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Design and Optimisation of Multi-Element Wing Sails for Multihull Yachts

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Abstract

Since the announcement that the 34th America's Cup will be sailed in catamarans powered by multi-element wing sails, interest in wing sail technology has increased enormously. Unfortunately, there is very little information available in the open peer-reviewed literature about designing wings for yachts. While there has been a huge amount of research carried out on the design of multi-element wings for aircraft, the flow domain is very different for yachts and aircraft, as well as the performance objectives. Airline wings at cruise operate at Reynolds numbers in excess of 10 million compared with yacht sail Reynolds numbers in the region of 0.2 to 8 million. Whereas aircraft wings at cruise are designed for minimum drag at a required lift force, yacht wings must provide maximum thrust for specific roll/pitching moments, as well as sailing on either tack, and therefore the optimisation problems are very different. This paper reviews the literature on wing sail design for high performance yachts, and describes the results of a wind tunnel investigation of a multi-element wing similar to that used in the AC45 catamaran wing sail.

Introduction

In 2010, the 33rd America's Cup was won by BMW Oracle Racing in an enormous 100-foot trimaran powered by a 60meter high wing sail. The dimensions and unbelievable performance of the wing sail re-ignited the yachting world's interest in wing sails and since then, there has been a large amount of development.

While the use of wing sails is growing in popularity, the majority of the effort, so far, into understanding the science of their design has been undertaken by race teams such as Emirates Team NZ and BMW Oracle Racing. The goal of winning the Americas Cup for each team means all their design work and fluid analysis remains unpublished, sometimes long after the regatta has finished. This results in slow progress of wing sail development as amateur designers, without the resources of big teams, have to design their wings based on previous successful designs, aeronautical research and basic fluid analysis. Typically, this involves 'guessing' a better design and testing it against previous iterations. This is not cost effective and more research into the science behind wing sail optimisation needs to be published to ensure work isn't repeated.

While there has been some published work and yachts like the C-Class have been relatively open about their designs, the work has been very specific and designed under very narrow criteria. General wing sail design philosophies are not well understood by both designers and sailors. Fortunately this is not a completely new field as the aeronautical industry has a wealth of knowledge in wing design. However as is shown later, the difference in aircraft wing design and wing sail design means careful understanding of which research is relevant is very important.

How to design and optimise wing sails is a large field, but with new research being done every week, newer designs should be more efficient, easier to control and faster.

Benefits of Wing Sails

Aerodynamic Efficiency

Wing sails are inherently more efficient than traditional soft sails. The separation bubbles from large high drag profiled masts can be eliminated, and wings, with their low drag coefficients, can reduce the aerodynamic drag on a yacht resulting in better performance than traditional rigs. The evolution of wing sails and their increased performance is perhaps most clearly demonstrated in the open design C-Class competition dubbed the 'Little America's Cup'. The C-Class is a 25-ft catamaran with a maximum allowable sail area of 200ft^2 whose limited design specifications has allowed designers to experiment extensively with new technologies. Following Marchaj's demonstration[1] of reduced drag achieved with wing masts over traditional cylindrical masts, C-Class designers began to implement wing masts on their yachts. It became clear that the larger the mast/sail chord-ratio, the higher the aerodynamic performance. Despite some success enjoyed by traditional soft sails, which was largely due to weight savings, all C-Class yachts have been powered by wing sails ever since. These yachts now sail upwind at about 1.5 times the true wind speed and downwind at 2-3 times the true wind speed.

Research into wings for aircraft has resulted in many high-lift devices which are perfect for yachts. While the aerodynamic drag is important in yacht performance, the largest limiting factor for speed is hydrodynamic drag. High-lift devices allow exceptionally high lift coefficients with an increase in drag. The drag is still often several times smaller than conventional rigs while the lift coefficient is 2-3 times larger. Downwind and reaching this is especially beneficial. Perhaps the most common high-lift devices used on wing sails to date are slotted and external aerofoil flaps shown in figure 1.

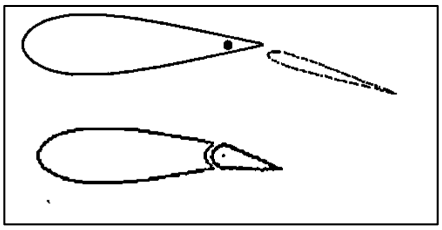

Figure 1. This figure shows 2 common high-lift devices often used in wings. Top is an "external aerofoil flap" and bottom is a "slotted flap". High-performance wing sails today are often made of a composite of these two devices.

Smith showed in his famous paper [2], that a wing of (n+1)-elements will generally have a higher maximum lift coefficient than a wing of n-elements. The slot allows the recovery of pressure, reducing adverse pressure gradients on the suction side of the aerofoil delaying stall and resulting in higher maximum lift. The AC45 wing sail is a 2-element wing or essentially an external aerofoil flap where each element has roughly the same chord length. Most C-Class yachts, current AC72 wings, USA-17 and USA-1 all have a similar arrangement where the wings are 2-

elements of 40-60% chord ratio and the main load bearing element has a slotted-flap trailing edge. While America's Cup teams haven't released their design processes, some papers have been written on C-Class campaigns. Generally it is felt this wing configuration provides sufficient lift coefficients, while maintaining controllability and remaining light weight. More elements would increase mass, complexity and cost, while reducing controllability and these are greater than the potential increase in maximum lift.

While high-lift devices such as slotted and external aerofoil flaps are very common on aircraft primarily for take-off and landing, there is still some confusion as to how they work. Many misconceptions such as "high energy air flows through the flap increasing speed over flap" exist and there is risk that these misconceptions will prevail in the yachting world. How these devices can be optimised for a wing sail that must work on both tacks (i.e. be symmetrical), within the high turbulence atmospheric boundary layer, have a non-elliptical span-wise lift distribution and be efficient across a wide range of Reynolds numbers, requires more research than currently available and clear understanding of slot behaviour.

Rigidity and Controllability

The benefits of rigid sails are huge especially for multi-hull yachts. Yachts are subjected to rolling moments primarily from the sail's centre-of-effort (CoE) being high above the centre of mass. Monohulls can balance this moment by increasing mass in the keel and righting moment increases with heel, but multihulls are limited in righting moment by crew weight, beam/buoyancy and daggerboard lift all of which reduce in effectiveness with increasing heel. Therefore the design criterion for multihulls is maximum thrust for a given rolling moment. In high winds, soft sails can be depowered by altering the twist so less lift is generated near the top of the sail. Rigid wing sails allow this to be taken a step further with negative lift at the top of the sail. This lowers the rolling moment while an overall increase in thrust is obtained. Optimal lift distributions have been studied for soft sails, but the results of negative lift were always discarded as soft sails are not capable of being trimmed in this fashion.

The other main benefit of rigid sails for yachts is that the hull can be significantly lighter than with traditional soft sails. The mainsheet loads required to maintain leech/sail shape are several tonnes for high-performance yachts. This entire load is transferred and spread through the hull from the mainsheet anchor point. Having the rigidity built into the sail reduces the weight in the hull and minimises stress concentrations as a mainsheet only has to counter the wing's pitching moment which is generally very small.

Rigidity also means a wing sail has extremely good predictable and constant lift and drag results at different angles of attack. This property is one of the drivers behind Walker Wing's, Harbour Wing Technologies Ltd, and Elkaim's work in autonomous marine vehicle design[3-9]. Rigid wings allow the sail to be controlled accurately and as they hold their shape, use smaller actuators than would be required for soft sails. Autonomous wing sail control has many applications from ferry transport, commercial shipping, oil spill robots and marine research.

The inability of rigid sails to easily reduce in area and the logistical issues associated with that has been the main factor for the slow adoption of wing sails. Wing sails won't be suitable for mainstream use until this issue is resolved. Many designs for semi-rigid wing sails consisting of flexible, camber adjustable ribs wrapped in a sail cloth have emerged in the last 60 years [10-14]. These designs allow the sail area to be reduced and being a cambered aerofoil profile increases the lift and reduces drag over most soft sails, but doesn't benefit from the lower mainsheet loads or controllability that rigid wings have. If cost and reliability can be optimised, these designs may be where wing sails first become mainstream.

Yacht Design vs Aircraft Design

While wing sails are effectively vertically mounted wings, the design criteria are very different.

Aircraft mostly operate well above the atmospheric boundary layer and at very high speeds. This means the onset flow to the wing is at constant speed and apparent angle, while being very low in turbulence. Yachts sail through the atmospheric boundary layer resulting in an apparent wind distribution that varies in velocity and angle up the height of the wing. The wind is also highly turbulent (gusty) this close to the ground which can result in time-varying apparent wind velocity and twist profiles. Choosing a wing design with an extremely high maximum lift coefficient may not be the best option if it is subject to sudden stall due to the dynamic fluctuation of apparent wind angle. A wing with a slightly lower maximum lift but which stays high over a wider range of angles-of-attack may result in the sail operating at the desired lift most of the time.

To perform well, an aircraft wing must generate a certain amount of lift in one direction to remain flying and with minimum drag to reduce fuel costs, the exception being during take-off and landing. Multi-hull yachts require maximum thrust for a required heeling moment. As mentioned previously, the ability to lower the aerodynamic CoE is extremely encouraging, however analytical wing lift and drag predictions based on traditional elliptical distribution approximations such as lifting line theory may not be accurate.

Traditional sail design involves designing a sail, solving its aerodynamic properties in a wind tunnel or with computational fluid dynamics, and then inputting this data into a velocity prediction program (VPP) which determines which sail will get a yacht around a course fastest. Inverse design methodology involves solving what aerodynamic properties will get the yacht around the course fastest, then designing a sail capable of the required characteristics. Both methods require knowledge of the aerodynamic characteristics of the sail.

Aerodynamic Performance Measurements

Computational Fluid Dynamics (CFD)

CFD offers many possibilities for wing designers. Emirates TeamNZ have been very open about the significant amount of resources they have put in full Reynolds-Averaged-Navier-Stokes (RANS) simulations combined with smaller yacht on-the-water two-boat testing. Measuring pressures on smaller SL33 yachts allow validation of the CFD models, and scaling issues associated with small wind tunnel models are reduced.

Another possibility for CFD analysis would be to use a panel-code. Panel-codes require significantly less computational resources than RANS-based codes, however are not accurate where separation or high viscous effects are present. This is another region where more research into their accuracy around slotted foils is required.

Wind Tunnel Testing

Wind tunnels have been used successfully in sail performance analysis. There are issues with wind tunnel testing as well, most significantly scaling effects. For a traditional sail, scale effects are small and can often be ignored, however for wings, the Reynolds number effects are more significant. If a model is tested at a lower wind speed than would be realistic, the size of the model must be increased to maintain the same Reynolds number.

This means in a low-speed wind tunnel, a very large wing would be required. This then raises blockage issues as well as the effect on walls when testing high-lift devices. Wind tunnels are often used to validate analytical/computation predictions but the results of the tunnel testing must also be queried. Questions on scaling and blockage need to be answered before the results of wind tunnel tested wings can be used for validation.

In the following sections some early wind tunnel testing of 2-dimensional wings is presented. The general methodology and some preliminary results are presented, however some of the questions outlined above have yet to be answered.

Wind Tunnel Testing of a 2-Dimensional Wing Sail

To investigate the difficulties of wind tunnel testing and how slot geometry affects performance, a scale 2-Dimensional model of an AC45 class wing was built for testing at the University of Auckland's Twisted Flow Wind Tunnel. The model spans the entire width of the wind tunnel when the high-speed contraction is in place. This minimises tip vortices and makes the flow as two-dimensional as possible. Details of each wing section are listed in table 1.

Element 1	
Chord	485 mm
Max Thickness	25% Chord
Span	2500 mm

Element 2	
Chord	485mm
Max Thickness	10% Chord
Span	2500 mm

Table 1: Main geometric properties of the 2-Dimensional wings built based on AC45 wing sail geometry.

A mounting mechanism was devised where the relative camber, slot gap and pivot location can be set, then the angle of attack for the entire wing can be changed quickly. Figure 2 shows the model mounted horizontally in the Twisted Flow Wind Tunnel.

Figure 2. This figure shows the test model mounted horizontally in the TFWT with contraction in place. The Pitot - static tube in front of the wings measures the reference static and dynamic pressure to convert values to coefficients

The central section of each wing was built separately and measures the pressure distribution across the wings surface. Pressure tubes are cut flush to the surface and run down the half-span of the wing to two 64-channel pressure transducer boxes. Figure 3 shows the central section of Element 1 with pressure tubing during construction. Currently, force is not being measured directly but this is something that will be investigated in future testing.

Pressures are converted to coefficients. These are then transformed into local x & y coordinates for each element. The pressure at the trailing edge is assumed to be zero and the total force per unit span acting on each element is calculated using a trapezium type integration. These forces are then converted to lift and drag components, and then normalised by the chord length of the main wing, Element 1.

Figure 3. Pressure tapped central section of element 1 showing pressure tubing running through the inside of the wing.

<u>Individual Wing Testing</u>

Initially, each element was tested to get base values and to find zero degrees angle of attack based on pressure distributions. Figure 4 below shows the corresponding lift and drag slopes. Note that the drag is pressure drag only.

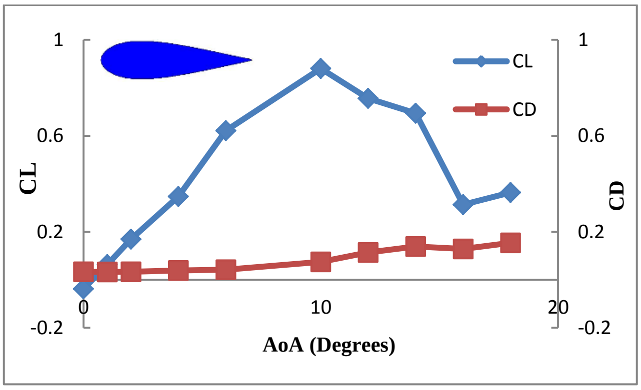

Figure 4. Lift and pressure drag coefficients with changing angle of attack at Re = 220,000. Note sharp decrease in lift from 10° indicating stall.

The second element was then tested for base readings. Figure 5 below shows the Lift and Drag coefficients with changing angle of attack.

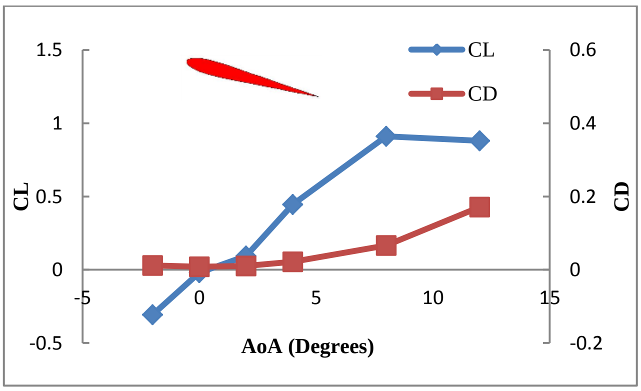

Figure 5. Lift and pressure drag coefficients with changing AoA at Re=220,000. Note change in lift gradient from 8-12° AoA

Next the two wings were tested together with zero degrees flap deflection at 2 different nominal gap sizes, 2% and 6% of the 1st element chord. Figure 6 below shows the variation of lift and drag coefficient slopes at both gap sizes.

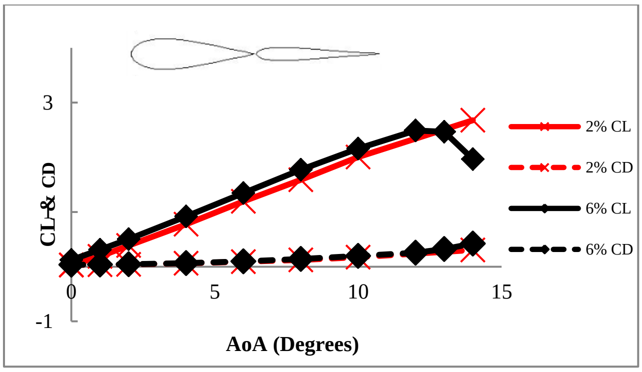

Figure 6. Lift and pressure drag for both elements with 0° flap deflection and gap sizes 2% and 6% of 1st element chord length. Note similar gradients but delayed stall with only 2% gap.

Clearly, even at zero degrees flap deflection the gap plays an important role in the characteristics of the wing. With a 6% gap, stall occurs from 12° AoA but with a 2% gap, there is no sign of stall past 14° AoA.

A 15° flap deflection was then tested with the pivot being located at 85% of the 1st-element chord. Figure 7 shows the lift and pressure drag curves for various AoA.

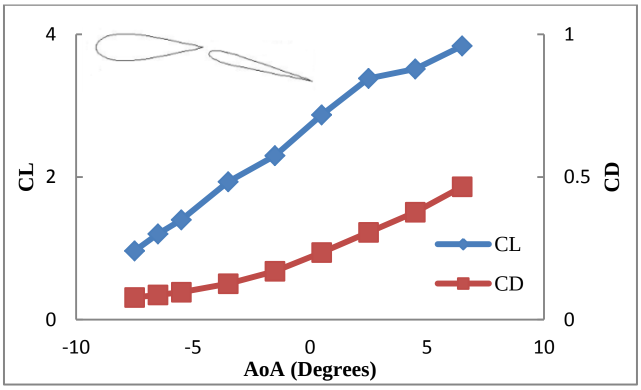

Figure 7. Lift and pressure drag curves with 15 Degrees Camber (flap deflection), 2% Gap, 85% Pivot-point, at multiple angles of attack. Note AoA is the apparent wind angle on the leading element.

To check the effect of gap size again, the two elements were kept at constant flap deflection of 15°, and the gap was varied from 0.5% to 6% while keeping the 85% pivot point.

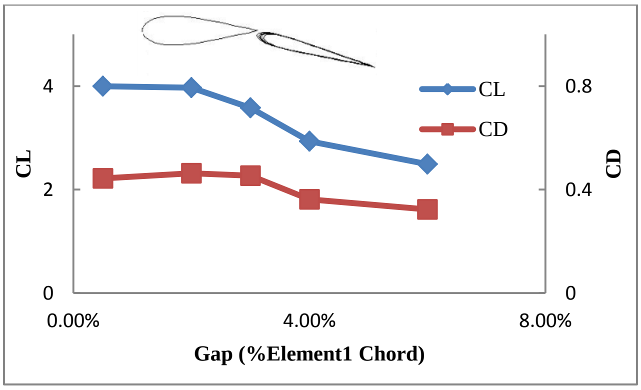

Figure 8. Lift and pressure drag coefficient variation with increasing gap size for 2-element AC45 wings. Flap deflection was kept constant at 15°, with a pivot-location 85% of the main element chord line, Constant AoA of 6.5° to Element 1.

Discussion and Conclusions

These results show trends similar to those expected from previous studies in multi-element aerofoil design for aircraft. Figures 6 and 8 show how the design of a slot for slotted aerofoils is very important, as having a larger gap results in stall earlier than a gap between 0 & 2% of the main element chord. More work is planned using hot wire and hot films to measure boundary layer characteristics and the pressure field around the slot.

Figure 7 shows the very large lift coefficients that can be obtained using external aerofoil flaps to induce camber from symmetrical profiles suitable for tacking yachts. What thickness ratios, chord ratios, and gap size variations do to the overall aerodynamic characteristics of a wing sail is yet to be understood, however these results can be used to validate CFD codes which could potentially solve the many possible geometric possibilities.

These plots show some quite low drag values. This is because the results presented are pressure drag. Although the resolution across the thickness (especially for element 1) is quite good, there are inherent inaccuracies in the approximations used and viscous drag is not accounted for. Future testing will use wake surveys to calculate individual components of drag to compare to these results.

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