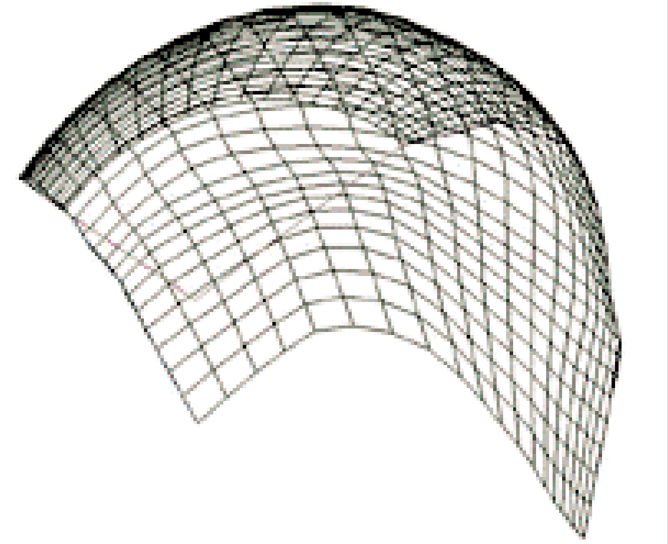
The biggest issue - Part II

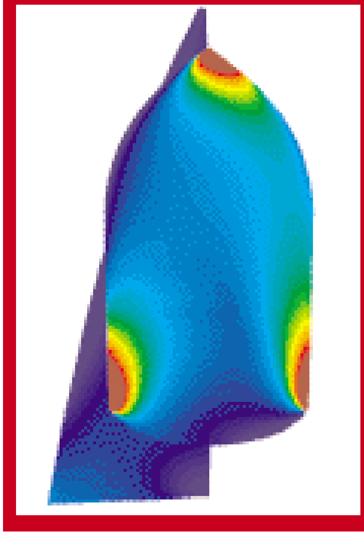
Rig and boat design are converging says Rob Ranzenbach

In Part I of this series Quantum Technical Director Dr Rob Ranzenbach examined the background of America's Cup sail design prior to and during the last event, including the methods and tools used in aerodynamic analysis, and gave a sneak preview of the power of integrating elements of sail design with VPP analysis.

In Part II Dr Ranzenbach examines in more detail the coupling between sail design and boat performance potential, with some examples from the last Young America programme, and takes a look into the work Quantum is currently supporting in the field of aero-structural coupling, with applications for the America's Cup, Volvo Ocean Race and IMS venues.

The second part of JB Braun's article, which will run next month, will look inside the mechanics of North Sail's latest IACC and VO60 sail design technology





Left; A view of the three-dimensional flying shape of a real spinnaker using photogrammetric techniques developed at GLMWT in collaboration with Quantum. This view has the head of the sail 'turned off' to improve the clarity of the lower sections. Lower left; A contour plot of principal strain in a mainsail and spinnaker case study Lower right; A comparable vector plot of stress in a mainsail and spinnaker case study

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Aero-structural coupling

A number of important factors determine the 'flying' shape of a sail under real sailing conditions. The first is of course the 'design' shape selected by the sailmaker. Second, there is the aerodynamic pressure distribution and the forces produced by the rig and sail trim controls acting upon the sail. Finally, the structural characteristics of the sail, ie. the yarn, tape or panel layout, and the relative distribution of the materials such as Kevlar and carbon must be considered. All these factors contribute to the resulting flying shape - which is very different from the design shape.

Flying shapes are different because sails are not made of an inextensible material, ie. they do stretch. But more importantly, the free edge(s) can deform under the forces acting upon the sail. There is an infinite number of flying shapes over a narrow range that a sail of a particular design can achieve under varying trim and sailing conditions. However, there are limitations: a sail designed to be very full cannot become extremely flat or vice versa, nor can a sail properly designed to handle only a small amount of wind survive a big blow. This is why *both* the design shape and the structural properties of a light #1 jib differ from a heavy #1 jib.

The marriage of aerodynamics and structural dynamics into an integrated calculation is an extremely complex problem. A generally applicable analytical scheme to solve this problem has not been found and so numerical methods are required.

One method is to integrate CFD with a Finite Element Method (FEM) structural dynamics code. Ideally the sail is modelled by non-linear, orthotropic membrane elements. (Orthotropic is just a fancy word to acknowledge that sailcloth is generally strong in one direction and not in the other and that this effect is taken into account.) The non-linear nature is necessary to account for the large deformations of sails. Finally, a specialised membrane element is required because, unlike beam elements used to model the spars of the rig, as an example, membranes like sails cannot absorb compression forces, only tension.

During the last Cup, Membrain, a code developed by North Sails, was used extensively by many of the teams to study the aero-structural problem. In the case of Young America, a technologist from the GLMWT tunnel facility supported the design team's efforts by planning experiments, producing computational solutions, obtaining sailing data and performing validation exercises that compared predicted flying shapes to measured flying shapes produced by Young America's own sail vision system.

Other teams were certainly performing similar studies. One very important contribution from these studies was the qualitative and quantitative knowledge of just how much the distribution and orientation of the materials within a sail can affect its flying shape, often by as much or more than the design shape itself. While sailmakers already knew this empirically, as is evident from the constant progression of panel layouts developed over the years, now the potential exists to study these problems computationally rather than simply though empirical trial and error.

Interestingly, although many teams had access to the same predictive capability, the layouts of the mainsail yarn varied dramatically between teams. The fact that different designers came to so many differ-

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ent conclusions is of course the essence of design, and is continuing proof that sailmaking, like many other disciplines, is still a carefully crafted mix of art and science.

Maturing sail vision systems

The desire to tighten the designed shape/flying shape design spiral, and eventually to obtain necessary definition of flying geometries for inclusion into expert system trim simulators and CFD models, requires accurate flying shape surface definition. Opportunities for such systems to influence sail design and provide continuous, real-time, expert system trim information are vast and could potentially have some large payoffs.

Onboard cameras were widely used and achieved a much greater measure of success during the last America's Cup than in previous efforts. Several teams finally realised the objective of obtaining useful definition of sail shapes at the conclusion of a day's sailing without massive human intervention. As a result the data was available to be shared with other elements of the design/technology team in a more timely manner rather than months later.

This allowed several important interactions: sail shape data was used to provide flying shapes that could be studied with the team's most powerful aerodynamic codes; results were used as validation data for comparison to aero-structural predictions of upwind sail shapes; and finally the results of these studies, combined with on-the-water performance data, were used to validate the results of the VPP.

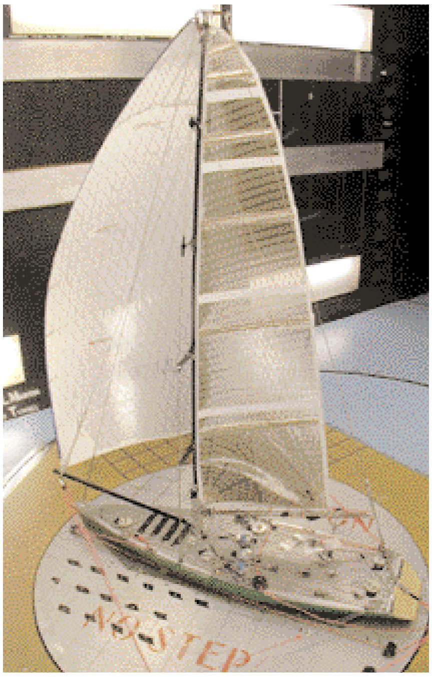
Technology for the 2003 America's Cup and beyond

Building upon the key elements of the sail-development process from the last America's Cup, Quantum's design team is meeting the increased challenges of technology-driven sail design by assembling a suite of aerodynamic analysis tools from industry leaders and universities. These tools include potential methods, RANS codes, aero-structural codes and experimental methods.

For example, a potential flow code, S2KV, developed at MIT, has been integrated with the Quantum upwind sail design program. S2KV is based upon a vortex lattice formulation with a novel method of integrating a viscous boundary layer solver in a more direct method. The code was used extensively by Young America during the 2000 America's Cup to study sail aerodynamics.

Quantum are also using RANS codes for special applications that can afford the large resources necessary to apply this technology successfully and more generally to help extend the confidence boundaries of their potential flow methods. The two methods available to Quantum include the Shyne and the Overflow codes. Shyne was developed by the Center for Numerical Methods in Engineering (CIMNE), in Barcelona, Spain, where it has been used in concert with CIMNE structural codes to study the aerodynamic and structural performance of sails, under government grants in collaboration with Quantum Europe. Overflow, which was developed as a NASA research code, has been used by several America's Cup teams to study the sail problem as well as the flowfields about appendages.

Quantum, in collaboration with the GLMWT, have developed Very Low Uncertainty (VLU) sail test methodologies which have been used extensively to study offwind sail performance for the America's Cup, Volvo and other grand prix applications. Several studies were closely linked with extensive on-the-water sail efforts that have allowed excellent opportunities to evaluate and validate the methodologies used in the wind tunnel testing programme



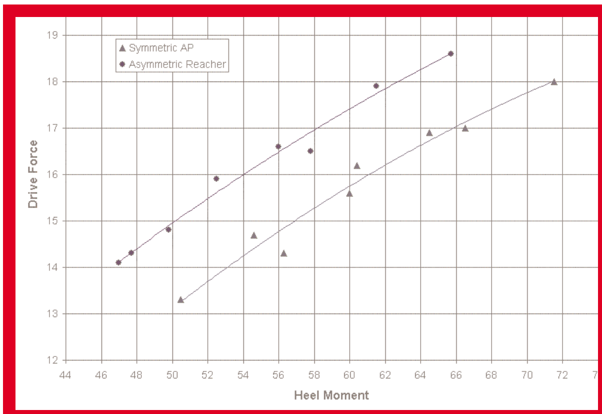
During the last Cup the focus shifted to more specific running sails better suited to America's Cup courses. Development continues, primarily focused recently on the performance of asymmetrical spinnakers, particular when flown from sprits.

Quantum are continuing to develop enhanced aerodynamic models to increase the fidelity of VPP results. This effort is not limited to upwind models, as in the past, but is also extended using wind-tunnel data to offwind aerodynamic models which include the effects of depowering.

Quantum are also developing their own VPP under the leadership of consultant Jim Teeters, which will assist sail designers in specialising inventories for a particular boat. Direct application of wind-tunnel results in a VPP has already been used to study the optimum sail selection for an IMS entry in the 2000 Newport-Bermuda race. In this case a combination of reaching and running symmetric and asymmetric spinnakers was evaluated in the wind tunnel over a wide range of apparent wind angles. While normal practice in the wind tunnel is to trim the sails for maximum thrust, here the trimming methodology was modified to obtain a broad array of data that eventually defined the largest achievable thrust over an array of limiting heel moments.

The results for thrust, side force and heeling moment produced by each sail were used in the VPP to compute the maximum boatspeed using various sails at varying trim. The boat's performance, sail selection and rating consequences were then studied to select the best inventory for anticipated conditions.

Not surprisingly, similar studies are under way to study the reaching spinnaker



This figure shows wind tunnel results from a depowering study performed at the GLMWT. All data shown was obtained at one apparent wind angle, in this case 80 degrees. Every data point represents a different trim setting, i.e. you can reduce heel by easing the vang or lowering the pole tip. Of course these trim changes also result in less thrust. The relationship between drive force and heel moment partly depends upon the design of the sail. To what degree this impacts a boat's performance can be calculated using a VPP. The resulting figure graphically demonstrates the achievable thrust or driving force of a particular sail at a given heel moment, or vice versa, how much heel moment is generated while achieving a given level of thrust. As expected, a reaching asymmetric is much more efficient than a symmetric AP sail at generating thrust without generating large heel moment at just forward of a beam reach. This relationship potentially changes at each apparent wind angle. This is just an example at one apparent wind angle. Now depending upon the boat's stability and the wind strength, a particular boat may be able to trim its sails for more thrust and not be overpowered, while another may not. Integrating such data with a VPP provides powerful insight into a number of important questions for both yacht designers and sailmakers. The depowering information obtained in the wind tunnel is a significant improvement over the relatively crude depowering models that exist in most VPP's, particularly for offwind sails

inventory of a current Volvo 60.

Several codes are now available for studying the aero-structural response of upwind sails. Each provides varying levels of sophistication, cost, functionality and confidence for different applications. Quantum's own efforts are focused in two areas. Firstly, the CIMNE code CALSEF, in concert with the Shyne code described previously, is being used to study the structural loads in sail membranes. It is particularly useful as a calibration code because it has been so well validated against NAFEMS (National Agency for Finite Element Methods & Standards) problems. Secondly, Quantum have collaborated with a commercial FEM code developer to study the aero-structural problem with particular emphasis on the link with the structural dynamics of the rig.

It is anticipated that efforts during this America's Cup will focus on improving existing aero-structural code capabilities and possibly extending them to offwind sails. The flying shape and design shape of these sails differ dramatically when compared to upwind sails, because of the desirably light weight of the construction materials and their variable shapes (all three edges are free to take shape unattached to spars). This severely limits the ability of sail designers to interact easily with existing sail design programmes.

It would be extremely desirable to be able to predict the flying shape of an offwind sail during the design process rather than having to wait until scale models are evaluated or actual sails are constructed.

A GLMWT PhD student is currently pursuing the development of a capability to predict the flying shape of an offwind sail using a code originally developed under the support of the US Army for parachute studies. The baseline code used is considered to be the state of the art in the aero-structural field and has been subjected to substantial validation efforts on a variety of non-sail related problems.

New methods under development by Quantum that do not depend upon onboard cameras for continuous real-time determination of mainsail shapes offer great promise but require further work before successful application. A photogrammetric system has already been developed to determine the flying shapes of offwind sails and is ready for validation in the real-world environment.

The broader application

Benefits to the broader sailing community from the significant investment that is occurring in sail performance by sailmakers and America's Cup teams include:

1. Custom grand prix boats may see a reduction in the time and resources required for a successful sail development programme because more effort can be placed in engineering analysis before the first sail is built.

2. As our ability to predict the precise structural loading patterns, the relationship between flying shape and design shape and the complex interaction between a mast's structural properties and a sail's flying shape improves, sails will perform better over a broader range of conditions for a longer period of time.

3. Improved handicapping (See the CSYS paper, *Aerodynamic Performance of Offwind Sails attached to Sprits* by Ranzenbach and Teeters).

Conclusions

Continually improving experimental methods and computer horsepower are dramatically impacting on the collaboration between yacht designer, sailmaker and sparmaker. These improvements are altering the classic relationship between the various parties and ultimately the manner by which sails, rigs and boats are designed. Quantum have reacted to this changing environment by creating their own in-house design/technology team, consisting of designers, consulting and collaborative technologists from industry and academia, and manufacturing experts.

America's Cup teams that are best able to manage this fast-changing environment, and apply the valuable knowledge that results to the overall design of the yacht, will present themselves with a competitive advantage compared with teams who are not able to do so because of poor funding, lack of technical sophistication or imperfect relationships with their sailmaker.

Dr Robert Ranzenbach is a naval architect and aerodynamicist. He is now Technical Director for Quantum Sail Design Group where he leads a team of technologists to improve Quantum's expertise in a broad array of boat performance issues. He is also the Mgr. Research & Business Development at the Glenn L Martin Wind Tunnel (GLMWT) where he was responsible for the development of the first experimental-based offwind sail evaluation capability in the US. Located at the GLMWT, this has been used extensively to study the aerodynamic performance of offwind sails for the Volvo Ocean Race and America's Cup. He has participated in a number of America's Cup campaigns, most recently with Young America.

This article was prepared in association with (Dr) Dobbs Davis of Seahorse ❑