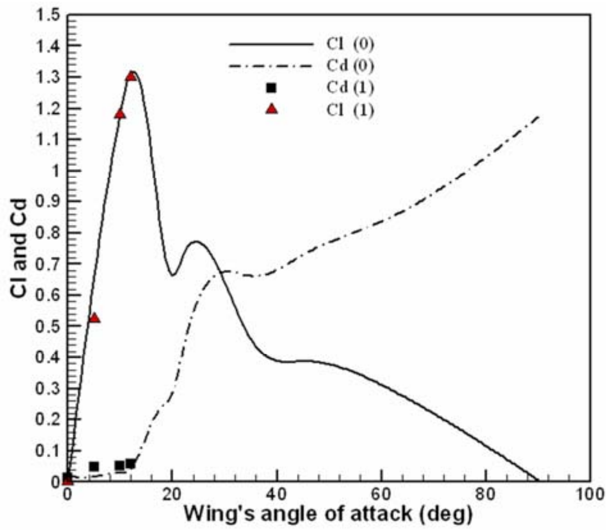


Figure 5. C_L and C_D versus Wing's angle of attack for a NACA 0012 wing at Re = 3 × 10^5.

of land yacht travel is the drive force (F_T).The resultant aerodynamic force has a large component perpendicular to the direction of travel. This side force (F_S) must be resisted by the land yacht's wheel. When the wheels generate equal and opposite side force (R_S), a drag force is also produced (R_D). When the thrust or driving force is equal to drag, the vehicle is in equilibrium and the maximum steady state speed has been reached. The equations of the land yachts' motion can be written as:

$$\begin{bmatrix} \cos(\theta+\alpha) & \sin(\theta+\alpha) \\ \sin(\theta+\alpha) & -\cos(\theta+\alpha) \end{bmatrix} \begin{pmatrix} F_L \\ F_D \end{pmatrix} - \begin{pmatrix} R_S \\ R_D \end{pmatrix} = \begin{pmatrix} m\ddot{x} \\ m\ddot{y} \end{pmatrix} \quad (8)$$

Where $\ddot{x}$ and $\ddot{y}$ are the land yacht's accelerations in x and y direction respectively and R_D is total drag force that is calculated by:

$$R_D = F_{DB} + F_{DA} + F_{DW} \quad (9)$$

Where,

F_{DB} = Drag force of the body
F_{DA} = Drag force of the rear axle
F_{DW} = Drag force of the wheels

The drag force of the body is calculated by:

$$F_{DB} = \frac{1}{2}\rho_{air} V_F{}^2 C_{DB} A_{PB} \quad (10)$$

Where,

A_{PB} = Total frontal fuselage projected area
C_{DB} = Vehicle fuselage drag coefficient obtained from wind tunnel

V_F is the apparent wind speed component in travel direction of the land yacht and is calculated by:

$$V_F = V_A \times \cos\beta \quad (11)$$

The drag force of the rear axle can be written as:

$$F_{DA} = \frac{1}{2}\rho_{air} V_F{}^2 C_{DA} A_{PA} \quad (12)$$

Where,

A_{PA} = Linear approximation to adjust effective rear axle wing area based on angle of attack
C_{DA} = Drag coefficient of the rear axle wing

The drag force of the wheels can be expressed by:

$$F_{DW} = B_W (RPS_{FW} + 2RPS_{RW}) \quad (13)$$

Where, B_W is the drag coefficient of rolling wheel and RPS_{FW} and RPS_{RW} are calculated by:

$$RPS = \frac{V_L}{\pi D} \quad (14)$$

D = Front wheel or rear wheel diameter

The total available sideways friction force (R_S) is calculated by:

$$R_S = \mu \times F_{Down} = \mu \times (W + F_{LA}) \quad (15)$$

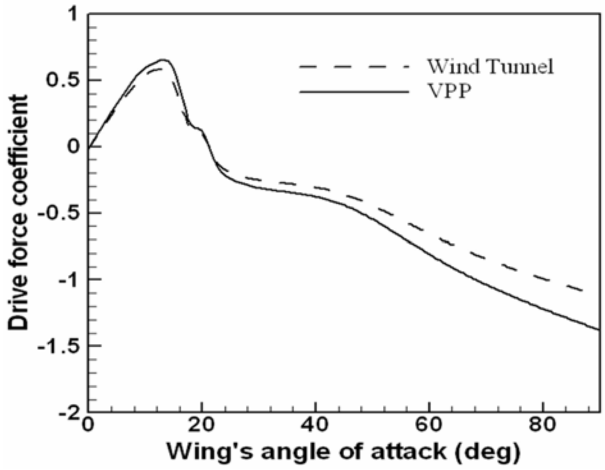
In Equation 15, μ is the coefficient of friction between wheels and road, W is the land yacht's weight, and F_{LA} is the lift force of the rear axle and can be written as:

$$F_{LA} = \frac{1}{2}\rho_{air} V_F{}^2 C_{LA} A_{PA} \quad (16)$$

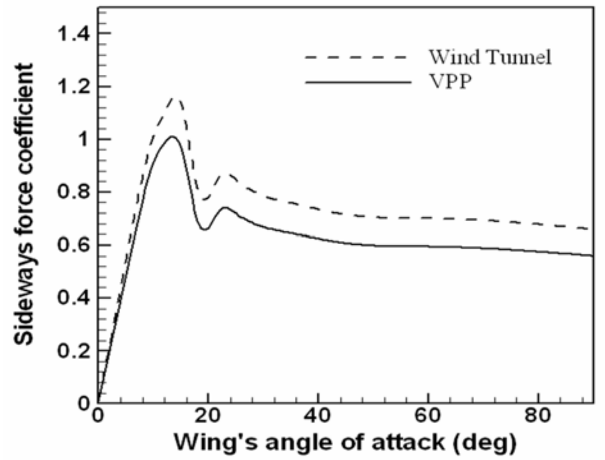
Where,

C_{LA} = Lift coefficient of the rear axle wing

By using VPP code, the forces and velocities can be solved for simultaneous equations or an iterative process involving guessing the land yacht speed until $\ddot{x}$ and $\ddot{y}$ are equal to zero. It means by guessing the land yacht speed, the new apparent wind speed and apparent wind angle are estimated. Then the total drag forces and aerodynamic forces are calculated in each time step. The process is iterative until convergence is reached. When $\ddot{x} = 0$ and $\ddot{y} = 0$, the land yacht is in equilibrium and its maximum steady state speed has been reached.



(a)



(b)

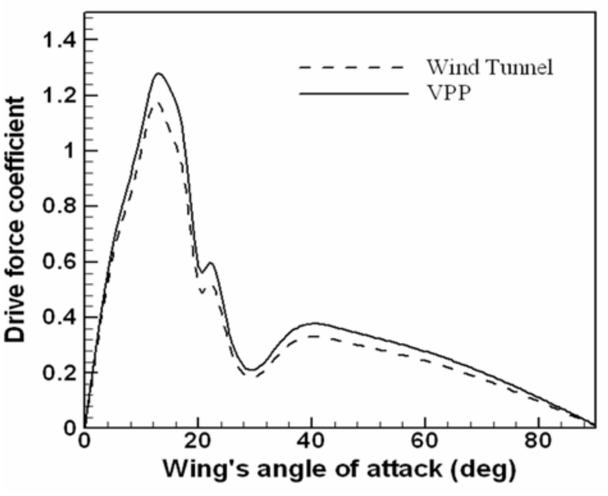
Figure 6. Aerodynamic coefficients at the body angle of 30°with respect to the wind: (a) drive force coefficient, (b) sideways force coefficient.

5. VALIDATION OF THE VPP

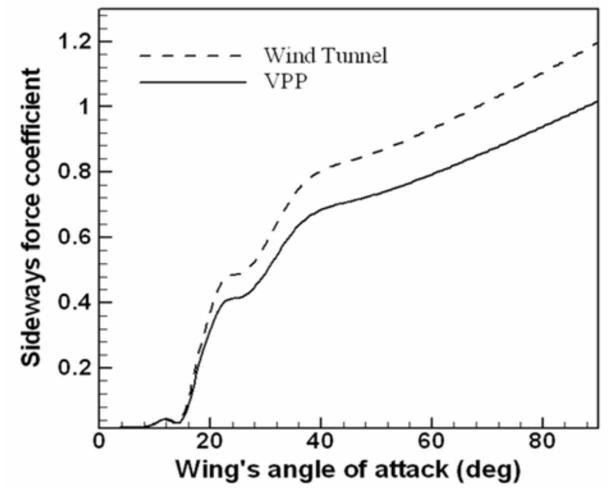
Three parts should be validated to check whether the program is suitable for comparative studies. These are the aerodynamic module, the parasitic drag module and the "solver" module. For validation of the aerodynamic module, the drive and sideways forces coefficients for land yacht with rigid wing, that are measured in three different cases in the wind tunnel are compared with the VPP results [6]. The VPP results show reasonably good agreement in tendency with the experimental data obtained from the wind tunnel test (Figures 6-8).

For validation of the parasitic drag module, the parasitic drag of the model is determined by measuring the forces acting on the land yacht body without any sail. Measurements are conducted for the upwind and downwind test configuration to ensure that the effect of twist profiles is correctly accounted for. The total horizontal parasitic drag (R_D) measured in the wind tunnel is approximately similar to predicted by the VPP [6]. This comparison is shown in Figure 9.

To validate the method of solving, the real speed of the land yacht with rigid wing is measured

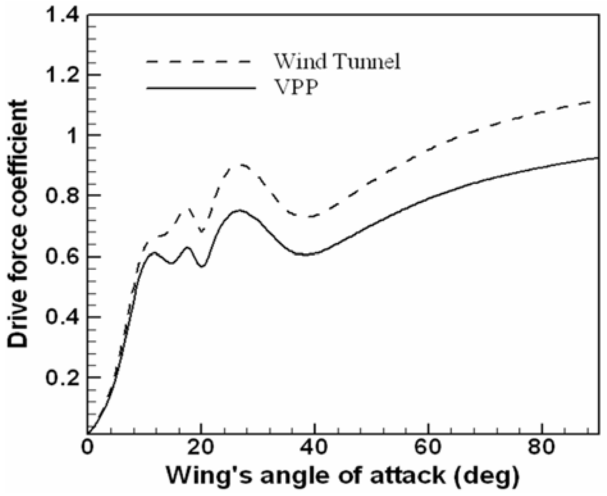


(a)

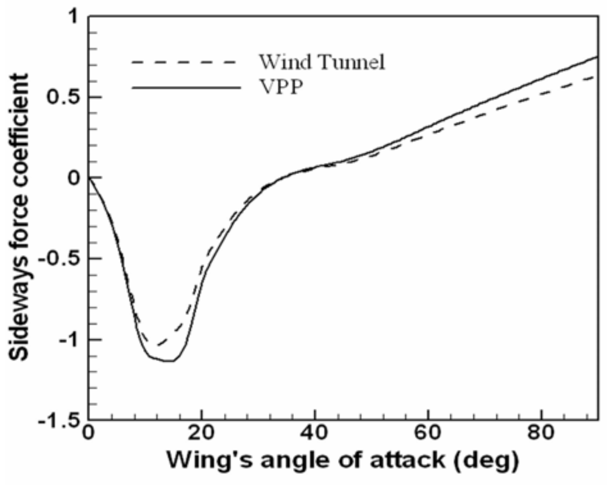


(b)

Figure 7. Aerodynamic coefficients at the body angle of 90˚with respect to the wind: (a) drive force coefficient, (b) sideways force coefficient.



(a)



(b)

Figure 8. Aerodynamic coefficients at the body angle of 150˚with respect to the wind: (a) drive force coefficient, (b) sideways force coefficient.

by using a cycle computer and is compared with the VPP data. This device measures the model speed accurately and shows the current speed, trip distance, maximum speed, average speed, and elapsed time [7]. Figure 10 shows the maximum speed of the land yacht at different true wind speed for both real and VPP data. The computed results show reasonably good agreement in tendency with the real speed obtained from the land yacht road test.

6. RESULTS AND DISCUSSIONS

The “Velocity Prediction Program” is run for a land yacht with technical specifications that are expressed in Table 1.

According to VPP solution algorithm [1], for each true wind angle (ϕ) ,the program will iterate land yacht speed and sail conditions so that the sum of the aerodynamic forces and moments on the land yacht is zero and the land yacht maximum

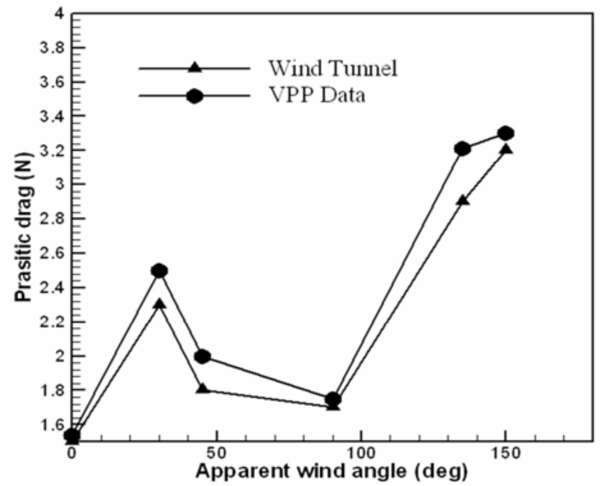


Figure 9. Parasitic drag of model in horizontal plane and predicted by the VPP at tunnel speed of 9 m/s.

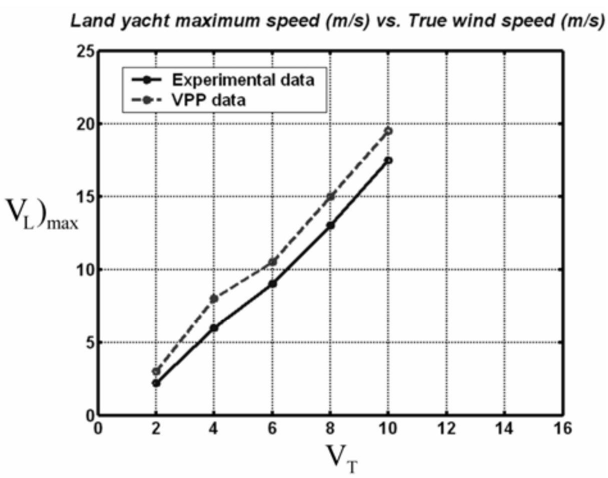


Figure 10. Maximum speed of the land yacht at various true wind speeds obtained by testing the land yacht model and the VPP.

speed for this course is reached. It will be evident that the final maximum speed of the land yacht is the greatest maximum speed which is reached in each true wind angle. The sailing condition is very sensitive to apparent wind effects as the sails are often stalled and requires more complex wind calculations for more accurate results. Figures 11-13 show the convergence process of the land yacht maximum speed, the apparent wind speed and, the apparent wind angle versus non dimensional time

TABLE 1. Characteristics of the Land Yacht Model.

Land Yacht Weight	12.5 kg
Front Wheel Diameter	0.1 m
Rear Wheel Diameter	0.2 m
Track	1.1 m
Wheel Base	1.375 m
Rear Axle Wing Chord Line	0.1 m
Rear Axle Thickness	0.012 m
Vehicle Fuselage Drag Coefficient	0.473
Coefficient Of Friction Between Wheels And Road	0.75
Drag Coefficient Of Rolling Wheel, Per Wheel (B_W)	0.0136 kg/(rev/s)
Vertical Wing Span	1.2 m
Vertical Wing Chord Line	0.5 m
Wing Stall Angle	12°

respectively, for true wind speed 5 m/s and true wind angle of 106°. As it shown in these figures, for $\bar{t} > 21$, equilibrium state for this special true wind angle is reached.

The Reynolds number effects of the rigid wing section design must be accounted for in order to maximize the efficiency of the wing. Flow about an airfoil at low Reynolds numbers is almost entirely laminar. Furthermore, as soon as the sections' angle of attack is increased, the laminar separation bubble bursts, causing large scale flow separation and effectively limiting the maximum lift coefficient, C_L, attainable. The designers correctly identified the proper Reynolds number range for sail operation as 200,000 to 1.2 million [8].

In order to match the total force on the original sail at a wind speed of 5 m/s with a theoretical lift coefficient of 1.8, Equation 17 is solved for a resulting Reynolds number of 229,000. It is desirable for the section to achieve a maximum lift coefficient at a Reynolds number range of 200,000 to 250,000.

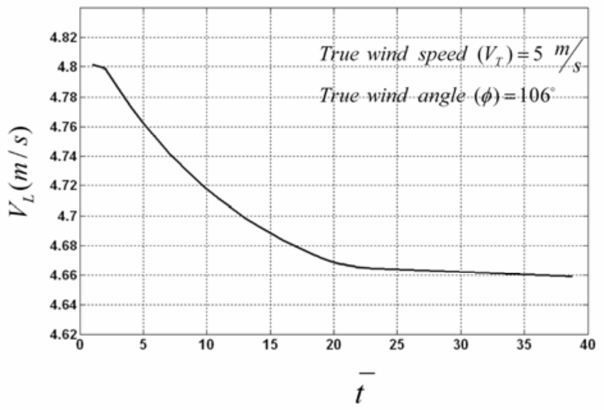


Figure 11. Maximum land yacht speed versus non dimensional time during the convergence of the calculation.

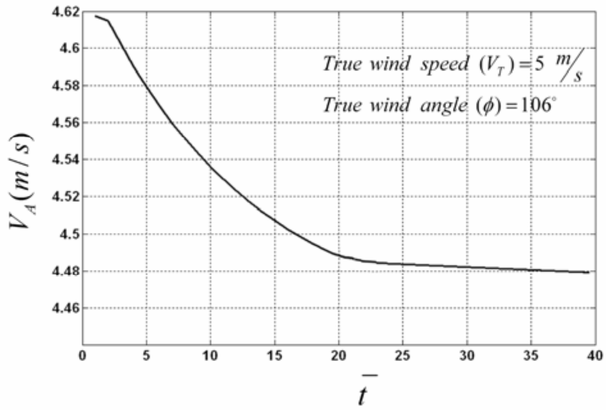


Figure 12. Apparent speed versus non dimensional time during the convergence of the calculation.

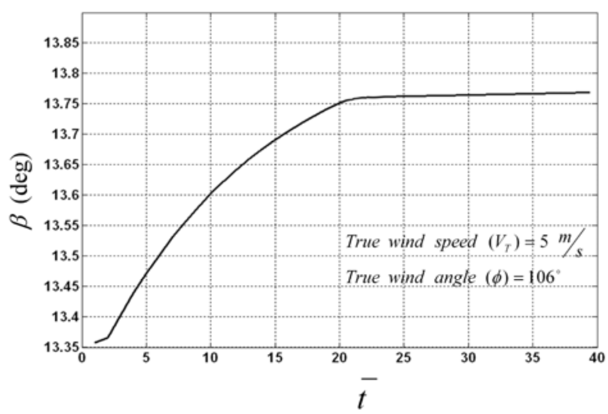


Figure 13. Apparent wind angle versus non dimensional time during the convergence of the calculation.

$$\mathrm{Re} = \frac{V.L}{\nu} \tag{17}$$

Where,

V= Air velocity
L= Chord length of the wing
ν = Kinematic viscosity of the air

Figure 14, shows the wind velocity required to achieve this Reynolds number (Re = 229000), as a function of true wind angle. This figure shows that the range of minimum wind speeds is from 3.8 to 6 m/s. The wing has one third the sails area, but generates three times the lift at its design points. This was chosen to enable a comparison of performance between the wing and sail. The difficult thing to achieve is performance at low Reynolds numbers. Once that has been achieved, the same airfoil section can achieve a higher coefficient of lift at greater Reynolds number.

Figure 15 shows a polar diagram in which land yacht speed is a function of true wind angle for a given true wind speed. For sailors, polar diagrams help to tune a land yacht and to find the quickest course to a mark. As it shown in this figure, higher land yacht speeds can be achieved when the wind is stronger and Reynolds number is higher. Also illustrates the well known fact that if the yacht tries to sail too much into the wind the drag forces exceed any thrust and the yacht cannot move forwards. .According to this figure, the maximum land yacht speed occurs in 100 to 130 degree of true wind angles.

For designers, polar diagrams help provide comparisons between different configurations of the same land yacht. In Figures 16 and 17 we have compared the land yacht speed for two different cases: a single land yacht model with a rigid wing and cloth sail. These figures are obtained from our calculation method (coupling method). The characteristics of this land yacht are expressed in Table 1. The results show that, the land yacht with a rigid wing has a better performance with respect to cloth sail.

There are three main reasons to use a rigid wing instead of a cloth sail: efficiency, less actuation force required, and self-trimming. The first and most obvious is that a rigid wing is far more efficient than a cloth sail. The Lift/Drag (L/D) ratio of the rigid wing is in the 10-30 range, whereas the

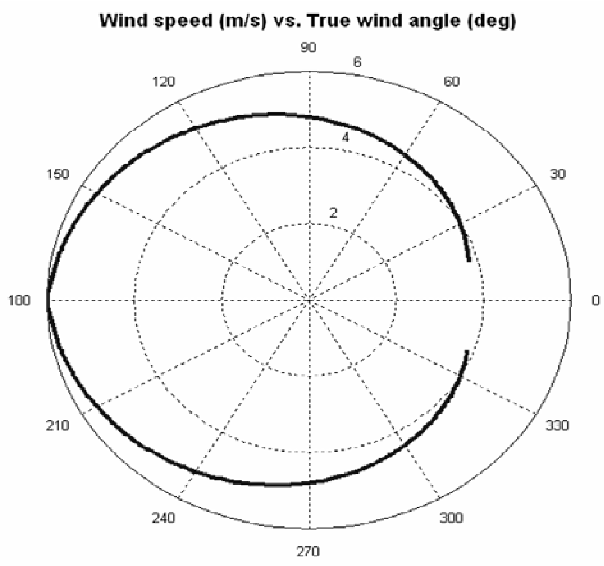


Figure 14. Polar plot of the true wind speed versus true wind angle at a Reynolds number of 229000.

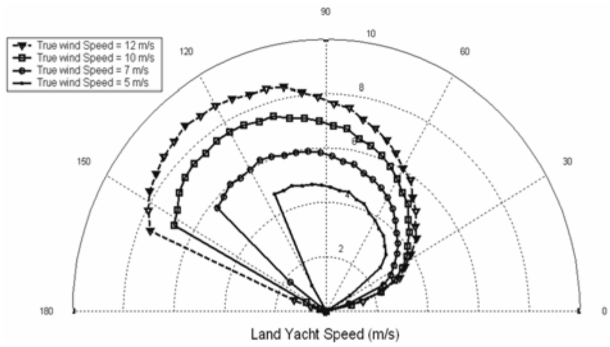


Figure 15. Land yacht speed versus true wind angle at various values of true wind speed.

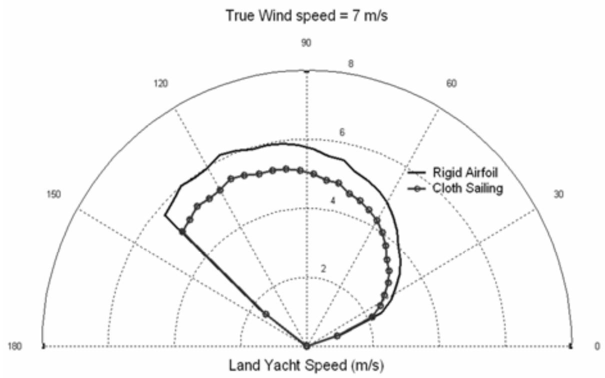


Figure 16. Comparison of land yacht speed for two different cases at various true wind angle in true wind speed 7 m/s.

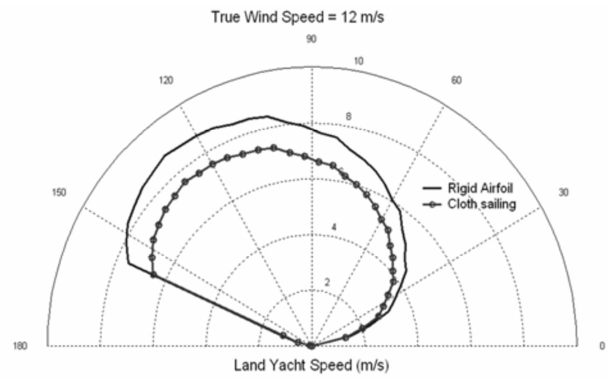


Figure 17. Comparison of land yacht speed for two different cases at various true wind angle in true wind speed 12 m/s.

L/D of the conventional sail is in the 3-5 range. Further, a cloth sail suffers from aero-elastic collapse when pointed high into the wind (the sail is said to be luffing). This causes a great deal of drag when sailing close-hauled and effectively limits how high the land yacht can point into the wind. The rigid wing, by contrast, suffers no aero-elastic problems; it can point straight into the wind with very little drag.

The second main reason to use a rigid wing for propulsion is that less force is required to actuate the wing itself. A cloth sail is fixed to the mast and trimmed from the boom. Since the pressure center of the sail is the aft of the leading edge, the trim force must overcome a portion of the lift of the sail.

The third main advantage of a rigid wing over a cloth sail is the ability to make the rigid wing self-trimming. The benefit of this is that, the wing will absorb gusts without transmitting the force of the gusts through to the guidance system. By decoupling the propulsion system from the guidance system through passive stability (self-trimming), the control system design is greatly simplified. In fact the rigid wing will readjust automatically to a change in either wind speed or wind direction, with no intervention from pilot or control system. The self-trimming capability makes the rigid wing ideal for an autonomous land yacht because it eliminates the requirement for a very large and fast acting actuator to constantly re-trim the sails.

7. CONCLUSION

We have presented the first results obtained by coupling aerodynamic computing with wind tunnel data, in order to predict the performance of a land yacht. By the use of static and dynamic characteristics of land yacht, it is possible to predict the velocity achieved for a given course angle and true wind speed. The equilibrium state of the land yacht is obtained by solving a simplified Newton equation to compute the land yacht speed by iterative process. This method is used for the initial design of land yachts and allows for a faster and more efficient design process, saving both time and money. The results show that a land yacht with a rigid wing has a better performance than cloth sails.

8. ACKNOWLEDGMENT

This research was supported by the Malek Ashtar University of technology. The authors wish to thank the contributions of Adel Abedian to this work.

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