Comparison Final Velocity for Land Yacht with a Rigid Wing and Cloth Sail

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***Abstract*—The powering requirement of a land yacht is one of the most important aspects of land yacht design. Wind tunnel testing of land yacht 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 but it is very 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 starting point for most of the 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 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 either in cloth sail and occurs in 100 to 130 degree angle of courses.**

***Index Terms*—Land yacht, Sail Craft, Velocity Prediction Program**

I. INTRODUCTION

In the land yacht, high performance means high speed relative to the true wind speed and high absolute speed. Velocity Prediction Programs (VPPs) in land yachts predict the performance of a land yacht. We present recent results concerning the mathematical simulation of a land yacht. 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 motion of a land yacht downwind and upwind to keep the flow attached on the sail. At each time step, forces on the sail are computed and from the knowledge of the body velocity, the parasitic drag is calculated. The acceleration is estimated by the solution of the Newton's equation and then the velocity of the land yacht is estimated from the acceleration.

Next our subject is the using of a rigid wing instead of cloth sail. We can design a rigid airfoil with high lift coefficient (up to 2), and therefore we can obtain a high velocity of land yacht. Another advantage of rigid wing is more longevity than cloth sail. In present work, we have used a typical airfoil with maximum lift coefficient about 1.3.

We have used the velocity calculating method for this land yacht with cloth sail and rigid wing. This method is applicable to all sail craft with appropriate substitutions for references to land [1]. The results show reasonably good agreement in tendency with the experimental results which obtained from the road test of the land yacht. Finally we have compared the velocity of the land yacht with a rigid wing and cloth sail.

II. VELOCITY TRIANGLE

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

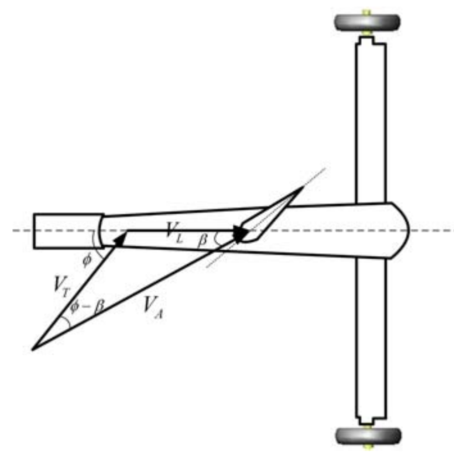

Fig. 1. Velocity triangle in horizontal plane

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

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

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

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$$V_{A=}\sqrt{V_T^{\ 2}+V_L^{\ 2}+2V_LV_T\cos\phi} \quad (3)$$

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

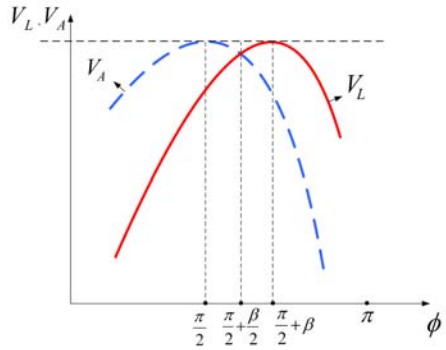

Fig. 2. Schematic behaviour of V_A and V_L in different true wind angles (Constant V_T and β)

III. Aerodynamic calculation

It is the apparent wind speed and direction that determine 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 Fig. 3.

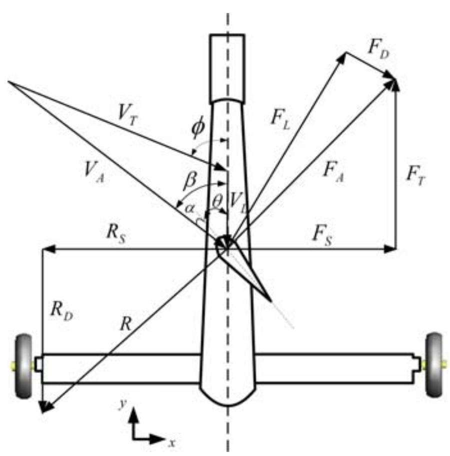

Fig. 3. Aerodynamic force components

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

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

Where,

$C=$ Lift or drag coefficient
$\rho=$ 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 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].

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

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 play an effect in 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]

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

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), windage (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].

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

Windage 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).

Fig. 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.

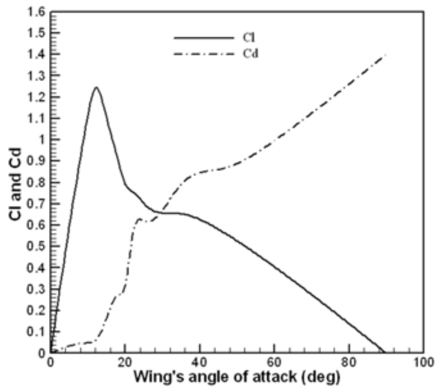

Fig. 4. C_L and C_D versus Wing's angle of attack for cloth sail at $\mathrm{Re}=3\times10^5$

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

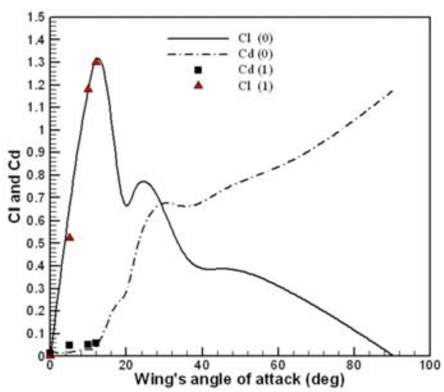

Fig. 5. C_L and C_D versus Wing's angle of attack for a NACA 0012 wing at $\mathrm{Re}=3\times10^5$

IV. Coupling method

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

$$RPS = \frac{V_L}{\pi D} \tag{14}$$

D = Front wheel or rear wheel diameter

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

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

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:

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

Where,

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

By use of the 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.

V. 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 force and sideways force 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.(Figs 6 to 8)

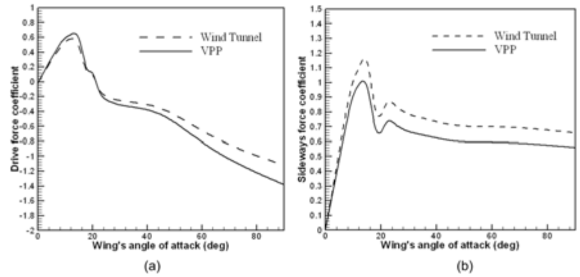

Fig. 6. Aerodynamic coefficients at the body angle of 30° with respect to the wind:(a) drive force coefficient, (b) sideways force coefficient

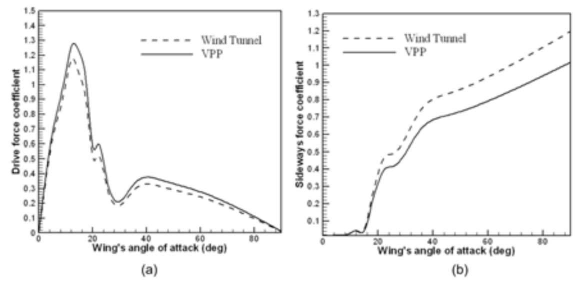

Fig. 7. Aerodynamic coefficients at the body angle of 90° with respect to the wind:(a) drive force coefficient, (b) sideways force coefficient

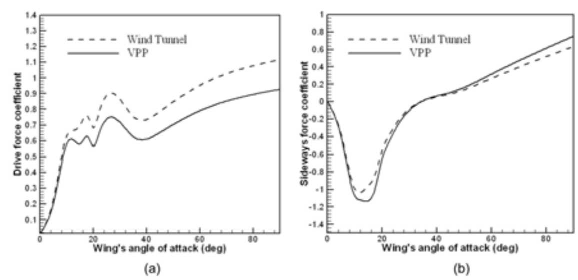

Fig. 8. Aerodynamic coefficients at the body angle of 150° with respect to the wind:(a) drive force coefficient, (b) sideways force coefficient

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 Fig. 9.

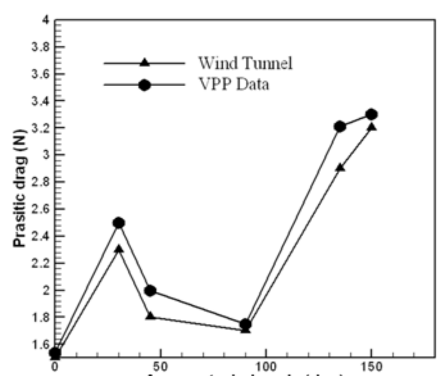

Fig. 9. Parasitic drag of model in horizontal plane and predicted by the VPP at tunnel speed of 9 m/s

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

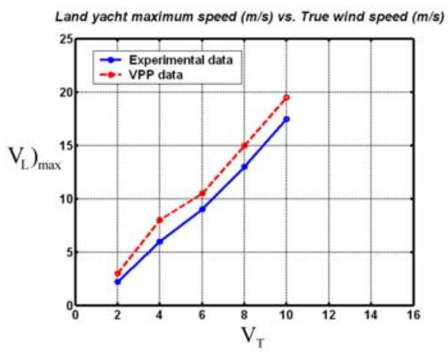

Fig.10. Maximum speed of the land yacht at various true wind speeds obtained by testing the land yacht model and the VPP

VI. Results and Discussions

The "Velocity Prediction Program" is run for a land yacht with technical specifications that are expressed in Table Ⅰ.

Table Ⅰ. 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 $^\circ$

Figs. 11 to 13 show the variation of the land yacht maximum speed, the apparent wind speed and, the apparent wind angle versus non dimensional time respectively, during the convergence of the calculation. As it shown in these figures, for $\bar{t} > 21$, equilibrium state is reached.

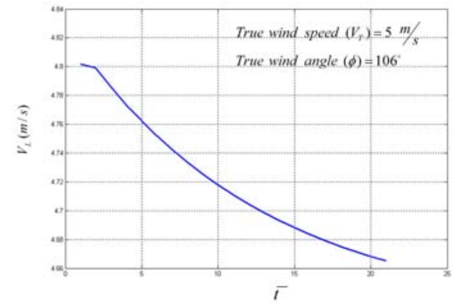

Fig.11. Maximum land yacht speed versus non dimensional time during the convergence of the calculation

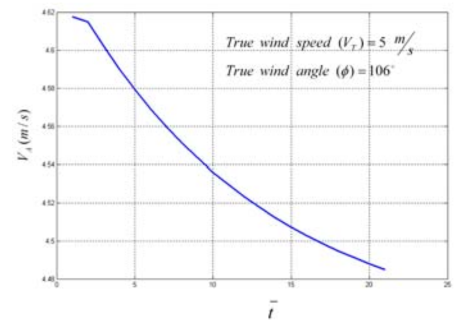

Fig.12. Apparent speed versus non dimensional time during the convergence of the calculation

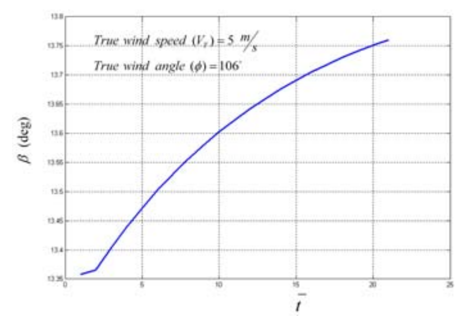

Fig.13. Apparent wind angle versus non dimensional time during the convergence of the calculation

Fig. (14) shows the land yacht speed versus true wind angle for various true wind speed. As it shown in this figure, when the true wind speed increases the land yacht speed increases too. The maximum land yacht speed occurs in 100 to 130 degree of true wind angles.

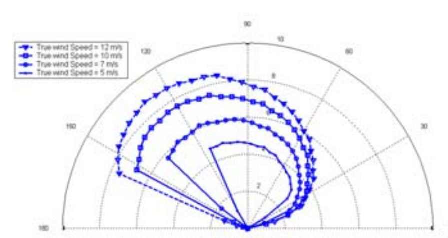

Fig.14. Land yacht speed versus true wind angle at various values of true wind speed

In Figs. 15, 16 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 I. The results show that, the land yacht with a rigid wing has a better performance with respect to cloth sail.

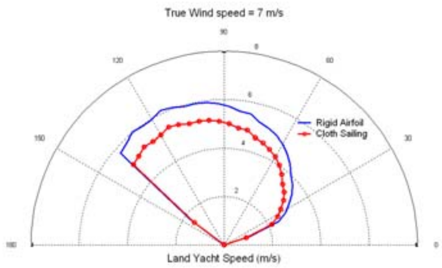

Fig.15. Comparison of land yacht speed for two different cases at various true wind angle in true wind speed 7 m/s

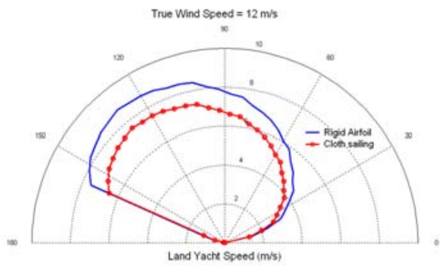

Fig.16. Comparison of land yacht speed for two different cases at various true wind angle in true wind speed 12 m/s

VII. Conclusion

We have presented the first results obtained by the coupling of an aerodynamic computing with wind tunnel data set, in order to predict the performance of a land yacht. By use of static and dynamic characteristics of a land yacht it is possible to predict the velocity achieved by a land yacht 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 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 with respect to cloth sail.

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