Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 336 – 341

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Numerical prediction of the best heel and trim of a Laser dinghy

Mikka Pennanen[a,b], Rickard Lindstrand Levin[b], Lars Larsson[b], Christian Finnsgård[c,d,*]

[a]BlueWorks Inc., Veneentekijäntie 2, 00210 Helsinki, Finland
[b]Dept. of Shipping and Marine Technology, Div. of Marine Technology, Chalmers University of Technology, 412 96 Göteborg, Sweden
[c]Centre for Sports and technology, Chalmers University of Technology, 412 96 Göteborg, Sweden
[c]SSPA Sweden AB, Research, Box 24001, 400 22 Göteborg, Sweden

Abstract

As the Laser Olympic dinghy is one of the highest-level sail racing classes in the world, there is an interest in obtaining physical facts around the experience that already exist. For this reason, a numerical investigation has been carried out to find the best heel and trim angles in upwind sailing. Flat water is assumed. The core of the work is a newly developed Inverse Velocity Prediction Program (IVPP) that computes the required wind speed for a given boat speed. Input to the program is both available towing tank data and CFD results. By keeping speed constant interpolation is avoided in the very non-linear resistance-speed relation, reducing considerably the required number of CFD computations. Another reduction is obtained by a special technique for avoiding interpolation in leeway. Systematic CFD computations are carried out to find the optimum trim versus heel at the speeds 2, 3, 4, 5 knots. Using this relation the required wind speed at the four boat speeds can be expressed as a function of heel only. The heel angle corresponding to the smallest wind speed is the best. Knowing this, and the corresponding optimum trim, the position of the sailor is computed. It turns out that the predicted best positions correspond well with practical experience. However, the results highlight the benefit of a small heel in higher winds, which often is regarded as undesired by sailors.

Peer-review under responsibility of the organizing committee of ISEA 2016
Keywords: Sailing; VPP; CFD; Hydrodynamics; Laser; Dinghy

1. Introduction

Most research projects within sailing are aimed at improving the boat and the equipment, very few deal with the improvement of sailing skills. This is a project of the latter kind: the objective is to find the best position of the sailor in a Laser Dinghy. The Laser is one of the largest classes in the world and used in the Olympics. Among the top sailors the differences in speed are extremely small and the advantages of the correct position of the sailor can be decisive for a top position in a race.

Defining the best sailor position on a dinghy is not a trivial problem. Both trim and heel depends on the position, and this affects both aero- and hydrodynamics. For the Laser, the weight of the sailor is about the same as that of the boat so the sailor position has a profound influence on the location of the total centre of gravity. Moving the centre, the wetted surface area will change, which affects the frictional resistance. The shape of the underwater body as well as the waterline length will change, which affects the wave resistance. A variation in heel will change the effective draft and thereby the induced drag of the appendages. On the aerodynamic side the effective drive force varies with heel angle.

Within sailing yacht research and development Velocity Prediction Programs (VPP) are standard tools to evaluate the force balance and performance of the yacht. During the past two decades, Computational Fluid Dynamics (CFD) tools have also become available and now complement the VPP:s. Both tools are used in the present study, together with experimental data from a towing tank.

* Corresponding author. Tel.: +46 31 7729156; fax: +46 31 772 9124.
E-mail address: fch@chalmers.se

1877-7058
Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.304

CFD is used to compute a matrix of resistance and side forces to be imported in the VPP for the hydrodynamic modelling. As there are four main variables of the present problem, namely speed, trim, heel and leeway, the number of required CFD simulations could be excessive. Especially the speed is a challenge, since the resistance varies with speed in a very non-linear way. This problem is resolved through the development of an Inverse Velocity Prediction Program (IVPP), where the speed is given and the required wind speed computed. There are also some other techniques developed to keep the number of CFD simulations within reasonable limits.

In this project flat water is assumed and only upwind cases are addressed up to approximately eleven knots of true wind speed. This wind strength correlates to the maximum boat speed. Above this wind speed the boat speed does not increase at all or very little. However the rig aerodynamics would change significantly and waves would change the hull hydrodynamics.

2. The Laser Dinghy

The Laser was first designed and built in 1970 and officially unveiled at the New York Boat Show in 1971. Since 1996 it has Olympic status. It is a simple construction with a glass fibre hull, glass fibre appendages, an aluminum mast and a Dacron sail. It can easily be sailed even by a beginner. As the dinghy has no keel weight adding stability, the righting moment of the boat is mostly produced by the sailor hiking from the hiking straps. A body plan of the hull is shown in Figure 1.

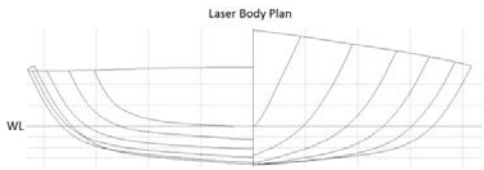

Fig. 1. Body plan of the Laser dinghy

3. Method

3.1. Procedure

The core of the work was the development of the IVPP. This was used twice. In the first round the resistance was taken from available tank tests of the Laser [1] without leeway and appendages. These were introduced in the IVPP by analytical formulae. The result was a good estimate of the equilibrium, and the leeway obtained was used in the subsequent CFD computations. This eliminated leeway as a variable in the systematic CFD computations, which were carried out for 2, 3, 4 and 5 knots. At each speed (except 2 knots) a matrix of heel and trim was computed. From this matrix the optimum trim for each heel could be obtained. By linking optimum trim to heel, the only remaining variable for each speed was heel. In the second IVPP round the resistance from CFD was used with a small correction for the effect of the error in leeway in these computations. The correction was based on the same empirical relations as in the IVPP. For each speed the required wind speed could then be computed as a function of heel only and the best heel angle was that where the required wind speed was the smallest. The best trim followed from the optimum trim/heel relation.

3.2. IVPP

Due to the space limitations only a brief description can here be made of the IVPP, for a full description see [2]. The logic of the program is similar to that of conventional VPPs (see [3]), the main difference being that the wind speed is guessed initially, rather than the boat speed and the result is wind speed rather than boat speed. The force and moment balances are

Aerodynamic Drive - Hydrodynamic Resistance
Aerodynamic Side Force - Hydrodynamic Side Force
Heeling moment - Righting moment

The advantage of the IVPP compared to a conventional VPP is the lack of interpolation between speeds. Since the speed-resistance relation is very non-linear, interpolation would be too inaccurate, unless a very large number of speeds were computed using the CFD method.

As explained above the hydrodynamic forces on the hull are taken either form the tank test results (first round) or CFD simulations (second round). To compute the forces on the appendages the ITTC-78 formula [4] is used for friction drag, and the Hoerner form factor for estimating viscous pressure drag [5]. The induced drag is calculated using formulae from lifting line theory (see e.g. [6]).

The aerodynamic forces in the IVPP are obtained from Hazen´s sail model incorporating a flattening factor to account for sail shape changes at the top end of the wind range [7].

3.3. CFD

Again, the description will have to be very brief. For a full account, see [2]. The simulations were carried out using the Reynolds-Averaged Navier-Stokes solver in Star CCM+. The free surface was handled by the VOF technique and the turbulence model used was k-ω SST. An unstructured mesh with prism layers close to the hull was used and the hull was embedded in a grid block overlapping the background grid. The hull block was allowed to move relative to the background grid when the hull attained equilibrium in sinkage.

Wall functions were used close to the hull and the y+ value of the innermost grid point was kept around 30. The boundary condition used at the inlet and the sides, top and bottom was *velocity inlet*, meaning that a constant free stream velocity would be defined at these interfaces. The boundary condition at the outlet of the domain behind the boat was *pressure outlet*, defining the pressure, but leaving velocities to be computed from inside the computational domain.

Verification of the mesh was carried out using three systematically varied grids comprising approximately 7, 10 and 15 million cells. The effect on the resistance was very small, less than 1% difference between the coarsest and finest grids, so the coarsest grid was chosen for the further computations. A systematic variation was also made of the number of prism layers, which varied from 6 to 10 cells on the rudder and from 7 to 11 cells on the centreboard. The y^+ values of the first cells and the total thickness of the prism layer region were kept constant. This study showed clearly that the number of prism layers on the foils had almost no effect on the results.

The accuracy of the CFD computations was validated by simulating some of the cases that had been tested in the tank. Tested upright cases with the trims producing least resistance were chosen for comparison. The resistance graphs for the tank test results and the simulations are shown in Figure 2. The comparison errors range from -0.5% to 5.7% over the speed range.

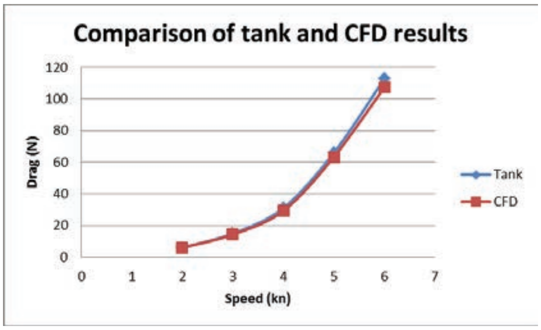

Fig. 2. Comparison of upright resistances measured in tank tests and CFD simulations

As the goal of the study was to optimize the trim and heel of the boat, the absolute values of resistance and their error have little effect on the results. However, it is important that the trends are caught correctly, i.e. the effects of trim and heel are recognized. Therefore a comparison between tank test results and CFD results with increasing heel was made at four knots of boat speed. The comparison was done without appendages. Both trim and heel were set to be equivalent in the tank and in CFD calculations for each case. The trend was quite well captured by the simulations over the whole heel range, although the tank tests showed an 11 % reduction of resistance at the maximum tested heel angle, while the reduction in the CFD results was 8,2 %.

4. Results and discussion

In this section the results for the best sailor position at each speed will be presented and discussed. Also a summary is provided and the results are reflected against experiences of top level sailors.

4.1. Best trim and heel at two knots

The tank test performed on the Laser dinghy showed a very clear tendency for the resistance to reduce with increasing bow-down trim. The maximum bow-down trim in practice was estimated to be around 2 degrees. Therefore all further analysis for two knots boat speed was done for a constant trim of 2 degrees bow-down.

In the IVPP results in Figure 3, a clear minimum of needed wind can be found at a heel angle around 11 degrees. The larger the heel, the smaller the sail drive. On the other hand, the wetted surface area drops with heel, and therefore an optimum is in this case found at 11 degrees. Even if the minimum is clear, the difference between upright and 11 degrees is only 0,9 % in the required wind. This corresponds to a speed change of 0,013 knots, or 12 meters per nautical mile. A difference like this is hard to find with traditional speed tuning, but if a sailor relies on the improvement he could gain an advantage with even with such small differences [8].

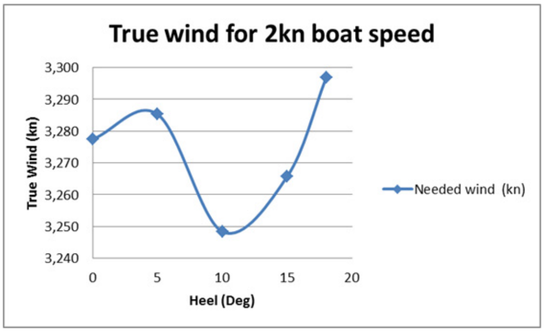

Fig. 3. 2kn - IVPP results for least needed wind

4.2. Best trim and heel at three, four, and five knots

At three, four and five knots boat speeds the matrix of CFD simulations comprised three heel angles the smallest being zero and the largest between ten and sixteen degrees. For each heel angle four or five different trim angles were investigated. In Figure 4, optimum trims as functions of heel are shown. Positive trim is bow-up.

It can clearly be seen that the optimum trim moves further forward as the boat heels and at zero degrees heel the best trim is approximately 0,25 degrees bow up, whereas the best trim for 16 degrees heel is approximately 0,5 degrees bow-down. This resembles the natural trim of the boat as it heels. As the boat is of relatively triangular shape the transom rises compared to the bow with increased heel if the centre of gravity is not moved in the longitudinal direction. Also the transom immersion is a significant factor affecting the resistance ([9], [10], [11]). With the bow-down trim increasing as a function of heel, the transom immersion will stay approximately constant. Figure 4 shows that the optimum trim varies almost linearly with heel

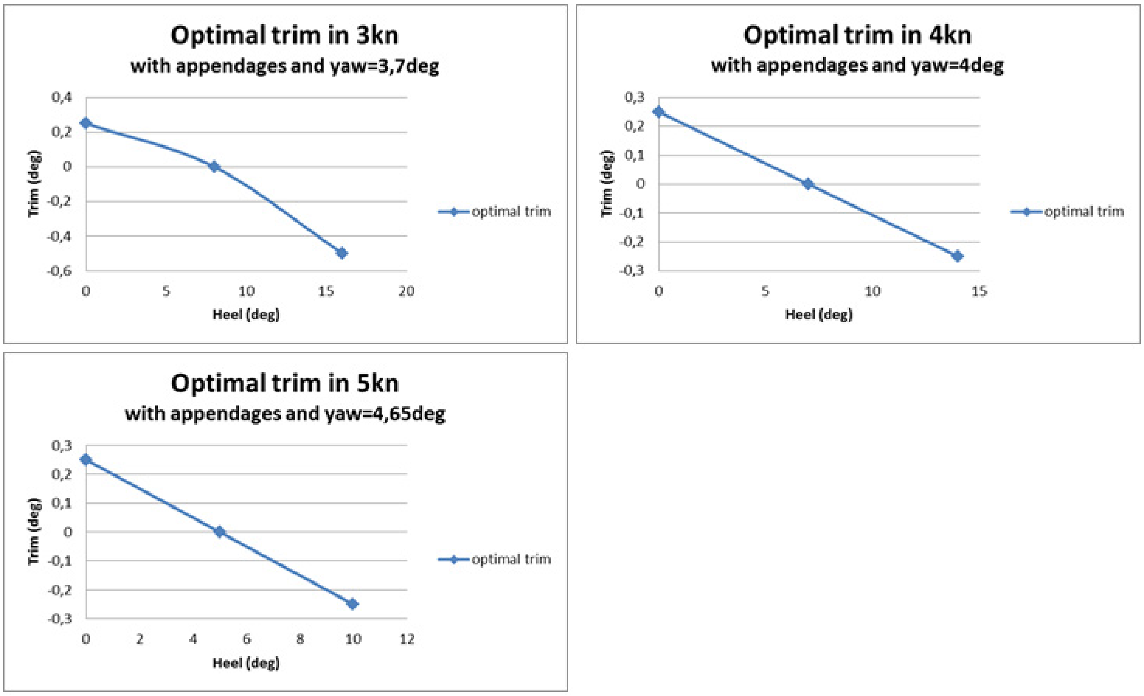

Fig. 4. Optimum trim as a function of heel from CFD simulations at 3, 4 and 5 knots

The smallest required wind from the IVPP to achieve three, four or five knots of boat speed is shown in Figure 5. The trends are quite clear, but the change of wind from zero to eight degrees are actually very small. The difference of needed wind between zero and 8 degrees heel at three knots of boat speed is only 0,035 knots which corresponds to a wind change of 0,7 %. At 4 knots the corresponding difference is 0,11 knots of wind or 1,6%. These are very small differences that could not even be felt by a professional sailor. However, the wind differences correspond to speed differences of approximately 0,07 knots and 0,24 knots, respectively. These correspond to 40 m/nm and 110 m/nm which is very significant and could easily be recognized by a competitive sailor.

At five knots of boat speed the IVPP result looks different. This is due to the flattening factor that had to be utilized at this boat speed. The reason is that at five knots of boat speed the maximum achievable righting moment is not sufficient to keep the boat at the desired heel angle without flattening the sail. In the IVPP result for five knots each point has a different flattening factor. The minimum required wind and therefore best sailing condition, is found at a heeling angle of approximately eight degrees. This relatively large needed heel is interesting and not necessary obvious to a sailor. In practice this means, that sailing with some heel and a fuller sail is beneficial compared to sailing the boat fully upright with a flatter sail. The dominant effect that makes the heeled condition faster is the addition of righting moment with heel. Therefore the sail can be significantly more powerful and a larger drive force is created.

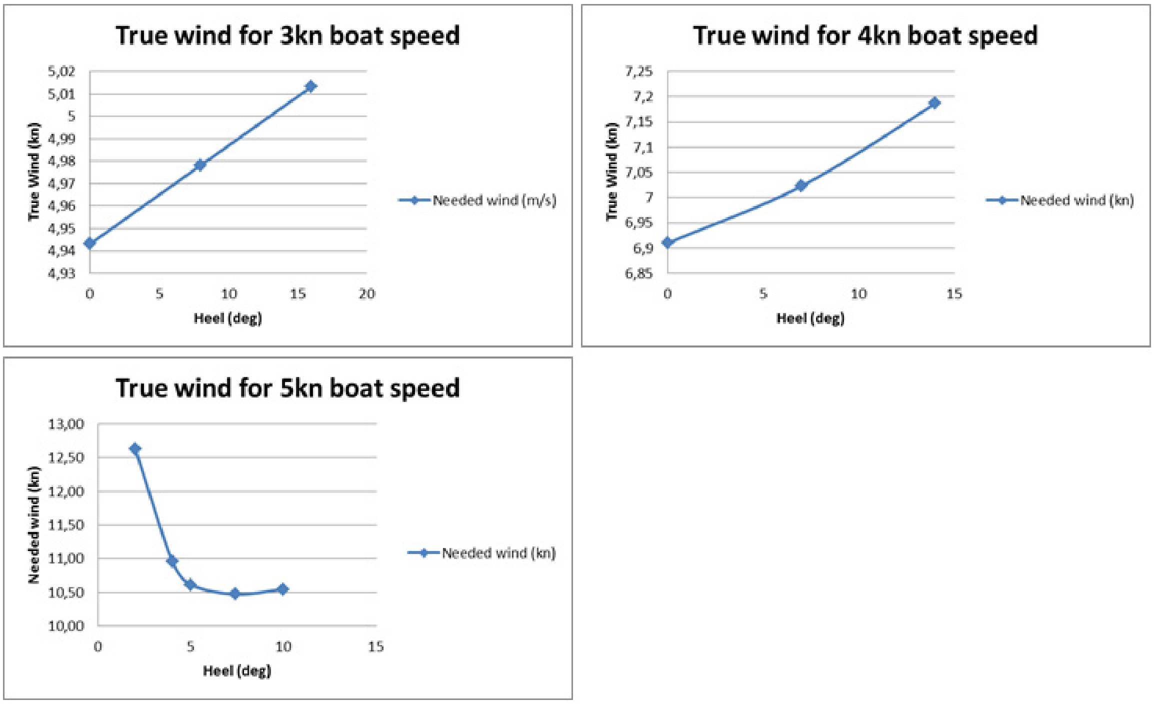

Fig. 5. IVPP results for least needed wind in 3, 4 and 5kn boat speed

4.3. Summary on best sailor position

Figure 6 shows a summary on best trims and sailor positions. It can be seen, that the boat has to be significantly heeled for very slow and fast speeds, while an upright attitude is best for the medium speeds. At low speeds the reason for the heel is the reduction of wetted surface area, at medium speeds the reason for the upright condition is the added sail power, and at higher speed the reason for the growing heel angle is the added righting moment which in turn makes an increase in sail power possible. To achieve these heel angles the sailor moves transversally outwards with increasing speed starting on the leeward side of the centreline and ending at a fully extended hiking position.

The best trim again is as far bow-down as possible in low speed and at medium and higher speed the best trim is very constant at approximately 0,25 degrees aft. In very low speed the best trim is achieved by moving as far forward as possible. In medium and higher speeds the best sailor position is between 160-166 cm from the transom. The sailor position therefore changes surprisingly little.

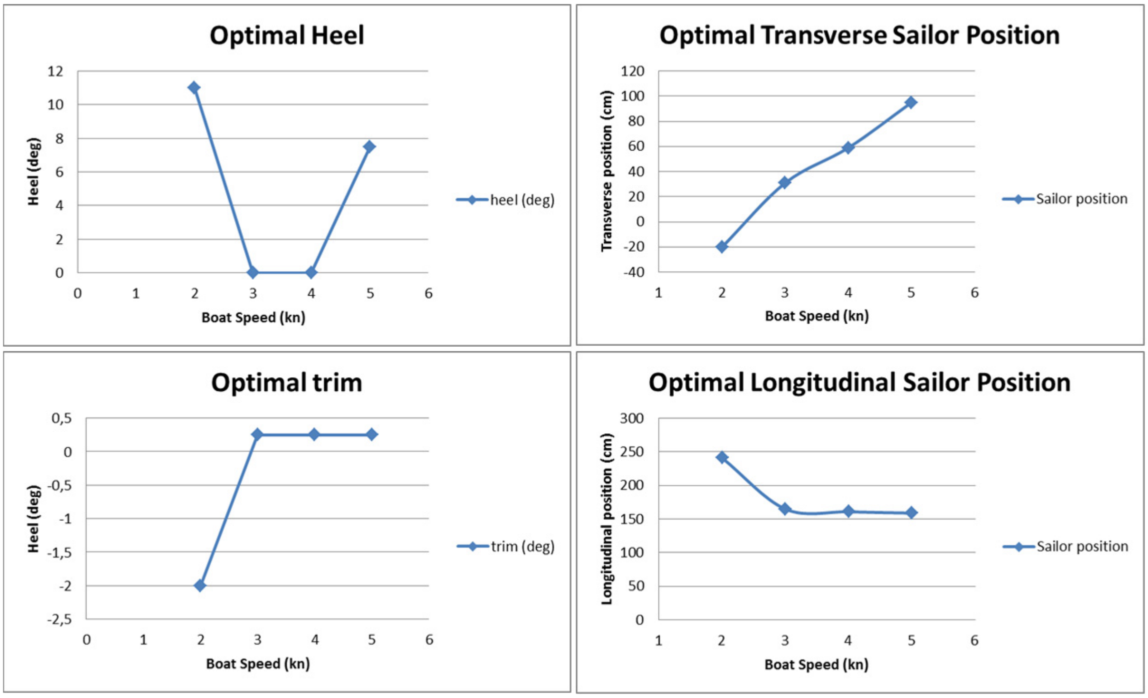

Fig. 6. Summary on best heel and trim angles and sailor positions

5. Conclusions

To investigate the best sailor position on a Laser dinghy sailing upwind a special purpose Inverse Velocity Prediction Program was developed. The program accepts CFD results as input and uses the computed results in a way that reduces the amount of needed CFD simulations significantly.

The results of the study essentially confirm sailing techniques learned over the years in competitive sailing, and thereby making important contributions to research on sailing. The beneficial heels at very low speed and at higher speeds when hiking, are not obvious results. Especially the result for a beneficial heel angle at higher speeds highlights the phenomenon of added power, which often is forgotten by sailors in practice. A major achievement of the work is that all trends have been explained physically.

References

[1] Peter, J. och Lindstrand Levin, R. (2014) *CFD prediction of the effect of heel and trim on the resistance of an Olympic dinghy*. Chalmers University of Technology (Report. X -14/304) Department of Shipping and Marine Technology, Chalmers University of Technology, Göteborg, Sweden,

[2] Pennanen, M. (2015) *Optimal sailor position on an olympic dinghy* Aalto University, Departement of Applied Mechanics, Helsinki, Finland

[3] Larsson, L., Eliasson, R. and Orych, M, (2014), *Principles of Yacht Design* (4th ed.)", Adlard Coles Ltd, London

[4] ITTC 2000. *Performance, Propulsion, 1978 Performance Prediction Method*. International Towing Tank Conference, Recommended Procedures

[5] Hoerner, S, 1992. *Fluid Dynamic Drag.* Published by author.

[6] Anderson, J, 2010. *Fundamentals of Aerodynamics.* McGraw-Hill

[7] Hazen, G S 1980. *A model of Sail Aerodynamics for diverse rig types.* New England Sailing Yacht Symposium.

[8] Frost, R, Henderson, K 1991. *Perfectionism and reactions to athletic competition.*
Journal of Sport & Exercise Psychology, Vol 13(4), Dec 1991, p. 323-335.

[9] Allroth, J, Wu, T, Orych, M, Larsson, L 2015. *Sailing Yacht Transom Sterns – A Systematic CFD Investigation.* 5th High Performance Sailing Yacht Conference, Auckland, March 2015.

[10] Eslamdoost, A, Larsson, L, Bensow, R 2015. *On transom clearance.* Ocean Engineering 99 (2015) 55-62.

[11] Orych, M, Larsson, L 2015. *Hydrodynamic Aspects of Transom Stern Optimization.* 5th High Performance Sailing Yacht Conference, Auckland, March 2015.