Application of Advanced Computational Fluid Dynamics in Yacht Design

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ABSTRACT

Nowadays, Computational Fluid Dynamics (CFD) methods are frequently used in sailing yacht design. Mostly these are panel methods calculating the inviscid flow around the hull with free water surface. They can predict the wave pattern and wave making resistance, and, for cases with leeway and heel angle, the side force and induced resistance on the keel and rudder.

One of the most advanced codes in this class is the code RAPID, developed by MARIN. It differs from most other codes by taking into account the full nonlinearity of the problem, incorporating the effect of the hull shape above the design waterline, the dynamic trim and sinkage and all effects of the wave steepness. This paper describes the recent extension of the code with modules for lifting surfaces (rudders and keels), asymmetric flows, and other features required for application to sailing yacht computations.

The results obtained from calculations with RAPID and with DAWSON, a conventional linearised method, are compared with model tests performed in the Delft Ship Hydromechanics Laboratory for a 3.5 meter model of a 1992 America’s Cup yacht. The nonlinear method is found to produce improved predictions of the bow wave height and the wave profile along the hull. Also, the calculated resistance is in much better agreement with the experiments.

LIST OF SYMBOLS

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<thead>
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<tr>
<td>C</td>
<td>Constant</td>
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<td>Fn</td>
<td>Froude number</td>
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<td>g</td>
<td>Acceleration of gravity</td>
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<td>Waterline length</td>
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<td>Leeway angle</td>
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<td>Wave elevation</td>
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<td>Fluid density</td>
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<td>Velocity potential</td>
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ABBREVIATIONS

CFD Computational Fluid Dynamics
FSBC Free Surface Boundary Condition
IACC International America’s Cup Class
VPP Velocity Prediction Program

1 Introduction

1.1 Predicting the performance of a sailing yacht

The speed and attitude of a sailing yacht are determined by a complicated force equilibrium. Aerodynamic, hydrodynamic, hydrostatic and gravity forces and moments on sails and hull in longitudinal, transverse, and vertical direction must be balanced. This leads to the yacht not just moving straight ahead, but taking a heel and yaw angle. Sail and hull forces depend on wind speed, ship speed, their relative direction, the heel angle and the yaw.

Consequently, sailing yacht design and optimisation is a complex matter. The combination of hydrodynamic and aerodynamic forces is difficult to evaluate without the use of extensive computations and model test results [1]. The optimisation is often done for one purpose: speed performance. How to evaluate different designs in that regard? And how do small design changes influence the force equilibrium and thereby the speed made good?

To solve the force equilibrium acting on a sailing ship and thereby determine its speed, the indispensable Velocity Prediction Programs (VPP) are often used. A VPP determines the sail forces, the hydrodynamic forces, boat speed, heel and yaw angle for any prescribed wind condition and sailing angle between the wind direction and course of the boat. Therefore a VPP requires as input the dependence of all forces and moments on speed, heel and yaw angle.

This can either be supplied by empirical rules, or by model tests, or by sophisticated computational tools. Empirical relations evidently do not address the specific quality of a design but just its main particulars and parameters. On the other hand, model testing still provides the most comprehensive representation of the hydrodynamics, but is an expensive and time-consuming procedure. Consequently, the third option, the use of computations, is an attractive alternative that permits to quickly investigate more design variations. It is not surprising that the syndicates of the America’s Cup, the most prestigious sailing race, do most research in this field and use the most powerful computational tools. But the use of computational tools is not restricted to America’s cup syndicates. Nowadays many programs are available on PC’s and many sailing yacht designers use them. Computational tools are used for calculations of motions, added resistance, sail forces, hydrodynamic resistance etc. These provide predictions for separate forces and quantities that play a role in the force equilibrium mentioned before.

1.2 The use of potential flow predictions

One quickly developing class of prediction tools is Computational Fluid Dynamics (CFD) programs. These are methods based on numerical solution of fundamental equations describing the flow field. As little specific empirical input is usually employed, the methods are not restricted
to a particular type of vessel; however, restrictions are often caused by basic assumptions made in the modelling. In the progressing development of CFD, such assumptions are removed one by one, producing quite complete and accurate tools requiring acceptable computational power. CFD allows predicting and optimising the hydrodynamic forces, the wave and induced resistance. Effects of hullform details and e.g. the design of appendages can be evaluated. Besides just providing forces a particular advantage is that such flow calculations give detailed insight in the flow field, permitting a directed optimisation of design features.

A breakthrough in the application of flow computations in sailing yacht design has been the use of potential flow calculations in the design of the Australia II, which won the America's Cup in 1983. While at that time the wave making and the interaction between side force and wave making could not yet be taken into account, already in the 1987 campaigns extensive use was made of free-surface potential flow codes that did incorporate these effects. MARIN applied a predecessor of the DAWSON [2] code in the design optimisation for eight different America's Cup syndicates.

The program DAWSON is based on the method proposed by C.W. Dawson [3], but from the beginning included the modelling of lift effects on keels, rudders or other foils. Starting in 1986 the method has been further developed over the years [4], which resulted in a mature program that has been extensively used in merchant ship design until around 1994. It has proven to be a most practical and efficient tool, giving much insight in the quality of a design and possibilities for improvement. An optimisation using DAWSON, preceding model tests, thus had become a standard component of a ship hullform design project at MARIN.

However, certain shortcomings inherent to the basic approach became apparent in these applications. Principal origin of the shortcomings was the linearisation of the boundary conditions typical of Dawson-type methods. Since the limits of the Dawson approach had been reached, a new deal was required for further improvement of the accuracy.

This was found in a so-called nonlinear method, which solves the complete inviscid flow problem without assumptions of low speed or small wave amplitude. In 1990 - 1994 such a method has been developed at MARIN, the Raised Panel Iterative Dawson (RAPID) method [5,6,7], which today is one of the most prominent wave pattern prediction methods for merchant vessels worldwide. Since 1994 the program is used on a routine basis at MARIN in ship design, now for some 300 calculations per year, having fully replaced DAWSON and proving very successful. In addition, the code is being used at a few major shipyards worldwide.

1.3 Recent developments

While the use of fully nonlinear wave pattern prediction methods is state of the art in merchant and naval ship design today, the situation for sailing yacht design is slightly different. The greater complexity of the problem, and the smaller commercial interest, has made this field slightly lag behind. Consequently, most computational techniques currently applied to sailing yachts still rely on linearisation, e.g. [8, 9]. Only recently some studies have been done in which fully or partly nonlinear methods have been applied [10,11]. While the usual slenderness of sailing yachts at first sight seems to justify a linearisation, there are many important aspects that are fundamentally nonlinear and could not be studied or taken into account.
Of MARIN's code RAPID, no sailing yacht version existed so far, as it was not capable to handle asymmetrical hull forms and lifting surfaces. In 1997 the CFD-Yacht Design project was started, a project sponsored by SENTER. The participants are Dutch yacht companies: Ocean Sailing Development Holland, Van de Stadt Design, De Vries Lentsch, De Voogt, and Standfast Yachts. The Ship Hydromechanics Laboratory of the Delft University of Technology was subcontracted for performing VPP analysis. In the course of this project DAWSON has been made available and introduced to the participants, and the RAPID program has been extended to make it suitable for calculations for sailing yachts.

This paper describes the modelling underlying the DAWSON and RAPID codes (Section 2), and the specific extensions made to the latter (Section 3). In Section 4 the results of a limited validation for an IACC yacht are discussed and finally in Section 5 the conclusions will be presented.

2 Theory

In this section we will describe the theory underlying free-surface panel methods, and the specific implementation of a linearised method.

2.1 General theory for free-surface panel methods

When looking at a yacht sailing in calm water one can distinguish the following flow phenomena:

- a wave pattern generated by the yacht
- a viscous boundary layer and wake field
- wave breaking and formation of spray
- lift effects on keel and rudder.

As is well known, it is a good approximation to suppose the wave making and the lift to be basically unaffected by viscosity. Correspondingly, the methods considered here take into account only an inviscid free-surface flow. The viscous boundary layer and wake field and the wave breaking and formation of spray are neglected. It is then consistent to assume the flow around the yacht to be irrotational. A velocity potential \( \phi \) may be defined, such that the velocity field is the gradient of that scalar potential. The incompressibility of the flow requires that the potential satisfy the Laplace equation:

\[
\nabla^2 \phi = 0
\]

In addition we have the Bernoulli equation for the pressure:

\[
p + \rho gh + \frac{1}{2} \rho \nabla \phi \cdot \nabla \phi = C
\]

The potential flow is subject to the following boundary conditions:

1. Boundary condition on the hull surface: On the wetted part of the hull the normal velocity is zero.

\[
\phi_n = 0
\]
An additional dynamic boundary condition on the hull can be imposed, requiring equilibrium between the hydrodynamic and hydrostatic pressure forces, the weight of the ship and any other forces (e.g. sail forces). This determines the dynamic trim and sinkage.

2. Boundary conditions on the water surface: The kinematic condition states that the flow must follow the wavy water surface; the dynamic condition requires that the pressure at the water surface is equal to the atmospheric pressure.

\[ \phi_y \eta_z + \phi_z \eta_y - \phi_y = 0 \quad \text{at} \quad y = \eta(x, z) \]

\[ \frac{1}{2} (V^2 - \phi_y^2 - \phi_z^2) - g \eta = 0 \quad \text{at} \quad y = \eta(x, z) \]

3. Radiation condition: No waves may occur upstream of a disturbance that generates them (say, upstream of the bow).

The potential flow satisfying these boundary conditions can be calculated by a so-called panel method. The boundaries of the flow domain (i.e. the underwater part of the hull surface and a surrounding part of the water surface) are covered with source panels, small quadrilateral elements that each are supposed to emit fluid in all directions at a certain rate, the (still unknown) source strength. Each source panel thus generates a flow field in the entire space, which is approximately radially directed away from (or towards, for negative source strength) the source panel, and has a velocity proportional to the source strength. The total flow field is now defined to be the sum of the velocity fields induced by all source panels (on the hull and the water surface) plus the incoming undisturbed flow (in a co-ordinate system moving with the ship).

This flow field must satisfy the boundary conditions at all points on the boundaries. In practice, the boundary conditions can only be enforced in a finite set of points, for which we can choose the panel centres. The velocities induced by all panels at the location of all panel centres are expressed in all unknown source strengths. Substituting these expressions in the boundary conditions produces a closed set of algebraic equations for the unknown source strengths. After solving this system it is easy to compute the velocity and pressure field, the wave pattern and all derived results such as the forces and moments on the hull.

This panel method in principle is a relatively standard technique, introduced by Hess and Smith in 1967. However, application to the wave-making problem introduces several complications. The principal one is the fact that the free surface boundary conditions are nonlinear (i.e. contain squares and cross products of unknowns) and must be imposed on a wave surface not known beforehand.

2.2 Dawson’s method

A well-known solution for these problems is the method proposed by Dawson in 1977. The nonlinearity is removed by linearising the free-surface boundary conditions and imposing them on the still water surface rather than on the actual wavy water surface.

As a first step, a flow without wavemaking must be computed, which means the water surface remains undisturbed. Computationally this is done by reflecting the underwater part of the hull in the still water plane, producing a ‘double body’. The hull and its mirror image are covered with
sources of equal strength. The velocity field so calculated is symmetric with respect to the still water surface and is commonly denoted as the “double-body flow”.

The second step is to include the wavemaking, assuming the flow with waves to be a small perturbation of that without waves, the double-body flow. The potential $\phi$ is thus decomposed in the double body potential and a perturbation; and only terms of first order in the perturbation are taken into account in the free-surface boundary conditions. A linear computational problem can thus be derived that can be solved in a single step.

With such a method the flow around a non-lifting body can be computed, but it is impossible to model lift on e.g. a keel, rudder or hydrofoil with only sources, and a special treatment is required. This will be discussed in relation to the nonlinear code, in Section 3.2 below.

### 2.3 Shortcomings of DAWSON

Dawson’s method has been implemented in numerous computer programs, differing mostly in numerical details. At MARIN the program DAWSON has been extensively used in practice and in several research projects. The experience with the program and the validation with model test data have shown its possibilities and impossibilities. The main shortcomings of the program, specifically for sailing yacht applications, are mentioned below:

- Due to the linearisation of the free-surface boundary conditions, bow waves and the diverging wave system emanating from the bow are substantially underestimated; an explanation is given in [12].
- As in the computation the hull is virtually cut off at the still waterline in view of the linearisation, no hull form feature above the still waterline plays any role in the calculated flow. Consequently, the effects of bow flare, overhanging bow and stern and strongly flared sections above the still waterline are disregarded. In particular for sailing yachts this is a large drawback, as the virtual lengthening of the wetted hull at higher speeds cannot be taken into account [7].
- In its standard form, the dynamic trim and sinkage of the hull are not taken into account. These can have an appreciable effect for yachts at higher speeds.
- The flow off a transom stern can be included only unsatisfactorily in a linearised method.

### 3 RAPID

These and similar drawbacks several years ago formed the motivation for starting the development of a new method, in which fully nonlinear free-surface boundary conditions (FSBC’s) would be satisfied. This is described concisely in this section.

#### 3.1 Differences between RAPID and DAWSON

The fully nonlinear free-surface potential flow code RAPID (Raised-Panel Iterative Dawson) shares several features with the Dawson code described before. However, the calculation consists of several steps that lead to a final solution satisfying the exact nonlinear free-surface boundary conditions. These steps are defined by linearising these boundary conditions in
perturbations of the result of the previous step. If the solution converges (i.e. approaches a fixed solution) these perturbations vanish and the exact FSBC’s are recovered. Usually, a RAPID calculation simply starts with a flat-water surface and a uniform flow field. Perturbations of that field are assumed to be small, and solution of the resulting linearised problem produces a correction of the wave pattern and flow field. In this way, a series of steps is carried out until the corrections vanish and the residual errors are below a given tolerance. In practice, 10 to 20 iterations usually suffice. In each iteration the linearised sub-problem is solved by a panel method fairly similar to that described above. However, there is a less usual treatment of the free surface: the source panels are not located on the (still or wavy) water surface but at a small distance above it. The FSBC’s are not imposed in the panel centres but in points on the current guess of the wave surface. These points are adjusted in every iteration. Once in a few iterations, also the free surface panels are adapted to (a given distance above) the current wave surface, and the dynamic trim and sinkage of the hull are adjusted and taken into account in a new hull panelling. Straightforward as this seems, in principle there is no guarantee that the solution will converge for all practical cases, and this is where several other attempts have failed. While in general RAPID is quite stable and robust, running it still is not for everybody, and some experience and insight are needed to handle it properly, to define suitable panel distributions, and to find a converged final solution. However, if well applied the method produces accurate results for a wide variety of cases, far superior to those of linearised methods.

3.2 Adaptation to sailing yachts

Applying this method to sailing yachts, however, is not possible without enhancements to the existing code. Features typical to sailing yachts have to be incorporated, such as asymmetric flows, lifting surfaces, and large flare of the hull form. In this section, a short description is given of the algorithm changes needed to make the code applicable to sailing yachts in general.

Asymmetry

One of the most important features that have been added is the possibility for asymmetry, for both the flow and the geometry. The asymmetry of the flow is due to the leeway angle of a yacht; asymmetry of the geometry is caused by the heeling angle. For symmetric cases, only one half of the hull and wave surfaces are represented by panelling. The symmetry is taken into account by mirroring in the centreplane. The asymmetry of both the hull and the wave pattern implies that both port and starboard sides of the hull and the water surface have to be used in the calculation. The bow contour can no longer be determined from the intersection with the symmetry plane, but has to be deduced from the foremost panels on the hull mesh. The same holds for the stern contour and special care is needed for the flow around an asymmetric transom stern. For the time being, the panels on the free surface are still hull-oriented, rather than flow (i.e. leeway) oriented; i.e. they are arranged in strips that extend fore and aft in a direction parallel to the hull centreline, not to the incoming stream. In principle this may be less efficient for larger
leeway angles and large domains, but for the calculations performed in this research no further adaptation was necessary.

**Lifting surfaces**

Another very distinguishing feature of sailing yachts is the relevance of lifting surfaces such as keels and rudders. These are modelled by using a source distribution over the actual surface (as on the hull surface), but additionally a distribution of dipoles is located in the camberplane, extending aft from the trailing edges as a wake sheet. The source panels on the outer surface of the lifting surfaces are arranged in chordwise strips. In the camberplane under each strip are strips of dipole panels. The dipole strengths have a specified distribution over the chord, such that only a single unknown is added for each strip of dipole panels. This unknown is the circulation at that spanwise location. A Kutta condition (smooth flow off the trailing edge) is imposed in a point just aft of the trailing edge in the middle of each strip. This is cast in the form of a prescribed flow direction (e.g. along the bisector of the section at the trailing edge). This is a linear form of the Kutta condition, which can be expressed in all source and dipole strengths, and is added to the system of equations to be solved. In this way, the interaction between free surface and lift is directly taken into account.

At the intersection of a lifting surface and a non-lifting body, special attention has to be given to the dipole distribution. If the dipole distribution would simply end at the junction, this would imply a strong trailing vortex running along the surface of the non-lifting body. This would produce an unrealistic lift and pressure distribution, and would probably cause numerical difficulties as well. To prevent such a trailing vortex at that position, the dipole distribution is extended over a certain distance inside the body; care must be taken to avoid an intersection of the corresponding wake line with body or free-surface panels, which again would cause numerical instabilities.

**Large flare**

One of the main advantages of a nonlinear method is the fact that it takes into account the effect of the hull shape above the still waterline on the wave pattern. Initially, a hull panelling is used that extends a specified distance above the still waterline, and is joined to a free surface panelling that fits around the hull at that location. In the course of the iteration process a wave pattern is computed, and the hull and free-surface panelling both have to be adapted from time to time. At the position of a wave crest, the actual waterline moves up, and in case of large flare it also moves outward a lot. The same is true for the inner edge of the free surface panelling, which is at a constant distance above the actual waterline. Consequently, for strongly flared hull forms like those of sailing yachts, free-surface panels close to the hull may become much narrower at wave crests, much wider at troughs. The quick changes and large variations in panel size may destabilise the iteration process and reduce the numerical accuracy. For conventional merchant vessels such problems rarely occur, but for the flat hull forms typical of many sailing yachts a solution had to be found.

A solution is the use of an estimated wave profile for the initial generation of the free-surface panels. Panels are generated along an intersection at the given distance above the estimated wave profile, and thus will be at approximately the correct lateral position for the final solution. In practice, first the normal procedure is used for generating the free-surface panels and performing
a few iterations. The intermediate result for the wave profile is used to regenerate the free-
surface panels, and the iteration process is started all over again. In some cases it appeared to
be necessary to repeat this procedure once.

**Post-processing**

Some other new features in the program package are related to the post-processing of the
results. Interesting quantities for sailing yachts are, among others, the transverse forces, yaw
moment, and induced resistance of the lifting surfaces. The side force is evaluated by integration
of pressure forces over the wetted area below the actual (wavy) waterline. Similarly, the
resistance is evaluated by pressure integration. This resistance includes both the wave
resistance component and the induced resistance, which acts primarily on the lifting
components. For analysis and optimisation purposes, it is of interest to be able to distinguish
these two contributions. This is made possible by a separate determination of the induced
resistance from the trailing vortex system, a so-called Trefftz-plane analysis. In addition, a
separate determination of the wave resistance component would be possible by extending an
available routine for analysis of the far-field wave pattern. This is a desirable option, as pressure
integration over thin foils is liable to be inaccurate due to the sharp suction peak near the leading
edge.

Besides the new extensions, evidently use is made of existing visualisation tools, which are
indispensable for inspection of the flow field, analysing phenomena as lift carry-over and the
interaction of side force and wavemaking, and so on. Some of the figures illustrate the
possibilities of such tools.

## 4 Validation and Comparison

In this section, some comparisons will be presented of calculations and experimental data for a
sailing yacht. The model test data were kindly made available by the Ship Hydromechanics
Laboratory of Delft University of Technology.

### 4.1 Model and experimental conditions

The model used (Error! Reference source not found.) resembles the 1992 IACC hull forms
[13]. It represents a typical modern racing yacht design. The main dimensions are given in
Table 1. In Error! Reference source not found. the planform and section of the keel are given.
The main particulars of the keel are given in Table 2.

The experiments consisted of:
- a series of runs with the model in upright condition, for Froude numbers varying from 0.25 to
  0.60, and at four leeway angles (0, 3, 6 and 8 degrees).
- a series with the model with a leeway angle of 6 degrees, at four heeling angles (0, 10, 20
  and 30 degrees).
The calculations were carried out for the same conditions; but only a selection of these runs was used for validation and will be discussed here.

4.2 Experimental setup

The experiments were conducted according to the standard Delft Ship Hydromechanics Laboratory method for sailing yachts. The model was connected to the towing carriage by two balanced connecting rods which leave the model free to heave and pitch but keep it restrained in surge, roll, sway and yaw (see Figure 3). The resistance, the side force and the yawing moment on the model as a whole were measured at the connection between the balanced rods and the model, by using strain gauge type dynamometers.

The keel was attached to the model by a rod protruding through the bottom of the model. This rod was connected to a six component dynamometer, which measured the side force, and the resistance of the keel.

All the tests have been carried out with carborundum stripes as turbulence simulators. Stripes were used on the canoe body and the appendages. The resistance tests were carried out twice: once with single and once with double width of the carborundum stripes. Twice the difference between these two measurements was subtracted from the raw measurement data to obtain the corrected resistance [13,14].

During the runs, photographs of the wave profile along the hull were taken. The photographs were taken from a forward and, in some cases, aft position at the port (windward) side. The wave height along the hull was measured by projecting the slides on a whiteboard and manually measuring the waveheight relative to a waterline and section grid painted on the model.

Some difficulties occurred in the interpretation of these pictures, due to the perspective used, and the fact that for most runs only one picture was available. Most pictures are taken from a forward position, under an angle of about 45 degrees. For the larger speeds, this means that the bow wave blocks the view of the wave profile at the fore shoulder, thus disabling part of the validation. Moreover, the wave heights have to be read from a grid on the hull surface. This hull surface is both trimmed and heeled, and, given the perspective used in the pictures, errors in reading the values will occur due to the large flare of the hull stations. Finally, in some cases it was difficult to distinguish the real wave and a thin water film along the hull surface.

Therefore, this procedure of determining the experimental wave profile is rather inaccurate. Nevertheless, these data give a useful indication of the validity of the predictions. Estimated error margins are given in the figures.

4.3 The computations

For the computations the hull and keel need to be represented as an initial panel distribution. For the present cases these were generated from a CAD-system, MARIN’s GMS system, which uses a B-spline surface representation of the hull form and covers the hull with a suitable panel distribution based on limited user input.
Hull panellings were used as depicted in Figure 2 through Figure 4. Note that these are the initial panellings, which subsequently are automatically adapted during the solution. Therefore the panelling of the hull surface extends above the still water line. The meshes shown are for the case of a heel angle of 10 degrees. Typically, the mesh on the hull consisted of about 2000 panels, of which 350 on the keel.

The panel density on the keel is illustrated in Figure 4. The panelling is denser close to the leading and trailing edge, in order to represent the local pressure distribution accurately. A study of the sensitivity of the wave profile to the keel panelling was made. It showed that using fewer keel panels has large influence on the local wave profile along the hull. Using more panels has no influence on the wave profile any more, but may increase accuracy of drag and lift of the keel.

The free-surface mesh consisted of 15 strips on both sides of the hull, with a total of about 2500 panels, see Figure 5.

In the nonlinear method, it is possible either to leave the model free in trim and sinkage, such that it finds its own equilibrium position, or to specify a trim and sinkage. In the present calculations, the latter option was chosen and experimental values were used, since the high application of the towing force in the experiments otherwise could have caused disagreement.

4.4 Comparison of calculated and measured wave heights

It is of interest to compare the calculated wave profiles along the hull with those derived from the experiments; this gives more precise indications of the validity of the predictions than merely a comparison of the forces. However, the appreciable uncertainty of the experimental wave profile data should be kept in mind.

The first comparison is made for an upright position at a speed of Fn=0.35 without leeway. Figure 6 shows the wave profiles. Both axes are scaled with the ship length. The bow is at x/L=-0.5, the stern at x/L=0.5. It can be seen that in general there is a good agreement between the measured wave profile and the calculated one. A slight phase shift is observed at the bow wave, but this may well be due to a thin water sheet commonly found in model tests rather than to an error in the actual bow wave prediction.

Also further aft there is a slight aft shift of the calculated wave profile, which so far is unexplained. The wave trough at midship is very well predicted. No measurements are available for the stern part of the hull.

Compared to the results of the linear program DAWSON shown in the same figure, the results of RAPID are far superior. The bow-wave height is better predicted, and the bow wave is also much steeper, again in agreement with the measurements. The influence of the keel for zero leeway is very small, as expected.

Figure 10 shows the calculated wave pattern for a much higher speed, Fn=0.60, with zero heel and leeway. No comparison with experimental wave profile data has been made, but the figure shows a most plausible result, with a predominance of diverging wave components and an
almost absent transverse wave. Due to the large dynamic trim and the stern wave, the flow now just detaches from the transom, which is far above the still waterline.

As a second step, a calculation has been performed for the yacht under a leeway angle of 6 degrees at the same Froude number 0.35. In Figure 7, it can be seen that again the correlation with the measured wave profile is quite good. The bow-wave height is predicted very nicely, and, as a comparison of Figure 6 and Figure 7 shows, the calculation correctly represent the decrease of the bow wave height at the windward side due to the leeway. The wave trough at the windward side, however, becomes much deeper as a result of the vicinity of the suction side of the keel. A separate calculation without keel shows that this is significant (Figure 7), but a comparison with the data suggests that the calculations overestimate the influence for this specific situation. A corresponding linear calculation using DAWSON shows similar differences as for the upright condition. Again the bow-wave height and steepness are better predicted by the nonlinear method.

The final comparison is for the yacht under a leeway angle of 6 degrees combined with a heeling angle of 10 degrees, at Fn=0.386. The calculation was fairly difficult, due to the large steepness of the bow wave system at the lee side, the large effect of the wave pattern on the shape of the actual waterline, and the resulting difficulty of achieving a sufficient resolution of all flow features. Nevertheless, as Figure 11 and Figure 12 show, the nonlinear calculation is far more plausible than the linear one. In the result of DAWSON, there is an effect of a numerical oscillation observed as a second wave crest outboard of the true bow wave crest. This is much less pronounced in the nonlinear result.

Besides this numerical error, the linear result shows a dramatic modelling error fundamental to the linearisation. In Dawson's method, the hull is cut off along the still waterline, which is fairly blunt at its aft end. A steep stern wave crest forms immediately behind, which can never exist since a stern overhang is present. In reality the stern wave follows the stern overhang over a much larger distance, making the actual waterline length much larger and the shape much smoother. This behaviour is only correctly represented in a nonlinear code. Figure 11 and Figure 12 indicate that consequently the stern wave system is much less pronounced in the nonlinear result. The large difference in the wetted hull shape and length as taken into account in both methods is evident in Figure 13 and Figure 14.

Figure 8 compares the calculated and measured wave profiles at the windward side. The bow wave shape again is well predicted, and much better in the nonlinear than in the linearised result. At this heel angle, the influence of the keel on the wave profile becomes much more dominant. This influence has not been captured completely by the prediction, although the wave trough has deepened considerably. There is no difference between linear and nonlinear predictions in this regard.

Figure 15 illustrates the overall hull pressure distribution for this condition. The detail of the keel in Figure 16 shows the pressure field on the hull caused by the lift on the keel.
4.5 Comparison of calculated and measured forces.

In the Delft measurements, the forces on keel and total hull were measured as well, besides the hull wave profile. In this section these forces are compared with the calculated forces. As the predictions only consider the inviscid flow, the comparison requires a correction for the viscous effects. To this end, we have subtracted an estimated viscous resistance of the model from the measured model resistance. The estimate was based on an assumed form factor of 1.10 for the canoe body, and an empirical form factor for the keel determined from its thickness ratio. Obviously this procedure introduces an uncertainty that is substantial at low speed, less so at high speed. No corrections for viscous effects on the side forces have been made. All forces shown in the figures and given in the tables are for full scale, and in a co-ordinate system aligned with the incoming flow.

Figure 9 shows the resistance curve for the yacht in upright position without leeway. It is clear that the resistance as predicted with RAPID is in much closer agreement with the measured resistance than the results from DAWSON, both in the lower Froude number range (but with the reservation made above) and at high speed. The large improvement obtained by including all nonlinear effects for Fn=0.60 is striking.

Table 4 shows the resistance of the hull and keel (R), and the drag and lift of the keel for the three cases previously studied in the wave-profile comparison. It can be seen that the results for the keel forces are the same for both calculation methods, indicating that the non-linearity has almost no influence on these quantities. The resistance of the hull, however, is strongly influenced by non-linearities. As for the upright case shown in Figure 9, the resistance predicted by the nonlinear method is in closer agreement with the measurements.

Table 5 shows the total side force acting on keel and canoe body. As expected, there is more difference between the linear and nonlinear result for this quantity, as there is a larger effect of the wave pattern. In this case it is found that the nonlinear result overestimates the side force by some 10%, while the linear prediction is actually closer. The cause of this is not clear at this stage, but will be studied. The lift/drag ratios for the nonlinear code actually are much closer to the experimental result than for the linear code, although this may partly have been fortuitous.

5 Conclusions

In this paper we presented the newly developed features of the non-linear CFD code RAPID for sailing yachts. The new features include asymmetric flow and hull shapes, lifting surfaces and special adaptations for ships with large flare. The results of this extended RAPID code were compared with results of the linear CFD code DAWSON, and with measurements performed at the Ship Hydrodynamics Laboratory of the Delft University of Technology. Several cases were used: upright condition with no leeway, upright condition with leeway, and heeling condition with leeway.

It was found that the nonlinear code predicts the wave profile along the hull much better than the linear code for all cases studied, and in particular accurately predicts the bow wave height. A large improvement is also obtained in the general appearance of the wave pattern, and in the
representation of important features such as the interaction of the stern wave system with the afterbody.

Also the calculated resistance was in much better agreement with experiments. Side force predictions generally were fairly accurate for both the linear and nonlinear method. While the forces in general still may differ from the experimental data by some 10 % or occasionally more, the predictions at least may be used with confidence for ranking purposes. The principal merit is that they provide a comprehensive insight in the quality of the flow in many respects, thereby permitting a rational optimisation of the detailed design.

In future research in this field we will focus on including surface-piercing foils (rudders), improving the modelling of lift produced by the canoe body, and improving the resolution and robustness for more extreme geometries and conditions. For more general validation, other sailing yacht hull forms have to be studied and more complete experimental data would be desired.

Even though, we think that the nonlinear RAPID code has become a valuable tool for optimising sailing yacht hull and keel design.

ACKNOWLEDGEMENTS

The authors are indebted to J.A. Keuning and R.W.M. Meulemans of the Ship Hydromechanics Laboratory of the Delft University of Technology for providing the experimental results in this paper.

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REFERENCES


Figure 1: Bodyplan of model

Figure 2: Keel plan form
Figure 1: Experimental setup

Figure 2: Calculation mesh, hull and keel front view
Figure 3: Calculation mesh, hull and keel side view

Figure 4: Calculation mesh, keel
Figure 5: Calculation mesh, water surface

Figure 6: Wave height comparison, upright position without leeway, Fn = 0.35
Figure 7: Wave height comparison, upright position, 6 degrees leeway, Fn = 0.35

Figure 8: Wave height comparison, 10 degrees heel, 6 degrees leeway, Fn = 0.386

Figure 9: Resistance, upright position, no leeway
Figure 10: Wave pattern from RAPID, $Fn = 0.60$, upright position, no leeway. Yacht seen from starboard side.

Figure 11: Wave pattern from RAPID, $Fn = 0.386$, 10 degrees heel, 6 degrees leeway. Yacht seen from portside (=leeside).

Figure 12: Wave pattern from DAWSON, $Fn = 0.386$, 10 degrees heel, 6 degrees leeway. Yacht seen from portside (=leeside).
Figure 13: Pressure at water surface from RAPID, $Fn = 0.386$, 10 degrees heel, 6 degrees leeway. Top view, yacht sailing to the right. (leeside = upper part of picture)

Figure 14: Pressure at water surface from DAWSON, $Fn = 0.386$, 10 degrees heel, 6 degrees leeway. Top view, yacht sailing to the right. (leeside = upper part of picture)
Figure 15: Pressure on under water body and keel from RAPID, Fn = 0.386, 10 degrees heel, 6 degrees leeway. Yacht sailing to the left. Yacht seen from portside (=leeside). Tufts indicate direction of the flow.
Figure 16: Detailed view of pressure on under water body and keel from RAPID, $Fn = 0.386$, 10 degrees heel, 6 degrees leeway. Yacht sailing to the right. Yacht seen from starboard side (=weatherside=suction side).
### Table 1: Main dimensions model

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<tr>
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### Table 2: Main particulars keel

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### Table 3: Measurement scheme

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<td>57</td>
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### Table 4: Comparison of forces

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<th>Keel Drag (N)</th>
<th>Keel Lift (N)</th>
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<th>Keel Lift (N)</th>
<th>Measurements</th>
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<td>764</td>
<td>21194</td>
<td>3003 1160 19920</td>
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Table 5: Comparison of total lift and lift drag ratios

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<th>DAWSON</th>
<th>Measurements</th>
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<td>Total Lift [kN]</td>
<td>Cl/Cd</td>
<td>Total Lift [kN]</td>
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<td>30.1</td>
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