KEYNOTE ADDRESS: NEW DIRECTIONS IN HIGH PERFORMANCE YACHT DESIGN

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Abstract. The last twenty years have seen unprecedented improvements in sailing yacht performance. This paper reviews the major technologies that have propelled these and discusses some of the external forces that have driven their adoption in the sailing world. Features and design questions that may impact the development of future high performance designs are also surveyed.

1. INTRODUCTION

For those of us employed in the yacht design industry these are exciting times. The pace of technological developments in yacht design and manufacture is staggering. Records that once stood for decades are now tumbling on a yearly, weekly or even daily basis in yachts that range from as simple as a board and a kite to 100’ or larger ocean going multi-hulls.

Twenty one years ago I witnessed the 1987 America’s Cup in Fremantle, Western Australia. As a fourteen year old I was enthralled by the America’s Cup; the fleet of 12-meters represented some of the most advanced yachts of the time. Following *Australia II*’s victory in 1983, winged keels were now fitted to the majority of the fleet. Many of the sails were now using Kevlar™ and Mylar™ materials and the asymmetric gennaker had begun to make an appearance. This America’s Cup also saw the construction of the first fibre-glass 12-meters in KZ-3, KZ-5 and KZ-7 for the New Zealand Challenge.

In the years since we have witnessed continuous advances in almost every area of sailing yacht design and construction. Comparing the 1987 era 12-meter to a modern canting keel race boat will highlight far more differences than similarities; with developments apparent everywhere from the top of the rig to the bottom of the keel.

This paper reviews some of these transformative changes of the last 20 years and considers some of the possible directions for continued performance improvements in the future. Also, I address some of the broader design questions that we are only beginning to be able to study in a scientific fashion; areas where the potential performance gains are substantial.

2. THE RECORDS KEEP FALLING

While a visual comparison of a 12-metre to a modern racing yacht can provide a fascinating example of the developments in the world of sailing, these developments are best illustrated by the rate at which sailing performance records have fallen in recent years. A review of the World Sailing Speed Record Council (WSSRC) website [1] (http://www.sailspeedrecords.com) provides some interesting historical perspective on a number of sailing speed records.

In just the past two months we have seen the absolute 500m speed record set at 50.57 knots by a kite boarder in Luderitz, Namibia. In the same period *Hydroptère*, the hydro-foiling French trimaran achieved 43.09 knots over one nautical mile and the second generation Volvo Open 70 *Ericsson 4* annihilated the 24 hour monohull distance record achieving 596.6 nautical miles. Many expect the crewed monohull 24 hour record run mark could increase to 650 nautical miles by the end of the 2008/2009 Volvo Ocean Race. The increases in the record 24 hour distance runs for both multihulls and monohulls are shown in Figure 1.

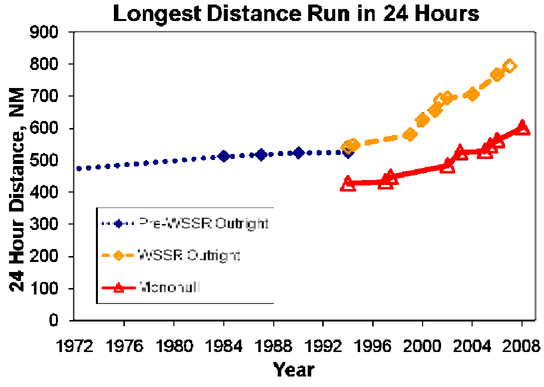

Figure 1. 24 Hour Distance Records

In 1990 the Jules Verne Trophy was established for the fastest eastabout circumnavigation with the initial challenge to sail around the world in less than 80 days. In 1993 Bruno Peyron’s *Commodore Explorer* catamaran achieved this with a record time of 79 days which was subsequently dropped to 74 days the following year by *Enza* under skippers Peter Blake and Robin Knox-Johnston. By 2004, Steve Fossett’s *Cheyenne* had completed the passage in 58 days and in 2005 the maxi catamaran *Orange II* lowered this mark to an incredible 50 days at an average speed of 17.89 knots. Perhaps, even more impressive are the singlehanded around the world records, where early in 2008 Francis Joyon’s *IDEC* trimaran achieved a record time of 57 days – the second fastest circumnavigation crewed or otherwise. Figure 2 shows the precipitous drop in circumnavigation

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times for the outright, singlehanded and monohull records.

While the crewed and singlehanded eastabout circumnavigation records are now both held by multihulls, there have also been significant improvements in the monohull circumnavigation times. At present, the Vendee Globe fleet of singlehanded IMOCA Open 60 monohulls sail southward with every indication that the current monohull circumnavigation record of 87 days could be broken. Given favourable conditions a time close to the 80 day mark may be possible, a mark that was only achieved with a fully crewed maxi catamaran in the early nineties.

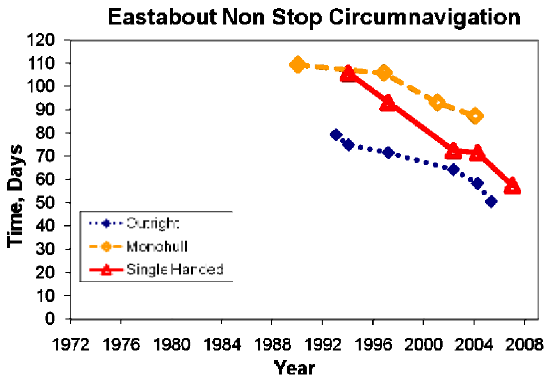

Figure 2. East-about Non-Stop Circumnavigation Records

While the brute force approach of the kite surfer recently broke through the 50 knot barrier, specialized craft such as *Hydroptère*, *Vestas Sail-Rocket*, *Wot-Rocket* and *Yellow Pages Endeavour* continue to work toward surpassing the 50 knot barrier and beyond. These craft are the most exotic of sailing vessels employing winged sails, planing hulls, hydrofoils and all manner of different configurations to achieve the fastest speeds possible. Figure 3 shows the improvements in record speeds over 500 metres and one nautical mile over recent years.

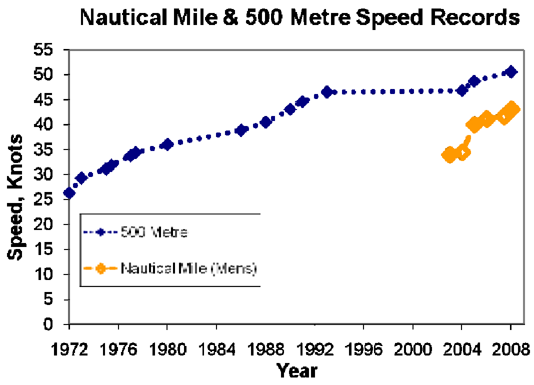

Figure 3. 500m and Nautical Mile Speed Records

All of these records serve to highlight the rapid improvements in performance across a broad range of sailing disciplines that have occurred in recent years.

3. MAJOR TECHNOLOGICAL ADVANCES

Given that my personal design focus to date has been with monohull yachts, I will direct the following discussion primarily to issues related to these boat types, although many of the developments and issues discussed will also be applicable to multihull design and development.

The exponential increases in performance as evidenced by the ever improving records can be traced to developments in five major areas:

3.1 Construction Materials/Techniques

The adoption of composite materials into the mainstream of yacht design has allowed the production of stronger, lighter and faster sailing yachts. The use of carbon fibre reinforcement coupled with foam or honeycomb cores (typically aramid, or aluminium) is now commonplace. Resin and processing systems are undergoing continual refinement. The ability to design composite structures allows unprecedented flexibility to optimize structures at a minimum weight permitting substantially higher stabilities, lower overall sailing displacements and stiffer and stronger structures. New techniques in the manufacture of female composite tools that retain accurate shape throughout curing cycles are also being refined, producing exceptionally finished hull surfaces with little or no filler and fairing required.

3.2 Variable/Moveable Ballast

First water ballast and now canting keels are significant developments of the past 20 years. Initially only seen on the fringes of the sport, canting keels (often combined with some measure of water ballast) are now commonplace features in many different designs. Both water ballast and canting keel technology allow on-demand increases in stability providing a dramatic boost in righting moment at typical sailing heel angles. While the addition of water ballast increases the displacement of the boat with the stability boost, canting keels permit this increase to occur without any change in displacement. The result is a much lighter boat with substantially greater sailing stability than any arrangement of conventional ballast.

In many cases these boats are so light weight and can achieve such impressive speeds that handling becomes very difficult when sailing upwind or downwind in significant sea states. In these cases, water ballast may be added to alter the trim of the boat for given conditions. For instance, Volvo Open 70's are allowed a single centreline tank of 1200 litres at the transom to help lift the bow and plant the rudders to improve steering in difficult conditions. Modern IMOCA Open 60's utilize transverse water ballast tanks in addition to the canting keel to provide both trimming versatility and a stability addition in certain conditions. These ballast tank capacities are significant and when full can increase the sailing displacement of the boat by up to 30% or more.

In addition to their stability benefit, they also provide for significant trim alterations. Forward tanks are used to hold the bow down in a seaway while middle tanks provide sizeable stability increases for reaching conditions. The aft-most tanks are filled in difficult handling conditions providing both stability and bow up trimming effects.

3.3 Spar/Rigging Materials/Construction

The evolution in the materials, design and manufacture of spars and rigging has also been substantial. Carbon fibre spars are now common throughout the industry on both cruising yachts and grand prix race boats alike. These spars are much stiffer, stronger and more tolerant than their aluminium forebears while significantly reducing weight aloft and improving stability. Through laminate optimization and material selection it is possible to finely tune the mast stiffness and deflection profiles to suit the sails and providing additional aerodynamic efficiency. Standing rigging has also seen a considerable evolution in recent years from the traditional rod or wire rigging to PBO (polybenzoxazole) and carbon fibre rigging products that can be 75% lighter than equivalent rod rigging resulting in a further stability gain. Interestingly, the advancement in termination technologies for both carbon and to a lesser extent PBO rigging has in many cases more than made up for a slight increase in windage caused by the thicker diameter PBO and carbon rigging elements.

Running rigging has also benefited from the application of new materials with PBO, Spectra™, Vectran™ and Dyneema™ amongst others all reducing line sizes to handle given loads with additional advantages such as improved reliability and longevity.

3.4 Sail Design and Construction

The development of “load path” or “membrane” sail manufacturing technologies in the past 20 years has dramatically improved the aerodynamic efficiency of sails for all types of sailing craft. By aligning high strength fibres to the principal load paths, light weight films can be used in the unloaded areas removing redundant materials and resulting in substantially lighter sails with better shape retention. Almost all of the sail makers now offer some form of “membrane” sails, each with different manufacturing approaches and using a wide array of high strength materials for the load carrying elements (aramid, carbon, Vectran™, Pentex™ etc.) One area of continued development is in advanced engineered composite fabrics such as Cuben™ fibre and the new North Sails NAS system. In these systems the fibres are reduced to monofilaments in very light weight films that can then be arranged in the desired orientation before being consolidated. These fabrics thus do away with the weight penalties associated with films and scrims and some of the adhesive weight that is present in laminate sail production.

The developments in sail manufacturing have been mirrored by substantial development on the sail design front where the coupled aero-elastic behaviour of the sail and rig can be predicted by computational analysis. These tools incorporate a full structural model of the rig and sails, including all sail control lines and a computational aerodynamics program to “pressurize” the sail. The structural and aerodynamic models iterate until a converged solution is reached. The mapping from design shape to flying shape occurs in the computer allowing the design of the sail shape and its underlying structure to be fine-tuned to produce sails that match the design characteristics of the yacht.

3.5 Systems

The developments in onboard systems – winches and deck hardware, electronics and instrumentation, sail handling systems etc. have also been revolutionary. Winches, blocks and deck hardware now incorporate the latest in composite and ceramic technologies to minimize weight and maximize load capacities. Without these developments it is doubtful that the loads experienced by maxi cats, trimarans or canting keel maxi’s would be possible. The explosion of singlehanded ocean records is also testament to the evolution of furling and reefing systems and the continued refinement of instrumentation, communication and autopilot systems.

The use of hydraulic actuation systems for both keel movement (canting or lifting of keels) and for primary and secondary sail control systems has also been accelerating in recent years and many improvements in ram engineering requirements, system layout and control system design have been realized. This is particularly true in relation to canting keel actuation where system failures can be catastrophic.

4. DRIVING FORCES OF INNOVATION

In section 3 I outlined some of the transformative technological developments that have shaped modern high performance yacht design. Few of these developments would have been so rapidly refined and in such widespread use today without the impact of a number of significant external forces. Examinations of three areas that I feel have played a major role in encouraging innovation follow:

4.1 The America’s Cup Effect

Despite the current America’s Cup legal wrangling, I think it is hard to argue that the America’s Cup has not been a driving force for innovation in our industry. Innovation and development has been a hallmark of the America’s Cup since the first event but the resources applied to winning the cup from 1983 to 2007 were exceptional. Many of the technological advances described previously were developed and perfected during America’s Cup development programs. This is especially so when considering some of the construction and engineering improvements and the many sail design and construction advances.

The advances in design tools and procedures developed through America's Cup program have infiltrated every type of yacht design. These programs have been one of the few opportunities for extensive large scale model testing of hulls and appendages that have done much to expand our understanding of both the nature of hull form and appendage hydrodynamics, and have provided substantial improvements in experimental techniques and procedures. The application of computational fluid dynamics (CFD) in the field of yacht design has been advanced by comprehensive validation and testing of both proprietary and commercially available codes and procedures. The combination of high accuracy requirements and the large range of operating conditions that must be simulated to assess a designs performance pace some unique demands on the CFD tools. As a result, substantial improvements to the codes, gridding and operating procedures have occurred. It is unlikely that these developments have been as rapid without the demands of these high profile programs. The confidence in these CFD tools that has resulted from involvement in these programs has lead to the widespread and ever increasing use of CFD in a wide range of other yacht design programs.

Velocity Prediction Programs (VPP), long the central arbiter of the design process in comparing the performance potential of design candidates, has also been continually developed through the America's Cup cycles. Improved, multi-degree of freedom aerodynamics models that closely mimic actual sail trimming are now commonly used and are derived from extensive computational and wind tunnel simulations of sail trim variations; refined added resistance and windage drag models have also resulted. An appreciation for the dynamic and tactical nature of match racing has seen a number of teams place considerable focus on understanding the manoeuvring and acceleration characteristics of America's Cup designs and incorporating these effects into selection of design characteristics.

Finally, the extensive two boat testing and full scale load and data acquisition programs carried out by these teams provides some of the most accurate data possible for use in the calibration of load predictions and in the refinement of performance prediction tools.

4.2 The Unshackling of the Rules

Away from the America's Cup and Volvo Ocean race, the majority of sailors compete in one design racing, handicap racing under different rules or in development classes. The impact of different rating systems on limiting technological innovation and design development should not be discounted.

First the IOR (International Offshore Rule) and later the IMS (International Measurement System) were both highly successful rules that gradually lost favour over time as designers continued to push their boundaries in the pursuit of ever lower/slower ratings. The tucked sterns of IOR and the IOR and IMS rules encouragement toward lower stability with large amounts of internal ballast produced boats that were both aesthetically unpleasing and often difficult to sail. In the case of IMS, the desire to rate all boats equitably did not mesh with grand-prix racing. IMS's late reaction to advancements such as canting keels and the evolution of light weight, fast boats such as the TP52 finally saw the final dramatic decline in IMS racing. For all its limitations, IMS was a scientifically based rule attempting to account for the characteristics of any design and to assess its performance in differing conditions. It was a laudable goal, that was successful for a number of years but ultimately it could not keep pace with the extensive resources being applied by design groups around the world. The drive to keep costs down was also an advantage but in any rule where rating credit is given for items and characteristics that make a boat slower, it is likely that the rule will encourage slow boats that aren't quite as slow as they are assessed.

Figure 4. The last generation of IMS design

The IRC rule was originally intended to rate club level competition between dual purpose cruiser/racers. With the significant reduction in IMS racing, IRC has since become one of the major international rules and is used to rate a wide range of boats from club racers all the way through to grand-prix classes. Unlike IMS, it is a single number handicapping system and as such certain design characteristics will be favoured by different conditions. It is also a secret rule that has efficiently adapted to at least attempt to rate a diverse set of boats, including those with canting keels on a reasonably equitable footing. At present it seems to do a nice job of encouraging dual purpose cruiser racers at smaller sizes while permitting more freedom at the larger sizes for lighter, faster boats such as canting keel maxis, STP 65's etc. At a minimum it does not measure stability directly and appears to strongly discourage internal ballast, thus avoiding some of the pitfalls of IMS and IOR. It is clearly not a perfect rule and there is some concern about the apparent subjectivity in items like the hull factor, but at this time it provides some excellent racing for a wide range of boats worldwide.

Aside from the many One Design rules where all aspects are tightly controlled to ensure equal competition, there has also been considerable growth in constrained development rules. The America's Cup Class rule, Volvo Open 70, IMOCA 60 are all examples of these rules as are the ORC Grand Prix "box" rules for the GP42, 33 and 26. These rules promote varying degrees of design freedom but insure competitive racing by controlling critical characteristics of the design to insure characterized by minimal constraints are hotbeds of innovation and many of the major performance leaps such as canting keels, hydrofoils, wing masts and winged sails can be traced to these classes. At the bigger sizes where the expenses associated with development classes can increase exponentially, it is typical for the constraints to be somewhat tighter (See the AC rule, Volvo 70 rule, TP52 for example). One difficulty with the more tightly constrained rules is that they may need to be periodically updated to keep the class "modern" and to incorporate new design trends or technologies. This is always a difficult balancing act between preserving the competitiveness of existing boats and the continued growth of the class with the building of newer boats. In the past year both the TP52 class and the IMOCA 60's have faced these challenges with varying degrees of success.

4.3 Sponsorship

Corporate sponsorship of sailing has been a major contributing factor to the exponential performance developments of recent years. It is clearly most apparent at the America's Cup and Volvo levels of the sport but many smaller companies are sponsoring yachts in a whole range of fleets. In France we have just witnessed 30 boats start the Vendee Globe, all of them with some degree of sponsorship. In some cases, these companies are not large multinationals but smaller firms that have invested their entire promotional budget into sponsoring a boat for the event. For both the Vendee Globe and the Volvo Ocean Race the internet and satellite data transmissions allow people the world over to follow the race throughout its duration – receiving position up-dates, playing virtual sailing games and seeing pictures and video beamed from the boats.

For many high profile programs sponsorship investment is the cornerstone that provides the funds for the research, design and construction and campaign costs. Perhaps more importantly, it is also a mechanism that pays for professional sailors to be involved on full or near full time basis. Many of the record barriers and speed records that have been broken are a direct result of the highly refined skills and experience of professional crews and skippers.

5. WHERE TO NEXT?

In the previous sections we have seen the improvements in sailing yacht performance that have occurred in the last 20 years and have considered some of the major forces that have contributed to these advances. Looking toward the future it is impossible to identify all of the features and performance breakthroughs that we could see in the next decade. Nevertheless, let's take the opportunity to gaze into the crystal ball and consider some of the features that may appear on high performance yachts of the future and some of the design questions that may arise along the way. I will also outline some of the more difficult problems that need to be addressed to advance our understanding and improve high speed performance.

5.1 Advances through Refinement

Without question the continued evolution and refinement of design tools and methods, advances in structural engineering and construction techniques and lighter and stronger composite materials will produce lighter, more stable boats capable of ever faster speeds. Continued development of sail and rig packages will also result in more efficient sail plans with lighter and stronger sails and reduced aerodynamic windage drag that will increase speeds. The impact of incremental improvements in all areas of yacht design and construction will continually lift the performance bar.

5.2 A Future on Foils?

One of the most spectacular developments of recent years is the increasing number of hydrofoil borne sailing craft such as the international moth (see

Figure 5) and the speed record holding *Hydroptère* (see Figure 6). There has also been a number of implementation of foils on skiff type dinghies – 18 footers, the RS600FF along with a number of custom hydrofoil craft. In many ways the developments in hydrofoil sailing are reminiscent of the early adopters of the canting keel technology that has now achieved widespread use throughout the world. It is probably unlikely that we will all be sailing foil borne yachts in the next ten years but I expect their development will continue and will become a bigger presence in the sailing community.

Ride control is one of the main issues that faces foil borne craft and that may prevent more widespread usage. Many of the current successful implementations these foil born craft use mechanical "wands" to alter the angle of attack on the trailing edge flap of the main lifting foil to govern the ride height in response to oncoming wave conditions. Even with these controls they are extremely athletic requiring rapid shifts in crew weight and position to maintain "stable" flight in wave and to successfully complete manoeuvres while foil born.

Extending this to larger craft where moveable crew weight is limited may require more stable design approaches and foil arrangements (see *Hydroptère* and *Bladerider* for examples) and further development of ride control mechanisms.

While fully foil born sailing craft for the masses may be a long way off, we have already seen applications of foils to reduce the effective displacement of yachts or to hydrodynamically generate stability allowing reduced amounts of lead ballast. Many of our canting keel boats incorporate daggerboards that are more vertical than would be expected for the typical sailing heel angles. This does cost a little bit of span and induced drag at these heel angles but the angle of the board creates a vertical force component that acts against the vertical sail forces that increase the boat's sailing displacement.

Figure 5. A modern foiling moth.

Figure 6. Alain Thébault's record breaking Hydroptère

Many readers will also be aware of Hugh Welbourne's and Gordon Kay's patented Dynamic Stability System (DSS) (http://www.dynamicstabilitysystems.com) that uses retractable, lateral foils projecting out of the hull to leeward to hydrodynamically generate righting moment with a reduced amount of ballast. Prototypes have been built and sailed which also indicate the system produces some improvement in sea keeping. At present it is unclear how different rating rules will deal with an appendage extending beyond maximum beam (DSS claim it is IRC legal) or if the licensing fees associated with the technology will provide too much of a financial burden for this to become a widely adopted technology.

5.3 Integrated Design

At Farr Yacht Design we have found significant improvements in the quality and performance of our designs by adopting a concurrent engineering approach. Within our organization we endeavour to develop the design with the input from all departments to insure the design objectives are met. We feel this produces a more integrated product with fewer build issues, more optimized structural and deck layouts, better weight control and more efficiency in producing the design deliverables. On a number of recent projects we have begun to work more closely with the spar and sail designers over the course of the design's gestation, resulting in improved spar and sail designs from the outset. This has typically only been possible with well funded and organised teams but the performance gains available from a sail plan that is well integrated with the concept and objectives of the design are substantial. Aerodynamic improvements afforded by optimizing the sail and spar engineering can result in better matched sails that respond to trim and pressure changes in a more efficient manner. Extending this integration into the yacht design process allows more optimal sizing of the sail sizes to suit the expected conditions, a better understanding of expected rigging loads and a more optimized deck layout and hardware specification. The cost and time savings in minimizing sail re-cuts and avoiding modifications to deck reinforcements can all be substantial and the available performance from improved balance and sail designs that are optimized toward the yachts objectives from the outset can be significant.

5.4 Better Understanding of High Speed Phenomena

With lower displacements for a given length and increases in stability from improved construction techniques and deep canting or lifting keels, the performance envelope over which a hull must operate efficiently has broadened substantially. Through five iterations of the America's Cup Class rule we now know a great deal about the effects of volume distribution and waterline ending treatments on these heavy displacement yachts. However, this understanding is focused on the limited range of sailing conditions and speed ranges appropriate for windward-leeward match racing.

As we start to work with boats that comfortably operate in the semi-planing and full planing regimes, the design space expands and the potential for very large speed gains in some conditions are available through even subtle changes in hull shape. Consider the development of Volvo Open 70's and IMOCA Open 60's yachts which represent the state-of-the-art in high speed mono hulls. These boats are approaching the power to weight (sail area to displacement) ratio of skiff type dinghies and there are a number of design features and lessons from skiff and dinghy design are applicable to these larger boats.

An examination of some of the latest generation of Open 60's and Volvo 70's show the familiar plumb stem, immersed transom and chined hull forms that are so familiar in high performance dinghies. In a centre-boarder the crew's weight represents a large proportion of the sailing displacement and is utilized to provide both stability and to drastically adjust the boats trim for different sailing conditions. In the larger keelboats the relative proportion of sailing weight that can be moved to adjust trim and influence stability is substantially lower and so the designs have developed to achieve the desired behaviour in alternate ways. As a further complexity the designers must account for the greater range of heel angles that these larger yachts see. These two considerations have a big influence on hull design for these boats. Transom immersion both upright and at heel can add to effective length when sailing at speed but at subcritical speeds the recirculation and wave breaking behind the boat can produce a drag increase. While this can be eased by shifting moveable weights forward (which also reduces hull wetted area), the magnitude of this available change is limited. Selection of the appropriate transom immersion both upright and at heel is thus closely coupled to the expected sailing/racing conditions. Hull rocker distributions are similarly related to the expected operating conditions and heel angles. Flat water sailing in moderate speeds favours very low rocker solutions that maximize effective length, however, as we approach transitional planing conditions or add the effects of waves to the mix we would tend toward more rocker in profile. At higher speeds, (usually with higher heel angles) we are faced with the challenge of trying to keep the bow up to promote hydrodynamic lift and planing performance. This is compounded by the substantial bow down pitching moment induced by the sail plan and can be accentuated by the broad stern, high form stability hull forms with significant volume aft that can cause the bow to drop as the boat heels.

To address this behaviour there are a number of available approaches:

- Move to fractional sails earlier to lower the effective centre of effort and thus the bow down trim moment of the sails. (In the Open 60 and Volvo 70 classes there has been a significant trend toward the usage of fractional sails at lower wind speeds than might have been previously expected for this reason).
- Aggressively fill out the bow sections, especially in the upper topsides to provide sufficient buoyant lift at the expense of added resistance in waves. (A common solution in a number of Open 60's and some Volvo 70's).
- Examine some other hull shaping and appendage concepts to improve the bow attitude at speed.

As our boat speeds approach those typically seen by power boats and other high speed craft, the lessons and developments in these shapes have also become a source of some inspiration. This is most evident in the advent of "strakes" in some of our latest designs that are positioned to dynamically lift the bow at speed and heel (see Figure 7 and Figure 8). The use of the strakes permits a finer waterline entry below the strake for light air/short chop sailing and additional buoyant volume above the strake when sailing in big waves. The results from model scale testing and computational simulation of the strakes indicated drag improvements in high speed sailing (5 - 8% in some cases) with very little drag penalty at lower speeds provided they are located correctly. They also serve to damp motions when sailing upwind in waves.

Figure 7. Volvo Open 70 bow "strakes".

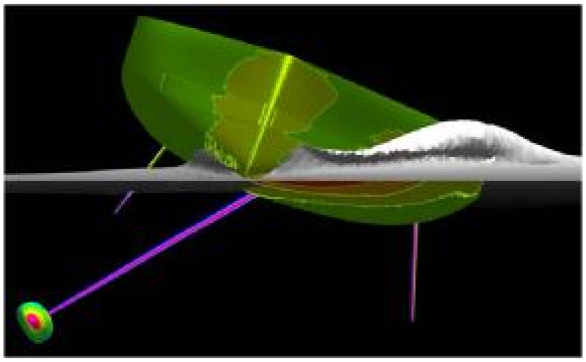

Figure 8. CFD simulation of strake effects.

Trim Tabs located at the transom are now a common feature on power boats to optimize the boats attitude for maximum efficiency in different conditions. Although their use is prohibited in rules such as the Volvo Open 70, they are permitted in the Open 60 class and we have them fitted to two of our designs, *Gitana 80* (see Figure 9) and the Barcelona World Race winner, *Paprec-Virbac 2*. Indications are that they more than make up for their associated weight penalty. By adding the trim tabs we essentially achieve a variable hull form that allows us to adjust transom immersion and hull rocker for differing conditions. The base hull thus has more rocker than we would have for a non-tabbed boat to better suit it for difficult handling conditions with tab retracted. In moderate speed and flat water conditions where maximum running length is desired, the tabs are lowered, increasing transom immersion, pressing the bow in and increasing length. Similarly when reaching at speed, the tab can be adjusted to the conditions to balance speed and handling. In very severe seas where handling governs the performance of the boat, the tab can be raised fully, thereby allowing the bow to lift and maintain rudder immersion.

Figure 9. IMOCA Open 60 trim tab arrangement.

An alternate solution featured on a number of Open 60's is the "interceptor" that consists of a full width vertical plate that can be lowered through a slot in the hull near the transom (See Figure 10). This is also called a gurney flap in some applications). When down this acts in a similar way to the deployed trim tabs by lifting at the stern of the boat, causing more bow down trim and maximizing effective length. At higher speeds where handling is of a concern the interceptor can be raised, essentially reverting to a boat with more rocker causing the bow to lift. While the system is lighter than the trim tab arrangement the range of variation is smaller.

Figure 10. IMOCA Open 60 interceptor slot.

As these yachts begin to sail at sustained speeds in excess of 20 knots a number of appendage issues have surfaced that need to be carefully considered in the design phase. The use of carbon fibre keel fins in the Open 60 class has become reasonably common-place, but in a number of cases they have developed severe flutter responses in certain conditions.

This is particularly related to the torsional properties of the fin and is thus exaggerated in the very deep and slender Open 60 keels. Simply designing a keel for traditional load cases (bending, grounding etc.), without proper consideration of the torsional rigidity and natural frequency of the candidate keel may result in unexpected flutter susceptibility that can lead to excessive vibration, drag or even catastrophic failure. Although most common with composite keels, steel keels of sufficient span with small structural chords and/or exotic construction techniques may face similar issues.

Cavitation has been a limiting factor on the performance of high speed multi-hulls and dedicated speed record craft. Delaying the onset of cavitation has been a prime consideration in the design of lifting appendages and control surfaces for these craft for some time. In the case of monohulls, understanding the cavitation characteristics of a particular foil section and its implications for appendage sizing has not been a primary design focus. Although it is impossible to avoid the onset of cavitation completely, its onset can be delayed through foil section design and through reducing the loading on the foil, typically through a somewhat larger chord and adjusted plan form.

There is a great deal of ground for further research and development in these areas. Computational tools are only now becoming sufficiently reliable and of high enough accuracy to allow us to begin understand these design issues and the associated trade-offs. Experimental analyses have their own complexities relating to scale issues and limitations in what range of operating conditions can be achieved without overloading load cells.

5.5 Dynamics and Unsteadiness

At a basic level our primary analysis tools are still focused on a steady-state vision of the world. We have made huge strides in model testing and CFD simulations but the majority of this work has been focused on improving the accuracy and computation time of calm water simulations. The non-linear effects of added resistance in waves, surfing and handling and control limits are then overlaid through empirical models and the yacht designer's experience.

Some of this is purely related to time and cost as it is prohibitive to complete sufficient simulations in waves to completely characterize a designs performance in a significant portion of expected wave conditions. Strip theory and other tools can give good estimates of hydrodynamic performance in waves for low beam to length boats such as ACC yachts but may have issues in properly capturing the effects of the overhangs on motions. For the lighter displacement, higher beam to length ratio boats with off-axis appendages the accuracy of these methods is less certain. Testing in head seas are possible in tow tanks and can give some indication of the effects of design characteristics on performance in waves. However, the head seas constraint is significant and the requirement that the model have scaled mass properties can be difficult or impossible to meet. Simulating surfing behaviour can be done in some tank facilities but with significant expense. As far as I am aware, CFD approaches to simulate these events are only beginning to be possible. Accurately simulating the effects of waves on yacht motion and added resistance requires a model of the aerodynamic damping provided by the sail plan.

A number of exceptional papers have been presented at previous symposia that outline various implementations of six degree-of-freedom time domain VPP's for use in the simulation of performance in waves and the modelling of manoeuvres and acceleration scenarios. In most cases this work has been carried out in conjunction with America's Cup programs as these are some of the few programs that can provide sufficient resources and validation data for these efforts. Some very interesting work using time domain sailing simulations for starting manoeuvre training was completed during the last America's Cup cycle and some of that work will be presented at this year's symposium.

The continued development and validation of six degree of freedom VPP technologies to the point that they are ready for use in the general yacht design process may still be some time off but it promises to allow designers to begin to quantify the dynamic and unsteady behaviour of designs, something that has generally only been assessed with experience and empirical estimates.

5.6 Aerodynamics – Sails and Windage

The continued refinement of sail and spar design and construction is likely to proceed at a rapid pace. Already we had some indication of the big advances that are possible by close collaboration between spar and sail designers, developing masts and sails that respond to changes of trim and wind conditions as a combined unit. The self de-powering rig so common for 18 foot skiffs has long been a quest for bigger boats as it makes changing gears and trim much more efficient. The jumper-less rigs used by BMW Oracle Racing in America's Cup 32 probably represent one of the highest profile attempt at developing a rig/sail system to twist and depower as puffs come on without requiring excessive trim changes. There is much more development to be completed in this regard but the advantages could be very significant for all types of sailing yachts. In a similar fashion the ability to engineer the structure of sails presents some interesting possibilities in potentially being able to design sail structures not just so they achieve the desired shape in specifically targeted wind conditions, but also so that the sail shape distorts in a favourable fashion across large changes in wind conditions.

6. CONCLUSIONS

The previous two decades have seen unprecedented performance improvements in all areas of the sailing discipline. This has been the result of some significant technological breakthroughs aligning with a range of external forces that have encouraged their refinement and widespread adoption. It is probably unlikely that the pace of development can continue at the same pace as it has in recent years. Without question, the current global economic difficulties are already resulting in a contraction in the number of new racing yacht projects and a significant reduction in the amount of corporate sponsorship money available for high performance yachting projects. This is compounded by the current legal stalemate over the America's Cup that will, in all likelihood, substantially reduce the size and scope of future campaigns and the research and design programs that can be supported by these efforts.

On a more positive note, conferences such the HPYD show that the innovative spirit in the sailing and yacht design world is alive and well and that the journey toward even faster, better handling yachts will continue. As a community we are fortunate that so many talented designers, engineers and scientists are willing to share their work with the broader community, helping us all to aim higher.

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