AERODYNAMIC DESIGN DEVELOPMENT OF AC72 WINGS

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Abstract. This paper reviews Emirates Team New Zealand’s aerodynamic wing design process for the 34\textsuperscript{th} America’s Cup Campaign. The program was structured around a series of milestone design iterations to support an aggressive timeline for development. A number of modern simulation tools and methods for aerodynamics were used in the design process, as well as wind tunnel and extensive sub-scale boat testing. Key design parameters and the background for major design decisions that balanced aerodynamic performance, control and structural design are discussed in the paper.

NOMENCLATURE

\begin{itemize}
  \item AWA Apparent Wind Angle
  \item CFD Computational Fluid Dynamics
  \item ETNZ Emirates Team New Zealand
  \item GGI Generalised Grid Interface
  \item HPC High Performance Computing
  \item OF Objective Function
  \item RANS Reynolds-Averaged Navier Stokes
  \item TWA True Wind Angle
  \item TWS True Wind Speed
  \item \(y^+\) Non-dimensional wall distance
  \item VMG Velocity Made Good
  \item VPP Velocity Prediction Program
  \item W\textsubscript{1} Main element angle
  \item W\textsubscript{2} Flap camber angle
\end{itemize}

1. INTRODUCTION

The replacement of the traditional mainsail with a wing for the 34\textsuperscript{th} America’s Cup was expected to be a major aerodynamic design challenge requiring a wide range of new expertise. As it turned out the design process involved some new tools and tricks but was largely a refinement of computational approach and methods used in the 32\textsuperscript{nd} America’s Cup. The main difference from previous Americas Cups was the increased fidelity and sheer volume of simulations afforded by the computational resources that we now have access to.

The most significant change from previous America’s Cup design cycles was the increased focus on apparent wind effects where downwind apparent wind angles (AWAs) were almost always finer than 30 degrees. This led to a focus on drag minimisation. At such fine AWAs the drag forces have more significant effects on boat speed.

Accurate performance prediction requires extensive data on yacht forces. Early in the program it was determined that wind tunnel results at Reynolds numbers significantly less than full-scale were unsuitable for analysis. This placed a premium on accurate simulations as a basis for analytical performance models.

Experience from the International C-Class Catamaran indicated that maximum lift coefficient would be an important parameter. However, unlike the C-Class Catamaran, the new AC72 rule allowed large headsails to be used downwind, which mitigated the need for very high wing lift. Initially high maximum lift was considered advantageous for sailing at deep true wind angles, which potentially provide performance and tactical advantages downwind. However with the advent of foiling and increasingly faster boatspeeds it became apparent that the AC72 would be significantly depowered in all but the lightest conditions downwind.

1.1 WING TERMINOLOGY

The general terminology used at Emirates Team New Zealand for describing the wing is illustrated in figure 1. The flap is attached to the main element and rotates about the flap hinge axis to generate camber. As the flap is rotated the inter-element slot opens up allowing flow to reenergise the boundary layer on the leeward side of the flap. This increases the two-dimensional maximum lift coefficient from around 1.2-1.6 for a symmetrical single element section, to as high as 3.0 for a two-element wing.

The wing main element also has a small movable trailing edge tab (in aircraft design terminology, a “plain flap”). The tab is used as a passive slot control device that is linked to the rotation of the flap with a short string. The
linkage is tuned so that the tab trailing edge follows the flap rotation at a predefined camber angle determined by the length of the string. The flap rotation point, the tab axis and the string length can be manipulated to control the slot geometry at different flap camber angles.

The entire wing rotates about the main element rotation axis as the sheet is trimmed. This axis passes through the wing ball at the bottom of the wing where it sits in a socket on the yacht, and passes approximately through the hounds. This axis of rotation is affected by the positioning of the standing rigging and is determined through FEA analysis.

Figure 2. ETNZ wing trim terminology.

The variables used to describe wing trim are illustrated in figure 2. The difference in main element and flap angles is referred to as W2 angle or camber. The difference between the flap angle at the bottom of the wing and the top of the wing is referred to as W2 Twist. W1 is the angle of the bottom of the main element and W1 Twist is the angle of the top of the main element relative to the bottom of the main element.

2. DESIGN PROGRAM OVERVIEW

The design program for the AC72 had to cover a lot of new ground and manage considerable technical and schedule risk. The approach for the design team was structured around a series of milestones that condensed on-going design decisions into a sequence of “snapshots” of the entire yacht as it progressed from initial design to final form.

2.1 MILESTONE METHOD OF DESIGN

The first draft of the AC72 Rule was released in September 2010, and the design team had its first meeting in November 2010. The full team did not gather until February 2011. This meant had just 8 months to design our AC72 wing in order to be able to launch not long after the 1 January 2012 date that was the earliest allowed in the protocol. Our design program was structured around a series of design milestones:

- Wing 0 (November 2010)
- Wing 0.5 (Feb 2011)
- Wing 0.7 (April 2011)
- Wing 0.9 (June 2011)
- Wing 0.95 (August 2011)
- Wing 1.0 (November 2011)
- Wing 2.0 (August 2012)

Roughly speaking this meant that by April 2011 we were 70% of the way towards our final designs. However, aerodynamic design must precede much of the structural wing design work and so in reality by March 2011 we were more than 70% of the way towards our final aerodynamic design of the wing.

With many of the design team resident overseas, design sessions would be scheduled in Auckland for two weeks leading up to milestone dates. During this period many new ideas and features were introduced and often incorporated into the design. The ideas proposed in these sessions would become the first items investigated in the design cycle for the next milestone. Design milestone dates were treated as firm deadlines where a candidate wing design would be presented along with a plan for further investigations to be carried out. Using this method of design management meant that we kept to time deadlines and ultimately presented the final design for Wing 1.0 on time in November 2011.

2.2 EARLY DEVELOPMENT/WIND TUNNEL

The first milestone, Wing 0, was designed at the first design meeting without the use of any simulation or analysis. A 1:20 scale wind tunnel model of Wing 0 was built and tested in an attempt to verify our early simulations. The tests were conducted at the University of Auckland’s Twisted Flow Wind Tunnel with the help of David Le Pelley. The maximum achievable Reynolds number was approximately 100 000 which was significantly lower than the operating Reynolds number range of an AC72 wing (3-10 Million).

CFD simulations prior to the wind tunnel tests had indicated that due to the low Reynolds number in the wind tunnel it would be difficult to reproduce lift coefficients anywhere near the levels expected in full

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scale. This was found to be the case in the wind tunnel where maximum lift coefficients were less than 50% of full-scale CFD predictions. At wind tunnel scale it was difficult to keep the flow attached around the leading edge of the flap. At full scale Reynolds numbers the wing can remain attached at W2 angles (camber) up to 35 degrees whereas in the wind tunnel we were unable maintain attached flow over the flap above a W2 angle of 20 degrees. Since at wind tunnel Reynolds number the flow is significantly different from what we were expecting for the full scale AC72 no further wind tunnel tests were performed in the campaign. However, the wind tunnel model proved to be an effective educational tool for those members of the design team (and sailing team) who had no experience with wings. It allowed the team to come together for the first time to discuss wing and sail aerodynamics and trim with a physical tool that we could use to visualise and manipulate.

![Figure 3. Wing tunnel model.](image)

### 2.3 PERFORMANCE METRICS FOR DESIGN

Considering the short timeline of the design process, we essentially had little or no real world input into the Wing design, and certainly no full-scale test data. Therefore, a very important aspect of our wing design process was using computer simulation to predict the effect of wing design choices on yacht performance.

Performance metrics were evaluated using a custom VPP, Gomboc, developed by Dan Berniscom⁶, which proved to be an invaluable tool. The VPP had all the key wing trim parameters (Wing Sheet, Wing Camber, W1 Twist, W2 Twist) as variables. This enabled us to gauge the effect of a particular design change throughout the wind range at optimum setup for velocity made good (VMG) sailing as well as for off-design scenarios.

Initial CFD results were compared using classical aerodynamic analysis of effective span, maximum lift and lift–drag polars as well as drive force to roll moment ratio. However once the VPP was operational it became clear that all six aerodynamic forces and moments are important to the performance of the yacht and it is necessary to adequately cover the trim space to fully analyse wing designs. Therefore the majority of analyses using the VPP were done with large aerodynamics databases (matrices of forces and moments) from RANS simulations. The production of the databases required large computational resources which led to the purchase of a 576 core Dell HPC cluster. With the high demand for VPP data we were required to extensively automate the simulation process.

As the VPP matured and became more sophisticated, the team became more reliant on it as a tool for design. In fact through most of the design process, we relied implicitly on the results of the VPP. It is well known that we first sailed on foils in August 2012 in the first AC72 yacht, however the design team had been “foiling” for 12 months prior to this by utilising the predictions of the VPP. This led to many changes in the design of our wing.

### 3. COMPUTATIONAL METHODS

The analytical tools used for the wing development included methods for 3D RANS analysis and specialized 2D airfoil design tools for section analysis and optimisation. RANS 3D methods were used for the bulk of the data generation for wing forces for VPP analysis. In addition, extensive 2D analysis across a range of design parameters for wing and flap configurations was used as a basis for many of the wing design trade-offs. Optimised wing and flap sections were developed using an approach that combined 3D RANS with 2D design using multi-point optimization.

#### 3.1 MSES

Two-dimensional analysis and design was carried out using MSES, a design and optimisation framework for 2D multi-element airfoils [1]. MSES was the principal tool for airfoil analysis and was used as the analytical engine for optimization. The ubiquitous XFOIL panel code (Drela) was also used for airfoil manipulation for final smoothing and shaping. All MSES analysis and optimisation studies were carried out by Harold Youngren a design team member for the 34th America’s Cup campaign.

MSES is formulated with a streamline based Euler flow solver with a closely coupled integral boundary layer method for viscous effects and uses a Newton-Raphson solution technique. MSES provides good estimates of airfoil drag and can provide analytical derivatives for design variables, an important factor for optimization work. MSES also provides capabilities for design using a discrete set of shape-changing geometric modes that

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alter the airfoil contour. Optimization was done using LINDOP, an optimizer tailored for use with MSES, to coordinate constrained multi-point optimization. MSES was used to analyze airfoil performance and generate flow sensitivities to the design variables (geometric modes) for use in LINDOP to do optimization. With this method geometric (such as thickness or area) or flow constraints can be applied to control optimization using quasi-Newton, steepest descent or conjugate gradient methods. This can be used to optimise an airfoil or airfoil component at one or more operating points, minimizing an objective function (OF) for lift, drag, or drive-to-side force or other aerodynamic forces.

The strength of MSES analysis lies in its speed (many times faster than RANS codes) and its ability to accurately predict laminar to turbulent transition for airfoil flows. The alternative - Reynolds-Averaged Navier Stokes (RANS) codes - are principally designed for fully turbulent flows and typically produce poor estimates of transition behaviour for airfoils[3]. An exception is the Menter-Langtry gamma-theta transition model [3] which has produced good results for RANS simulations where it has been well calibrated. However given the time scale of our project it was preferable use MSES which is vastly faster and well proven for airfoils with boundary layer transition.

In addition to analysis of 2D wing and flap geometries, MSES was also used in simulations of the wing and jib with the headsails modelled as a very thin airfoil element. Comparisons with three-dimensional RANS results produced good agreement of the pressure distributions so long as the cross-sections were taken away from the wing root or wing tip where the flow can be significantly three-dimensional. As can be seen in figure 5, the pressure distributions compare well between CFX and MSES with the only exception being slightly lower suction pressure on the leeward surface of the main element. This is believed to be primarily due to three-dimensional effects causing localised differences in angle of attack.

Figure 4. Converged MSES grid for a combined wing and sail simulation.

Figure 5. Pressure coefficient comparison between a slice from a three-dimensional RANS simulation (symbols) and a two-dimensional MSES simulation (solid line).

Initial two-dimensional studies were carried out using the wing in isolation looking at single element, two-element and three-element wings as well as studies comparing different main element to flap ratios for the two-element wing. However, early three dimensional RANS results indicated that the headsail had an important role in the aerodynamics. For high lift cases the headsail acts like a leading edge slat reducing the suction peak on the leeward side of the main element and allowing for an impressive increase in maximum lift. Headsails also have the advantage compared with a high-lift configuration such as a three-element wing in that they can be furled and dropped when high-lift is not required.

3.2 RANS

Three-dimensional Reynolds-Averaged Navier Stokes (RANS) simulations were carried out using ANSYS CFX 14.0. ANSYS CFX solves the RANS equations using a coupled finite volume solver with algebraic multi-grid. Spatial interpolation is carried out using a bounded high-resolution advection scheme and time integration for unsteady simulations is modelled with implicit second order backward Euler time-stepping [4].

In all simulations turbulence is modelled using the SST k-ω model of Menter [4, 5]. ANSYS CFX uses an automatic wall function implementation where wall function boundary conditions are used for wall regions that have near wall spacing greater that y+>11. In regions where the grid is sufficiently fine enough the code automatically switches and the near wall is modelled by integrating the SST model through the viscous sublayer.

A range of different meshing strategies were used, depending on the type of simulation. For upwind simulations where the lift coefficients are typically low unstructured grids were found to be acceptable. Also for simulations where the camber distribution on the wing inverts to have negative camber near the top an unstructured approach is the only option as a block
structured topology would collapse at the point where the wing inverts. Our unstructured meshes were created using Harpoon v4.2 [6] a fully automatic hex-dominant grid generator. Mesh sizes ranged from 20 to 70 million cells. Grid resolution studies were regularly carried out to ensure the grids were suitable for the task at hand.

For downwind simulations block-structured grids were generated using ANSYS ICEM HEXA. The block structured approach allowed us to get a high-resolution boundary layer grid whilst retaining manageable grid sizes. Grids were in the order of 20 to 30 million cells depending on the number of headsails included in the simulation. For downwind simulations a near wall distance \((y^+)\) of approximately 1.0 was used in order to ensure the boundary layer is accurately modelled, particularly in regions of high adverse pressure gradient and separation.

In order to retain high quality cells and a simple blocking topology we made use of generalised grid interfaces (GGI) [4] in ANSYS. The domain was broken up into two sub-domains: A small sub-domain around the platform and a block-structured domain for the wing, sails and far-field. The platform domain was meshed using Harpoon to generate unstructured, hex-dominant meshes. The GGI approach led to a simpler blocking topology and a more orthogonal mesh. It also allowed us to swap out different platforms with the unstructured sub-domain without having to regenerate the block-structured meshes for the wing and sail domain.

4. GENERAL DESIGN OVERVIEW

The AC72 design rule was very open and allowed for many different aerodynamic configurations of the wing. Early on we recognised that the design space was large and many options needed to be explored.

1. Number of elements (single, two-element or three-element).
2. Position of the wing rotation point.
3. Overall planform.
4. Tack location of upwind and downwind headsails.
5. Main element to flap ratio.
6. Main element twist.
7. Flap twist profile.
8. Wing sectional shapes.

The number of elements was decided early in the Wing 0.5 design Cycle. MSES results indicated that a two-element wing would have good performance over a wide range of lift coefficients. A single element wing would not produce enough lift for light airs downwind sailing and three-element wings were viewed as being too complex for a fairly minimal increase in maximum lift coefficient.
Consequently many decisions on these parameters were gains we were finding in the platform aerodynamics. Practically insignificant compared with aerodynamic the differences in performance were minimal and trimmed the wing to its optimum vertical center of effort found that when a full CFD matrix was run and the VPP produce quite different forces and moments. However we For a given fixed trim different designs could potentially line received plenty of attention early in the campaign. Flap ratio, planform shape and the shape of the flap hinge were foiling it was better to have no Code 0 at all and down the wind range to the point where whenever we platform aerodynamics this cross-over moved further however as the yacht got faster with better foils and the smaller Code zeros being faster above 11kts TWS, sails was not at the optimum position for light-air rigging. As a result the tack location for the downwind weight savings in the structure of the prod and under rigging. As a result the tack location for the downwind sails was not at the optimum position for light-air downwind sailing. The VPP suggested a cross-over with the smaller Code zeros being faster above 11kts TWS, however as the yacht got faster with better foils and platform aerodynamics this cross-over moved further down the wind range to the point where whenever we were foiling it was better to have no Code 0 at all and just use the jib.

Flap ratio, planform shape and the shape of the flap hinge line received plenty of attention early in the campaign. For a given fixed trim different designs could potentially produce quite different forces and moments. However we found that when a full CFD matrix was run and the VPP trimmed the wing to its optimum vertical center of effort the differences in performance were minimal and practically insignificant compared with aerodynamic gains we were finding in the platform aerodynamics. Consequently many decisions on these parameters were based around what was easier to engineer and build as well as a layout that worked well for the control system loads. It became clear that it was very important to have a wing that we could trim quickly to its optimal shape rather than a design that was difficult to trim.

W1 twist (or main element twist) was a feature that did stand out in the early VPP studies as a potential gain, particularly downwind. Mechanically this was very difficult to achieve, but by limiting the twist to the lower half of the wing we were able to achieve this, albeit at a weight penalty. The final design specification was for the lower half of the wing to twist up to 16 degrees. A benefit was that there was better interaction with the headsails where the leading edge of the main element was setup to closely follow the twist of the jib. The flap twist profile was modified when W1 twist was used to maintain a near linear twist profile even though the main element twist was only twisting through the lower half of the wing. This was done by within the wing control system where as W1 twist activated the control lines for the flap in the middle of the wing were automatically adjusted to compensate.

VPP results suggested that the wing should invert its lift distribution above approximately 12kts TWS whilst sailing upwind. This meant the angle of attack and camber would switch to negative at the top of the wing. Uprange upwind would entail as much as -15 degrees of camber at the head which would produce significant load to windward at the top of the rig. There is no real magic in this. For a conventional mainsail twist is used to lower the center of effort as the wind speed increases. This is usually continued until the head of the sail flogs at which point the sail is reefed to further lower the center of effort. With a wing we have the luxury that instead of reefing we can just continue to twist. There is nothing ground-breaking here; the boats performance doesn’t change in any way at the point of inversion, the center of effort just continues to decrease and the forces and moments continue along the same curves. With the specified wind range of 5-30kts TWS the VPP desired up to 60 degrees of twist however we ended up with approximately 45 degrees of combined W1 and W2 twist.

Flap twist profiles were also studied using CFD and the VPP with various non-linear profiles, however for all round conditions the optimum twist profile was close to linear. The option of adjusting the W2 twist profile while sailing was discussed but never implemented. However considerable experimentation was done in tuning the twist profile using adjustments in the control system ashore.

5. SECTION DESIGN AND OPTIMISATION
The sectional shape of the wing was an active area of development for Wing 1. Viscous drag made up only 10-20% of the total wing drag so there was limited potential for large performance gains with sectional design.
However, it is an area that lends itself well to optimisation within structural constraints such as minimum inertias. Early studies showed that there were limited gains from changes to the flap sectional shape. Consequently the focus here is on the main element section design. Optimisation work on the upper wing sections found that added flap thickness (up to 10% thickness to chord ratio) and increased leading edge radius improved upper wing performance.

Optimising for laminar flow is the most significant way to gain performance out of the section shape. Promoting laminar flow upstream of the pressure recovery region helps increase the maximum lift of the wing. With laminar flow the boundary layer is thinner and is able to sustain laminar rooftop pressure distributions with greater suction forces compared with turbulent flow [7]. Laminar boundary layers also exhibit less skin friction which can account for a significant reduction in drag. In general however, we were conservative in our attempts to exploit extensive laminar flow out of concerns for leading edge separation and stall at off-design conditions.

We used a multi-point optimisation scheme for the design of our airfoil sections. Multi-point optimisation avoids some of the problems with single point optimisation where performance at one operating point is improved at a cost of reduced off-design performance. Since an AC72 wing must operate over a very wide set of conditions it was deemed important to optimise across a range of sailing states. The objective function (or OF, the metric for the optimisation) combined several operating states using both free transition and fully turbulent forced transition simulations. The procedure follows closely the approach taken in the optimisation of laminar flow airfoils [8]. The optimiser was LINDOP, a gradient-based optimisation framework for MSES [9, 10]. Modifications were made to LINDOP to work with body axes (rather than wind axes) forces so that drive force and side forces could be used in the objective functions.

Different objective functions were used with different weightings to account for a range of wing configurations: powered up and depowered, upwind and downwind. Target two-dimensional lift-coefficients were extracted from the three-dimensional RANS CFD and used as targets for each operating point of the multi-point optimisation. Initially drag was used as the metric for the optimisation but drive force to side force ratio was also used for some of the later optimisations. For cases with jibs special care was needed to set the jib trim to ensure a stagnation point at the leading edge with no leading edge separation bubble.

Three different wing profiles were optimised at 25%, 50%, 75% wingspan. Simulations close to the head and foot of the wing were avoided as it was felt that cross-flow effects were too dominant for the two-dimensional flow simulations to be valid. Sections at 0% and 100% span were finalised using three-dimensional RANS analysis.

For the section at 25% wing height where a headsail is always present there is little risk of separation on the leading edge of the main element as the jib suppresses the leading edge suction peak on the wing. Here we placed significantly more weighting to the free transition design points by using two laminar operating points (upwind and downwind) and one turbulent upwind condition (to retain robust off-design performance). With the optimiser keen to promote laminar flow it pushed the point of maximum thickness quite far aft to establish a favourable pressure gradient, which helps delay transition to turbulent flow. This also pushed us to thicker main element sections as thickness increases the strength of the positive pressure gradient. In the end we actually choose somewhat thinner sections than the optimiser would have in order to save weight. Extra thickness leads to more spar surface area and assuming a minimum laminate thickness for robustness, this would lead to more weight.

At the section at 75% wing height, we assumed fully turbulent flow at three operating points. These sections lie in upwash above the jib and operate at lower Reynolds numbers, making them more prone to flow separation. The optimisation led to rounder nosed sections with the position of maximum thickness further forward. The optimiser was quite neutral on thickness depending on the weights applied to the low lift points compared with the high-lift points. At low lift coefficients in fully turbulent flow added thickness does result in a significant increase in drag. However for the high lift conditions a thicker section with a larger nose radius resists leading edge stall.

For the middle section we used an upwind laminar operating point and three turbulent conditions (two downwind, one upwind), which led to a wing section somewhere in between the sections at 25% and 75% span.

![Figure 9. Final Wing 1 sections at (a) 25% span (b) 50% span, and (c) 75% span.](image)
RANS simulations verified that these sections were significantly more resistant to stall. Streamline plots of the wing before and after the section optimisation are shown in figure 10.

Figure 10. RANS high-lift simulations with original sections (a) and optimised sections (b).

6. REAL WORLD VERIFICATION

6.1 SL33

Two identical wings were built for our 33 ft. SL33 catamarans and launched in late November and early December 2011. These were scaled versions of our AC72 Wing 0.9 design, which was very close to our final design for Wing 1.

This project was focused around gaining experience building wings and for validation of the control system design. However we also had the opportunity to verify and test many of our aerodynamic assumptions and choices.

The VPP had indicated that, for optimal VMG, the wing should be depowered downwind above 8kts TWS. This was viewed with some suspicion and questions remained whether or not it would be better to power up and sail lower and slower. We carefully sized the SL33 wings so that in the VPP the desired wing trims matched the AC72. Two-boat testing confirmed that the predicted target trims from the VPP were accurate. As the boats were easily able to sail very deep true wind angles (TWA) there is diminishing return for sailing lower and it is more advantageous to depower and sail the yacht fast.

W1 twist was another important aerodynamic feature to validate. Downwind with the yachts in the early stages of foiling development we found it difficult to test since the yacht that touched down less would always win the test. However a surprise came in using W1 twist upwind where the gain rate was higher than what had been predicted by the VPP. It was felt that this was a dynamic effect, with the slot between the wing and jib better setup the yacht was able to build speed and accelerate more efficiently. There was an obvious cost to implementing W1 twist in the structure and control system however after its success in the SL33 upwind it was hard to discount it.
We also used the SL33 to investigate laminar flow. An array of hot-film sensors was installed on the wing by David Le Pelley for estimating the turbulent transition location. The hot-film sensors were embedded in a thin Mylar and were recessed so as to not obscure the flow in the boundary later. This also had the advantage that it was simple to remove the mylar sheet and move the sensors to different positions on the wing.

![Figure 12. Mylar sheet with hot-film sensors installed on the SL33 main element.](image)

We ran the laminar flow tests on two separate days; first with the sensors at approximately 20% wing height and the second day with the sensors at 70% height. This way we had data for the area of the wing where we believe the presence of the jib would aid laminar flow (day 1) as well as data for the wing above the jib (day 2). Results indicated that upwind at the lower station we were typically getting laminar flow on 40-60% chord on the leeward side of the main element and 50-70% on the windward side. This was in line with what we had expected from MSES analysis. For the upper station we were surprised to find that we typically could get 20-50% laminar flow on both the leeward and windward side. Results depended on twist as with more twist the stagnation point can move around to the leeward side of the wing. MSES results confirmed that at the higher Reynolds number of AC72 wing there would still be a significant amount of laminar flow.

7. DEVELOPMENT FOR WING 2

The design for Wing 1 was signed off in November 2011, which was 7 months before launch. The design date for Wing 2 was set at August 2012, which would mean that there was limited opportunity to sail with Wing 1 and incorporate the design for Wing 2.

The design method was different to Wing 1, as much of the general background work had been done in the Wing 1 design process. Also we were starting to see the work of other teams on the water, with the first Artemis wing, as well as Oracle, both of which were more upwind oriented in nature due to their small flap chord ratios.

By this time it was clear that the boats would be foiling downwind and that the boats were impressively fast which had led to the apparent wind angle range downwind tightening from 25-45 degrees AWA to 20-30 AWA. Downwind wing trims were becoming a lot more like upwind with less camber required and the wing twisted in as little as 10kts TWS. Consequently we were interested in designing Wing 2 as a more upwind optimised wing. A single element wing, which has lower drag at low lift coefficients, was explored. This proved to be an advantage upwind, but seriously compromised the performance downwind. It also would have been difficult to engineer it so that it could twist sufficiently and lower its center of effort as much as a two-element wing.

Our next avenue of investigation was to look at wing designs with larger W1 and smaller W2 chords. W1 chord percentages of up to 60% were examined as tested and were found to be a small improvement upwind, and also gave better performance uprange downwind. However alongside the aerodynamic considerations, we had to keep an eye on the structural implications, as the larger W1 sections generated significantly more torque in the structural tube and higher mainsheet loads due to the flap suction peak being positioned further aft.

From the hot-film testing we had done on the SL33 and the fact that we were less concerned with maximum lift we decided we could push harder for laminar flow in the upper sections of the wing design. As per the Wing 1 development, this was done with a mixture of MSES runs and three-dimensional RANS simulations. Small gains were made here and a new tool was used for the upper spar. At the time the tool construction began we were still considering a wing with smaller flap ratio and the idea was the new tool shape with maximum thickness aft could accommodate either design.

In the end the potential gains from these refinements of the designs were relatively small (especially compared to the expected gains we were finding in the development of the hydrofoils and platform aerodynamics). Additionally there was a requirement to reduce costs by reusing the existing tooling that was used for Wing 1. There was also a desire to have the two wings close in design in case we had to swap wings or wing parts mid regatta. As a result, the two wings were essentially identical, just with the main element spar and rib shapes optimised more for laminar flow in the upper half of Wing 2.

It was necessary to save some weight in both wings and, since high-lift was no longer a priority the tab was removed from both wings. Without the tab present to condition the flow onto the flap, stall would occur at large flap angles. To offset this, the hinge point for the flap was moved aft to reduce the slot opening at large flap angles. Studies were carried out with MSES looking at lift to drag ratio and maximum lift coefficient for different flap leading edge locations. Here, for a range of camber angles the flap was translated around a grid of x-y locations near the main element trailing edge and
contour plots of the relevant performance metrics were generated. An example showing the maximum lift coefficient contours at 35 degrees camber is shown in figure 13. The black dot at the flap leading edge is the reference location for the flap positioning. For the given example maximum lift occurs with the flap leading edge very close to the trailing edge of the main element.

![Image](image.png)

**Figure 13.** Contours of maximum lift coefficients for different flap leading edge position for 35 degrees camber.

This data was used to establish a good compromise between maximum lift and lift to drag ratio through a range of camber. Moving the hinge point from 88% to 92.5% moved the flap angle where stall was observed from 31 to 36 degrees which allowed a significant increase in maximum lift without compromising the lift to drag ratio at low lift. With the tab we could achieve a maximum of 38 degrees flap angle without stalling the flap so the aft hinge location was seen as a good compromise given the weight savings of approximately 40 kg.

8. CONCLUSIONS

The story of the ETNZ’s aerodynamic wing design evolution during the 34th Americas Cup campaign involved elements of discovery, refinement and compromise. The computational methods and tools used for the aerodynamic simulations and many of the design tradeoffs in the wing development proved essential to the program success. Whilst wing aerodynamics was not the game-changer that was originally expected, a lot of analysis was required to establish the correct compromises with the structural and control system design.


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1. Note that in August 2011 the America’s Cup protocol was changed to move the earliest AC72 launch date back from January 1st 2012 to July 1st 2012.

2. Wing 0.95 was added in after the launch date for the AC72 was moved. This date would have been the start of construction for Wing 1.0 under the original schedule.