UNLOCKING HYDROFOIL HYDRODYNAMICS WITH EXPERIMENTAL RESULTS.

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Hydrofoil sailing has been able to unlock performance characteristics previously confined to speed records, making them available to multiple racing fora. The America's Cup is now regularly sailed at 40 knots, Moth sailing dinghies and A-Class catamarans achieve up to 30 knots on standard race courses.

The systems employed to achieve these speeds have been refined to such an extent that high speeds are regularly attained. However, there are still large gaps in our understanding of the fundamental hydrodynamic phenomena to enable safe control of these machines and continued increases in performance. For example, arbitrary ventilation pathways have been noticed and yet are not fully explained.

This paper provides the means to unlock the methods of quantitatively establishing a pathway for arbitrary ventilation and for measuring the flow regime complexity around such foils. These two methods have been developed over many years by the collaborators mentioned in this paper. The result is a valuable contribution to capability available to the sailing research community. An additional two methods of experimental analysis have been detailed within the paper.

NOMENCLATURE

f	Filter frequency (Hz)
γ	Intermittency
L	Characteristic length, typically chordlength (m)
PIV	Particle Image Velocimetry
St	Strouhal number
U	Velocity (m.s^{-1})

1. INTRODUCTION

High efficiency sailing has taken on a whole new meaning in the last ten years. In 2003 the world sailing speed record over one nautical mile was 33.96 knots, since then the record has steadily risen until in 2012 65.45 knots was achieved by the UK built Vestas Speed Rocket. To achieve these speeds over a full nautical mile is a clear demonstration of wind powered vessels achieving great performance through efficiency. Sailing vessels now routinely achieve speeds in excess of the 2003 record over entire races of tens of nautical miles. Performance gains have primarily been achieved by reducing hydrodynamic drag through the application of hydrofoils to lift the boat out of the water.

Figure 1: Recent start line from 24th July 2016 at the Portsmouth leg of the 35th America's Cup Louis Vuitton World Series. The ability of sailing craft to stay on hydrofoils has now encompassed the entire race (Image from Land Rover MENA released under https://creativecommons.org/licenses/by/2.0/**)**

Figure 2: Image from the 34th America's Cup. The leeward foil piecing the free surface can be clearly seen. (Image from Tom Purves released under https://creativecommons.org/licenses/by/2.0/)

Hydrofoiling has become common place in the Moth dinghy class, in the America's Cup and in many other sailing classes. As can be seen from the start line assembled in Figure 1, foiling throughout an entire race can certainly be expected from the 2017 edition of the America's Cup. The foils employed will operate in highly loaded scenarios close to the free surface. Figure 2 clearly shows that the "L-foils" employed are designed to come in close proximity to the free surface due to the potential to further decrease drag. The complexity of the hydrodynamics in this mode of sailing brings in physical phenomena not yet encountered in sailing yacht research, such as cavitation, unsteady loads, transitional flow and vortex/free-surface interaction.

Sailing yacht hydrodynamic research has been dominated by large experimental programs in controlled facilities focussed on producing forces and moments required to reliably predict forward boat speed through velocity prediction programs [1-5]. These studies have inevitably spent considerable time and effort on understanding how those forces scaled [4, 6-10].

Hydrofoil research has been conducted over many years (see for example [11]), resulting in a good ability to characterise the flow over a range of hydrofoil shapes. Indeed research into sailing hydrofoils predates the 34th America's Cup [12, 13]. As with the numerous studies listed above, the hydrofoil studies have concentrated on accurately predicting the total forces in steady conditions. These forces are certainly required to get boats foiling, however, the stakes are lifted considerably when racing is considered. If the aim is to not only foil but to foil better than the opposition, a whole new level of understanding is required. It is fair to say from anecdotal evidence that the approach to getting this understanding has been heavily focussed on numerical techniques.

To advance our understanding of the complex hydrodynamic phenomena which directly affect how a boat hydrofoils, advanced experimental techniques and facilities are required. This paper details four such methods with detailed results from two.

2. METHODS

2.1. VORTEX/FREE-SURFACE INTERACTION

2.1.1. Background

The primary methods for investigating these phenomena in this paper have been experimental based initially on qualitative observations in an open water test facility and then on quantitative measurements in a controlled environment. From two of the authors' personal experience, catastrophic ventilation for sailing hydrofoils is an area that has little understanding and certainly cannot be prevented by simple addition of fences on the main strut.

For ventilation to occur a pathway from the atmosphere to the zone of low pressure must be established [14, 15]. This was first noticed by the first author in a series of student research projects resulting in a clear indication of a fully ventilated tip vortex which travels upstream and eventually engulfs the entire suction side of the hydrofoil. Figure 3 shows this phenomena both in a controlled environment of the towing tank and in a lake testing facility.

Figure 3 Ventilation of a T-Foil, left is simulated in the towing tank, right is at full scale speeds in a lake testing facility. Time is increasing from the top image to the bottom image.

2.1.2. Experimental method

The next step in this investigation was to conduct detailed experiments on the motion of a fully ventilated vortex core. To achieve this an adaptation of Particle Image Velocimetry (PIV) has been performed [16] such that results can be obtained on measurement planes which intersect the free surface. Analysis methods have been developed to identify vortex cores as they interact with the free surface. A carriage mounted dual cavity Nd:YAG laser with underwater sheet optics, and a sCMOS double shutter 16 bit camera (2560 x 2160 pixels), were used to capture 2D PIV data.

To increase accuracy images normal to the flow direction were captured using a PIV system with a free stream velocity of 0.4 ms^{-1}. To get these planes perpendicular to the vortex line a downstream camera was required, achieved with an inverted periscope arrangement shown in Figure 4 in addition to a fairing (not shown). This setup allows for the use of high quality optics with a high degree of easy access permitting high levels of control.

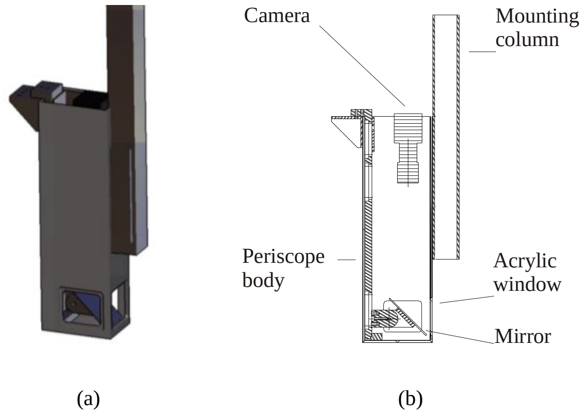

Figure 4. Carriage mounted periscope (a) 3D view (b) Section view

Each data set consisted of 128 instantaneous velocity fields captured at a frequency of 15 Hz, using an inter-frame interval of 2.5 milliseconds. With these settings and a light sheet thickness of approximately 4 mm it was estimated that 75% of particles would remain within the light sheet for each image pair. A 200 mm high by 300 mm wide field of view was obtained.

2.2. LAMINAR/TURBULENT TRANSITION

2.2.1. Background

The use of laminar flow sections in aero- and hydrodynamics has been widespread over a number of years. However quantifying the amount of laminar flow experimentally is extremely difficult due to:

- “a hostile environment which can damage instrumentation and prohibits detailed boundary layer traversing;
- the limited access points of full scale vessels, it is rare to be able to insert probes;
- the impractical nature of thermal probe calibration because of temperature variation between a controlled calibration environment and the naturally occurring experimental conditions; and
- the size and expense of full scale tests which precludes the conduct of a large number of tests.”[17]

The authors have developed a method which is applicable to a wide range of speeds and sufficiently robust to be installed in a number of full scale scenarios.

2.2.2. Post-processing

The analysis of the signal was conducted by a Kurtosis analysis as proposed by [17]. The response of a signal was defined as *3/K*, where *K* is the Kurtosis of the recorded signal. If laminar flow occurs *3/K* will be zero, as *K* for a flat signal is ∞, for an intermittent flow regime the unfiltered signal will achieve a maximum value of *3/K* of up to three due to the low frequency oscillation of a square wave oscillating between laminar and turbulent flow, while a fully turbulent signal will return unity for *3/K*. Subsequent to the applications of a high pass filter, the low frequency oscillations between laminar and turbulent flow regime are removed from the signal, and *3/K* can be interpreted as the laminar-turbulent intermittency. The high pass filter cut-off frequency was calculated to reduce the value of *3/K* to 0.5 at a position where a minimum of *K* occurred for the unfiltered signal, thereby removing the transitional oscillating component of the signal leaving just sections of laminar and sections of turbulent flow. A measure of intermittency can then be obtained by examining the filtered signal’s movement from very high *K* to a value of 3.

The advantages of this method are that no amplitude thresholds, turbulent time scales, nor any calibration are required for distinguishing between signals correlating to a laminar, transitional, or turbulent flow regime. In this particular research, the high pass filter frequency was determined for each sensor location separately for a range of speeds. An increase in signal oscillation frequency with increasing speed was evident over the wide range of speeds tested for the variation between turbulent and laminar flow. As such the filter frequency was required to be scaled with speed. Strouhal number ($St = f / (U L)$) was used to correlate flow velocity and filter frequency, where f is the filter frequency, U is the flow velocity, and L a linear length scale. Assuming a constant Strouhal number at each sensor, the high pass filter frequency scales linearly with speed ($f_{HPi} = f_{HPk} \times U_i / U_k$), where i indicates the individual sensor and k the sensor for which the high pass filter frequency was determined. This procedure ensures a consistent removal of the transitional flow without removing the statistically significant flow regime oscillations. The baseline filter frequency was estimated as a function of location on the foil and angle of attack. This procedure provides a robust method across many test sessions at wide speed ranges.

To utilize results across multiple speeds in a statistically meaningful manner, a curve fitting procedure was conducted to obtain a continuous result for interpolating and extrapolating the value of intermittency for speeds which have not been tested, or which have returned an invalid signal. The data was fitted to a hyperbolic tan function ranging from zero to unity: $\gamma = 0.5\tanh(aU + b) + 0.5$, where a and b are the fitting coefficients and U the flow velocity in knots.

2.3. UNSTEADY MOTIONS

The unsteady motions of hydrofoil vessels are certainly key to them flying on their foils and staying on their foils. This can be studied numerically and experimentally. The combination of both is likely to produce true breakthrough.

Publication of such studies is quite rare and generally confined to student research projects such as a numerical study produced by one author's student in [18]. In this study a simplified dynamic mesh was used to show oscillatory motions of a foil free to heave only. In this study a relationship between dihedral angle and heave oscillations was established for the confined motions analysed.

Experimental studies are perhaps where many America's Cup teams have headed such as those described in [19]. In this study it seems that a scaled down version of a foiling catamaran was used to produce unsteady motions with a human in the loop physical simulation.

2.4. CAVITATION

Modern numerical methods can certainly predict the onset of cavitation using a variety of methods. However, the complexity and the limiting factors of the assumptions required are shown by the most basic of 2D studies, see for example [20-22]. In these studies, the researchers have achieved very good agreement with experiments using very basic models on simplified geometries.

In contrast, experiments can encompass cavitation even up to the point of cavitation induced vibration [23]. Cavitation and its potential effects on high performance sailing hydrofoils is a prime example of an area that demands experimental methods to be employed to obtain meaningful results.

3. RESULTS

In the following sections results are presented for the first two experimental methods detailed previously. Results from the Team NZ study for the 34th America's Cup have not been made public. Results for the cavitation study are published in [23].

3.1. VORTEX TRACKING

Sample results for a surface piercing flat plate (a lifting surface) are presented in **Figure 5**. In these presentations velocity fields have been displayed 100 mm upstream of the trailing edge and 100 mm downstream of the trailing edge. These measurements have been obtained using the methods detailed in [16].

From **Figure 5**, the velocity fields clearly show the movement of the large vortex structure enabling the qualitative prediction of ventilation to proceed. Of particular note is the high velocity region (and hence low pressure region) on the top side of the vortex.

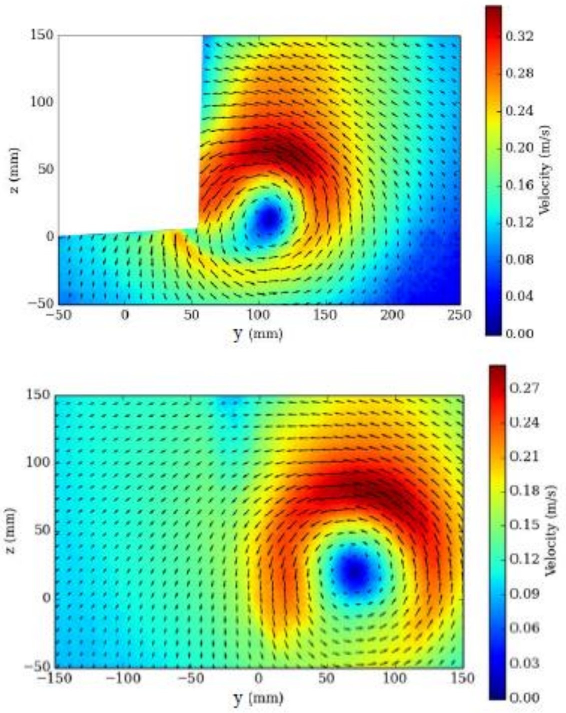

Figure 5 PIV obtained velocity fields from [16], showing the 2-D disturbance at the lifting surface 100 mm forward of the trailing edge (top image), and the disturbance 100 mm downstream of the trailing edge (bottom image).

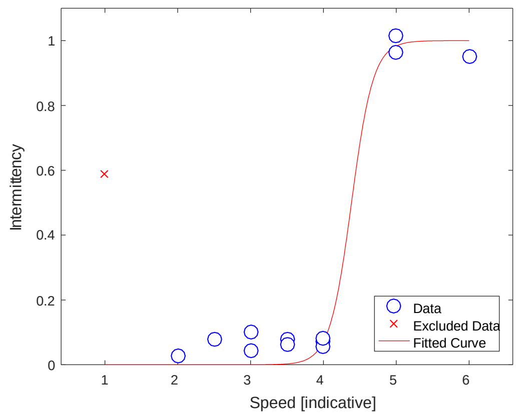

Figure 6 Intermittency for a range of speeds on the pressure side (when under +ve angle of attack) at a specific chordwise location. Data has been excluded where the Gaussian nature of the distribution has been corrupted by the digitisation process.

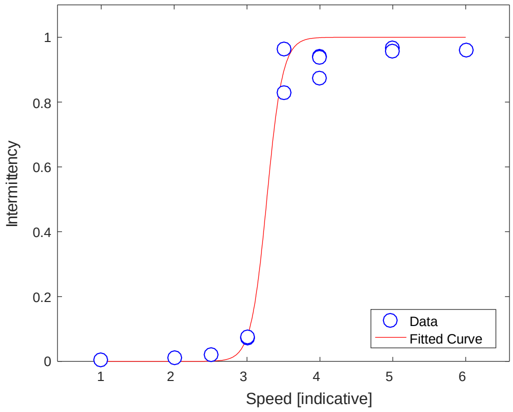

Figure 7 Intermittency for a range of speeds on the suction side (when under +ve angle of attack) at the same chordwise location as for Figure 6.

3.2. INTERMITTENCY

Sample results for a specific foil are shown in Figures 6 and 7. In these presentations the horizontal axis is the indicative full scale speed and the vertical axis is the intermittency. The results are shown for the pressure side (**Figure 6**) and the suction side (**Figure 7**) at the same chordwise location.

From **Figure 6** it can be concluded that the pressure side location is able to maintain laminar flow at a higher speed than the suction side (**Figure 7**), and has a slightly more gradual transition speed zone. This is in agreement with previous results [17] and shows for this case that the method has been successfully applied across the variation in vessel and operating conditions.

Such detailed experimentally based measurements are a critical design input. These results have been used to calibrate numerical models and provide instant design information.

4. CONCLUSIONS

The accurate analysis of sailing yacht dynamics requires analysis of a wide variety of boundary conditions and degrees of freedom [1]. The advent of hydrofoils has required this complexity to grow as dynamic heave and pitch have become critical. The complexity in such elements has necessitated a reliance on experimental research in the past, and in the future it will be the combination of experimental and computational efforts that will solve the pertinent problems of the industry.

In this paper we have demonstrated this through exploring four big questions. Those of tip ventilation, flow regime, vertical stability and cavitation induced vibration. To provide solutions to these areas, advanced experimental methods are being used to quantify:

- tip vortex motions;
- laminar/turbulent transition;
- hydrofoil stability; and
- cavitation and fluid structure interaction.

Two of the experimental methods focused on tip vortex tracking and flow regime measurements have been detailed further showing that useful design information can be obtained.

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REFERENCES

1. LARSSON, L., 'Scientific methods in yacht design', *Annual Review of Fluid Mechanics*, **22**(1): p. 349-385, 1990.

2. MILGRAM, J.H., 'Fluid mechanics for sailing vessel design', *Annual Review of Fluid Mechanics*, **30**(1): p. 613-653, 1998.

3. DEBORD JR, F.W., 'Review of the Current State-of-The-Art for Sailing Yacht Model Tests and Future Challenges Facing Testing Facilities', *Advances in Yacht Testing Technique. ITTC*, **87**, 1987.

4. HUTCHISON, C., BINNS, J., DUFFY, J., & BRANDNER, P., 'Model Testing-What is the point? A review of yacht testing and the implications for yacht designers', in *The 4th International High Performance Yacht Design Conference*, 2012.

5. DEBORD, F., KIRKMAN, K., & SAVITSKY, D., 'The evolving role of the towing tank for grand prix sailing yacht design', in *27th ATTC Conference*, 2004.

6. KIRKMAN, K.L. & PEDRICK, D.R., 'Scale effects in sailing yacht hydrodynamic testing', *Society of Naval Architects and Marine Engineers Annual Meeting*, 1974.

7. DEBORD, F. & TEETERS, J., 'Accuracy, test planning and quality control in sailing yacht performance model testing', in *Proceedings of the 1990 New England Sailing Yacht Symposium, The New England Section of The Society of Naval Architects and Marine Engineers*. New London, Connecticut, USA, 1990.

8. DEBORD, F., DOVELL, A., & EDWARDS, R., 'Extrapolation of sailing yacht model data to full scale', *Marine Technology Society, Houston*, 1985.

9. BINNS, J.R., KLAKA, K., & DOVELL, A., 'Hull-appendage interaction of a sailing yacht, investigated with wave cut techniques', in *The 13th Chesapeake Sailing Yacht Symposium*. Annapolis, USA: SNAME, 1997.

10. HUTCHISON, C., 'The use of hot-films to characterise flow regimes on a sailing yacht hull-guidance for scaling': University of Tasmania, thesis submitted for the degree of supervised by 2014.

11. WADLIN, K.L., SHUFORD JR, C.L., & MCGEHEE, J.R., 'Report 1232:"A theoretical an experimental investigation of the lift and drag characters of hydrofoils at subcritical and supercritical speed." 1952', *NACA RM L52D23a*.

12. BOSE, N., 'Model tests for a wind-propelled hydrofoil trimaran', *High-Speed Surface Craft*, **20**: p. 28-32, 1981.

13. BINNS, J.R., BRANDNER, P.A., & PLOUHINEC, J., 'The effect of heel angle and free-surface proximity on the performance and strut wake of a moth sailing dinghy rudder t-foil', in *The 3rd High Performance Yacht Design Conference*. Auckland, NZ: RINA, 2008.

14. SWALES, P., WRIGHT, A., MCGREGOR, R., & ROTHBLUM, R., 'The mechanism of ventilation inception on surface piercing foils', *Journal of Mechanical Engineering Science*, **16**(1): p. 18-24, 1974.

15. BARDEN, T. & BINNS, J., 'On the road to establishing ventilation probability for Moth sailing dinghies', in *18th Australasian Fluid Mechanics Conference*, 2012.

16. BRIGGS, A.A., FLEMING, A., OJEDA, R., & BINNS, J., 'Tracking the Vortex Core From a Surface-Piercing Foil by Particle Image Velocimetry (PIV) Using Fluorescing Particles', in *19th Australasian Fluid Mechanics Conference*. Melbourne, Australia: Australian Fluid Mechanics Society, 2014.

17. BINNS, J., ALBINA, F., & BURNS, I., 'Looking for ‘‘laminars": measuring intermittency on the America's Cup race course', *Experimental Thermal and Fluid Science*, **33**(5): p. 865-874, 2009.

18. IM, D., 'Optimising Dihedral Hydro foil "Investigation into the stability of dihedral hydrofoils"', in *Australian Maritime College*. Launceston, Australia: University of Tasmania, thesis submitted for the degree of Master of Engineering, supervised by A/Prof Jonathan Binns 2015.

19. WILKINS, I., 'Waka', in *Seahorse International Sailing*. Fairmead Ciommunications Ltd: UK. p. 9-11, 2013.

20. TAHER, A., KANFOUDI, H., ENNOURI, M., & ZGOLLI, R., 'Numerical Study of Unsteady Cavitating Flows around a Hydrofoil', *Journal of Applied Fluid Mechanics*, **10**(1), 2017.

21. BENXU, Y., LI, X., ZUCHAO, Z., LI, Y., & YUCHENG, J., 'Numerical study of unsteady cavitation on 2D NACA66 hydrofoil using OpenFOAM', in *2nd International Symposium of Cavitation and Multiphase Flow*: Zhenjiang, China, 2016.

22. PEARCE, B., BRANDNER, P., & BINNS, J., 'A numerical investigation of the viscous 2-D cavitating flow over a wall-mounted fence', in *17th Australasian Fluid Mechanics Conference*, 2010.

23. SMITH, S., PEARCE, B., BRANDNER, P., CLARKE, D., MOREAU, D., & XUE, Y., 'Steady and unsteady loads acting on a hydrofoil immersed in a turbulent boundary layer', in *20th Australasian Fluid Mechanics Conference (AFMC)*, 2016.

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