Computational Fluid Dynamics for Boat Design

(contribution to Dag Pike's powerboat design & performance book)

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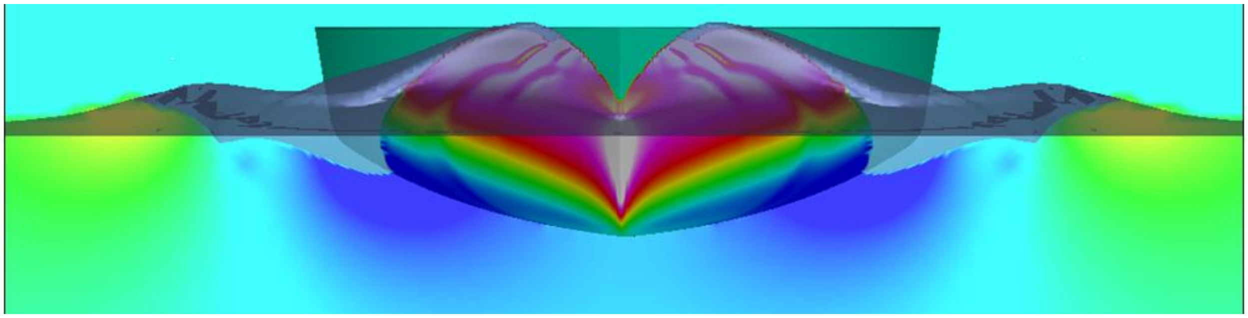


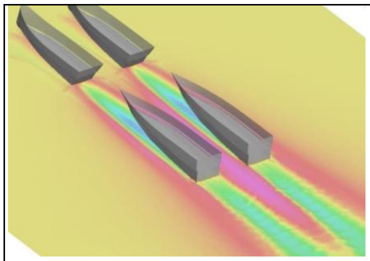
Computational Fluid Dynamics (CFD) is fast replacing build and test approaches like tow-tank testing as it is getting much easier to perform full-fledged engineering simulations on readily available super-computers like the Amazon cloud services. CFD enables the calculation of the fluid velocity and pressure over the entire flow-field around the hull by solving the fundamental equations that govern the fluid flow. Specialized software for boat hydrodynamics track the free surface and boat motions to provide the entire hydrodynamic profile of the boat at any given operating condition at a fraction of the cost of model testing.

Common applications of CFD for watercrafts include calculation of resistance, power requirements, fuel consumption, motions & added resistance in waves, g-forces, ride comfort, motion sickness index, slam loads, green water on deck, steerability in waves and wake wash. Coupling the hydrodynamic results from the CFD with its structural analysis counterpart, *i.e*. Finite Element Analysis, allows calculation of the structural loads, deformations and vibrations. After initial setup, subsequent changes to the virtual geometry can be easily performed by spline modifications or morphing between initial variants. It then becomes effortless (standing on the shoulders of the supercomputers of course) to optimized the geometry within a particular design envelop for any particular hydrodynamic property as per any desired trade-off criteria.

The example applications that follow are a assortment of simulations at various stages of the design spiral for different powerboat hulls. These were simulated using FlowCFD (www.FlowCFD.com), a specialized URANS software for boat hydrodynamic calculations.

The Mosler Tandem Cats

The Mosler tandem catamaran designs stemmed from Warren Mosler's deep intuitive understanding of the differences in motion between zero and long wheel-base vehicles and preliminary experiments with tandem mono-hulls and cats. He deduced that tandem catamarans would have a better ride quality and subsequently designed a 45' planing sports-fisher and a 100' displacement passenger ferry which was built by Gold Coast Yachts and currently ferries happy passengers between St. Croix and St. Thomas.



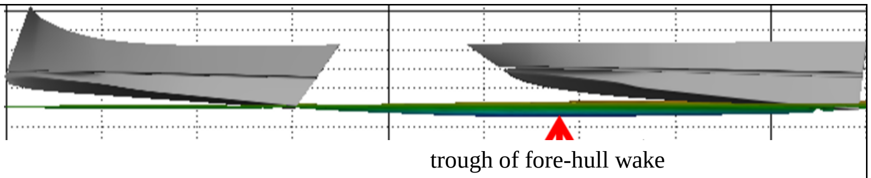


Fig. 1: Wake of tandem planing hulls, the trough of the fore-hull wake occurs just ahead of the aft hull, after which the flow angles upwards

A notable feature of the sports-fisher is its planing characteristics; the shorter tandem hulls allow for the boat to get on plane at lower speeds. FlowCFD was tasked with evaluating the initial sports-fisher design and optimizing the planing trim angles. Savitsky has shown the optimal trim angle of planing monohulls to be 4 degrees; however in tandem planing hulls, the aft hull rides the wake of the front hull and the effective angle of incidence changes. The initial design evaluation at 40 knots was carried out with static trim of both forward and aft hulls at 4 degrees. It was found out that the forward hull wake trough occurred just ahead of the aft hulls (Fig. 1) and the aft hulls were encountering the upward incidence angle after the trough making the effective planing angle much greater than 4 degrees. The geometry was then put through an optimizer which ran it through various configurations, searching for the least total resistance and converged at an optimal configuration of 2.4 and 3.1 degrees for the fore and aft hulls resp. Taking into account the encounter incidence angle and the overall dynamic trim of the boat, this configuration resulted in a dynamic trim close to 4 degrees for the aft hulls. The hulls were then simulated in moderate to high sea-states at different speeds and headings to get the safe operating envelope.

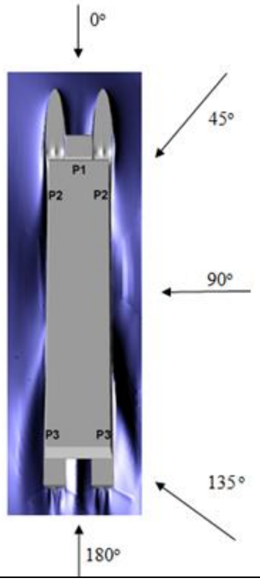
The 100' QE4 passenger ferry is a tamer displacement-hull version, with emphasis on ride comfort. A notable feature of this tandem displacement cat is that it is able to overcome the critical hull-speed barrier of conventional displacement hulls by virtue of its design. At critical hull speed, the trough of the bow wave reaches the aft end and hence conventional displacement hulls squat down and trim up high, causing a sharp rise in resistance. However, since the tandem hulls do not trim about their individual center of gravity and provide a restoring moment to each other, they do not trim up as much and are able to overcome their individual critical hull speed barrier. A 100' conventional displacement hull would encounter this hull speed barrier around 15 knots, but the QE4 cruises along at 20 knots.

FlowCFD was tasked with calculating the fuel-consumption and seakeeping performance in moderate and rough sea. The calm water resistance came out to be 21 KN, and with a overall propulsive coefficient of 0.6, the required delivered power was 360 KW at 20 knots. The fuel consumption was then calculated to be around 25 gallons/hr, *i.e.*, 0.92 MPG using the engine performance curves. Carrying 50 passenger, this gives passenger MPG = No. of passengers x MPG = 46, which puts it in the top 5% most energy efficient passenger ferries.

The design was then put through a worst case scenario testing with the boat operating at cruise speed, maximum load and maximum recorded wave heights at resonant conditions (when encounter frequency matches the natural frequency of the boat). NOAA buoy data for the past 5 years was used. The results indicated that the vertical accelerations exceed 1-g at maximum probable wave conditions in resonant waves due to wet-deck slam (Fig. 2), which have a less than 1% probability of occurrence at any given hour along the ferry route.

Fig. 2: Wet deck slamming occurs at high resonant wave conditions

The motion sickness incidence of the QE4 passenger ferry in sea-state 3 was analyzed both quantitatively and qualitatively using the British Standards Institution BSI and International Standards ISO. According to both standards, motion sickness problems arise when the human body is subjected to low frequency vibrations, with a steep decline in motion sickness when the frequency goes over 0.5 HZ.



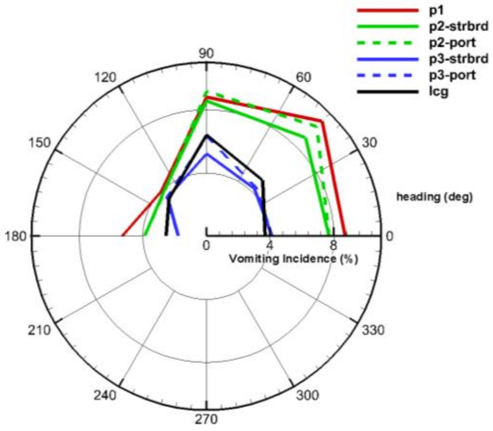


Fig. 3: Vomiting incidence % at various passenger seat locations after 30 minutes of continuous operation in sea state 3 as per BSI

The vomiting incidence (expressed as a percentage of population that get sick) is a function of both the vertical acceleration and the frequency of motion. These values were obtained from sea-keeping simulations carried out in irregular seas using the Bretschnieder spectrum at different wave headings and the vomiting incidence % was calculated at the helm, the forward & rear window seats for both port and starboard sides (Fig. 3). The highest accelerations occur in head and bow-quartering seas at the helm and forward-passenger seats. The rear-passenger seats have drastically reduced accelerations.

Unlike "zero wheel-base" catamarans where the frequency is predominantly affected by the encounter frequency, here for the tandem cat the frequency is mainly a function of its natural pitch and roll frequencies. Hence low frequency accelerations are mitigated in beam, stern-quartering and following seas where the encounter frequencies are low.

Based on construction and field experience, the next generation ferry's is being designed to make the hulls more slender with a tear-drop shaped taper, which reduces both the resistance and vertical accelerations.

Teknicraft semi-planing hulls

Nic de Waal from Teknicraft Ltd. designs high-speed semi-planing hulls, many of which are foil-assisted. A notable feature of these hulls is their low wake wash which make them suitable for operations in passage ways where beach erosion is an issue.

FlowCFD was tasked with simulating some of their designs. Due to their high speed and proximity of the foil to the free surface, the effects of air entrainment were also factored in as they affect both the lift and resistance. Entrainment reduces the frictional resistance a bit, but also causes a loss of lift and reduction in overall buoyancy which are detrimental. Fig. 4 shows the wave elevation and hull-surface pressure contours of the Teknicraft foil-assisted semi-planing catamaran (60' TenSeventy) at 30 knots. The performance at design speed was found to be close to the approximate observed upper edge of attainable performance for transport factors based on a large body of data.

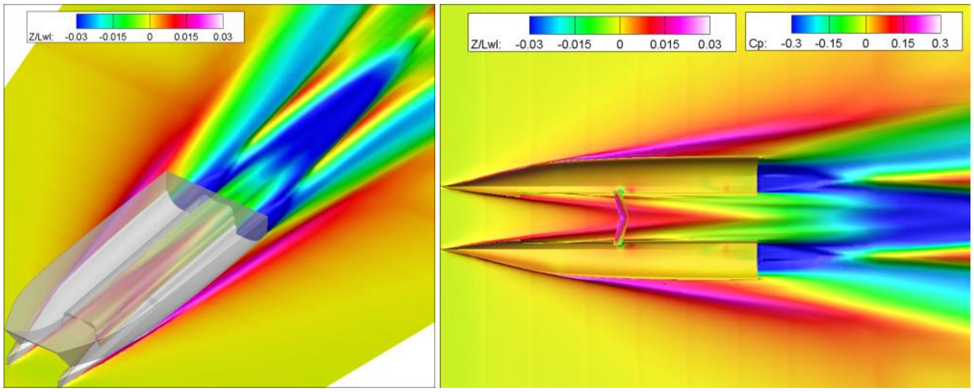


Fig. 4: Teknicraft foil-assisted semi-planing catamaran Ten-seventy at 30 knots - wave elevation and hull-surface pressure contours

Sometimes the wake wash effect is required at distances up to 300 m. Since the far-field wake has negligible non-linear viscous effects a transitional method is used wherein the far-field wake is calculated using fast and easy panel methods by extrapolating the near-field wave elevation of the high fidelity CFD calculations (Fig. 5).

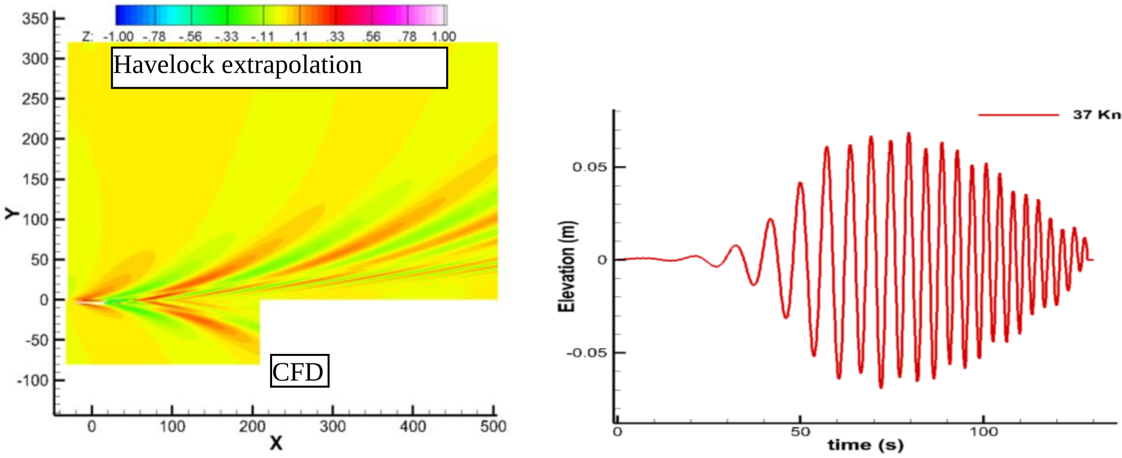


Fig. 5: Far-field wake calculation - (a) extrapolation of near field elevation to far wake; (b) wake train at 300 m

Teknicraft has a monohull test boat which comes in handy for code validation and to experiment on local flow characteristic. One such test was for the resistance effects of appending it with spray rails. The spray rails reduce the amplitude of the bow wave compared to the bare-hull. But since the wave trough amplitude is also reduced along with the wave crest (Fig. 6), the net wetted area remains almost the same as the bare-hull, which is a bit counter-intuitive. So there is negligible difference in frictional resistance due to the spray rails, but a 7% decrease in wave-resistance that gives a 5% decrease in total resistance. It should be noted however that there are cases where the spray rail does reduce the wetted surface area and frictional resistance too.

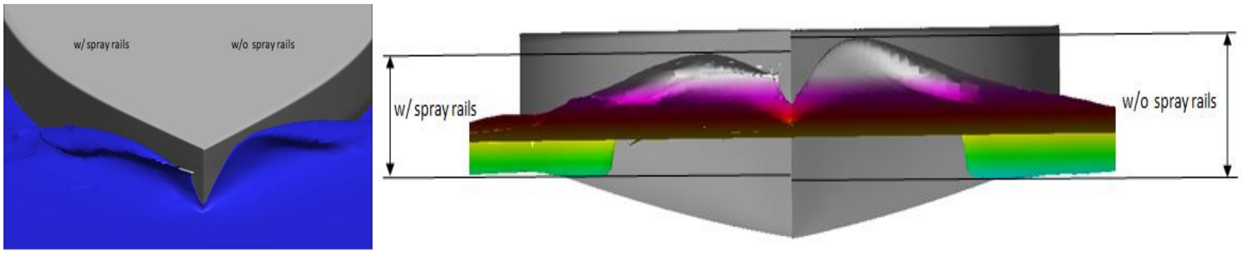


Fig. 6: Bow wave with and without sprayrails for the Teknicraft monohull

Horizon Powercats

The PC series of Horizon powercats are highly efficient semi-displacement symmetric hulls resulting from decades of design and development by Angelo Lavranos. The latest in the series, the 74' PC74 was designed with the previous PC52 and PC60 as baseline. With such a large length modification, a complex set of design criteria need to be handled with some limitations and compromises, and the Length/Beam ratio was needed to be reduced. FlowCFD was tasked with doing a study on effect of hull separation distances on the power requirements.

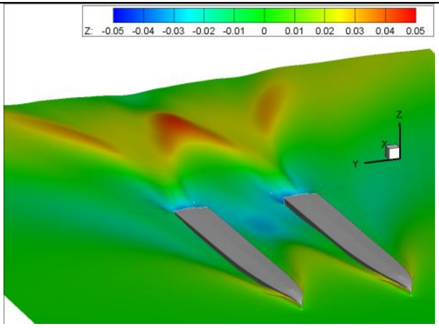
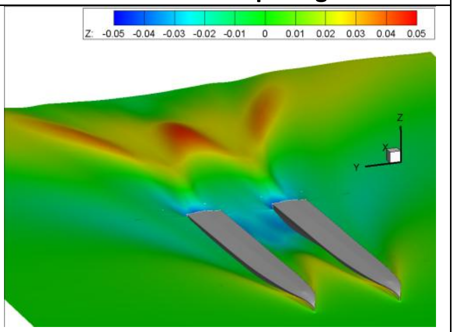
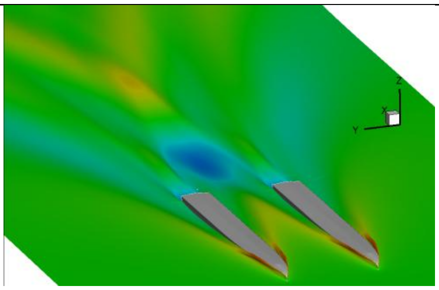
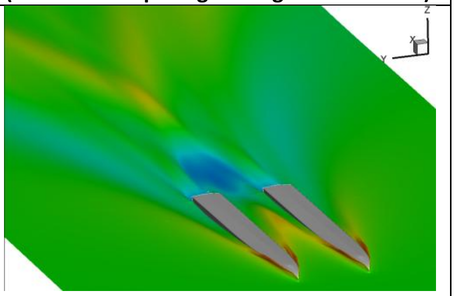
	Larger hull spacing	**Smaller hull spacing**
<u>14 knots</u> ***Adverse interference:*** **wave troughs interfere near the aft**		 **(smaller hull spacing has higher resistance)**
<u>22 knots</u> ***Favorable interference:*** **wave crests interfere near the aft**		 **(smaller hull spacing has lower resistance)**

Fig. 7: Hull spacing effect on interference at different speeds

The resistance of the catamaran was compared to twice the resistance of a single sponson to study the effect of wave interference between the two hulls. At lower speeds, the wave interference had adverse effects on the resistance as the two wave troughs interfere near the aft causing a bigger suction region and higher bow up trim. However at higher speeds, the wavelength is long enough and the diverging wave wedge angle sharp enough that the two bow wave crests interfere near the aft providing increased lift with a lower bow up trim which is very beneficial for semi-displacement hulls. Also, higher pressures in the aft provide a forward hydrodynamic thrust by 'pushing' the boat and lesser energy is lost to the wake. This effect was reflected in the hull spacing studies. The smaller hull spacing has stronger interference compared to the larger spacing. Hence the smaller hull spacing has a larger resistance at lower speeds due to stronger adverse interference, but a reduced resistance at higher speeds due to stronger favorable interference (Fig. 7). Taking advantage of this, the PC74 design spacing was optimized for cruise speed of 22 knots. The flow through the propeller pocket was also analyzed using 3D stream lines (Fig. 8).

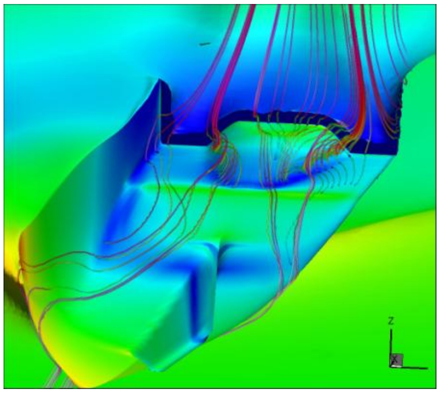
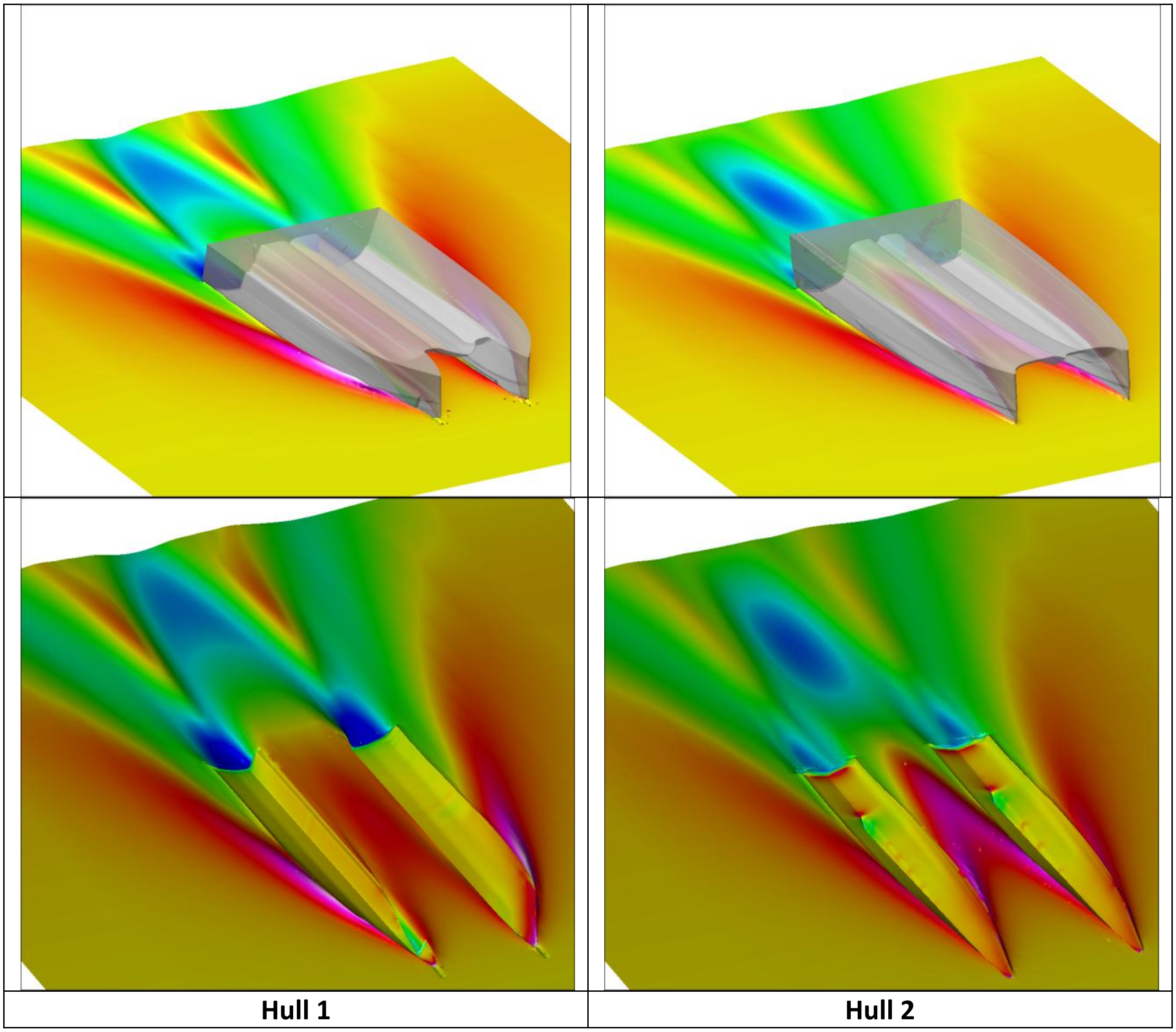


Fig. 8: 3D stream trace and hull surface pressure for HPC74

Setzer yachts

Ward Setzer of Setzer Yacht Architects specializes in the design of unique custom yachts. As part of an initial cost benefit study, FlowCFD was tasked with comparing the powering and sea-keeping performances of two 55' semi-planing catamarans. Hull-1 was asymmetric with vertical chines in the inner tunnel and an constant cross section from mid-ship to stern. Hull-2 was a symmetric hull with smoother curves, a keel and a slight taper up from midship to the stern.

The resistance calculations indicated that Hull-2 had ~10% lower drag than Hull-1 over the speed range. Figure 9 shows the wave elevation and hull surface pressures at 24 knots. The asymmetric Hull-1 has higher wave elevations on the outer side and smaller elevations inside the tunnel due to its flat inner hull surface. The vertical chines on the inner sides cause a separation of flow behind it at higher speeds, thereby reducing the wetted surface area and frictional drag. Hull-2 has a better pressure recovery with higher pressures in the aft, which provide a forward hydrodynamic thrust to the boat with lesser stern losses and a smaller rooster tail. Also, similar to the horizon power cats, the two bow wave crests interfere near the aft part of the hull at higher speeds and provide increased lift with lesser bow up trim. This beneficial wave interference is more pronounced in the symmetric Hull-2 as it has higher wave elevation inside the tunnel compared to Hull-1 which has flat inner surfaces. While this is advantageous in calm water, this increased interference wave height was found to cause wet-deck slamming in sea-state 3 for Hull-2.



Hull 1 **Hull 2**

Fig. 9: Wave elevation and hull-surface pressure comparison at 24 knots

The sea-keeping studies indicated that the roll motions of Hull-2 are lesser than Hull-1 for all speeds; however, the pitch and heave motions in head and bow waves are larger. The bow-steering tendencies of Hull-2 are lesser with smaller wave induced yaw moments in bow and stern quartering seas. The smaller moments and motions in stern seas at high speeds also indicate that the Hull-2 has a lesser tendency to dive.

The above examples of CFD simulations are but a few of the many ways CFD can assist boat designers. The time frames and costs for these calculations are much lesser than what would be incurred in tow tanks and wave basins. For instance, a five speed resistance curve for a catamaran can be done in less than a week, including the initial set-up time. Each sea-keeping calculation at a particular speed and heading take a couple of days after that. Changes to the design can be easily incorporated by directly modifying the computational grid. Along with the integral quantities such as resistance and motions, local flow features can be visualized at areas of interest using 3D stream lines, pressure contours and vortex extraction methods. Designers also get a visual feel for how their design works through animations (a few animations for the applications discussed in this section can be found at www.FlowCFD.com). With a certain amount of synergy between the boat owners/drivers, boat designers and CFD engineers it is possible to arrive at an optimal hull form to best suit the statement of requirements.