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Force and pressure investigation of modern asymmetric spinnakers

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Grant Spanhake

Thanks for letting me review your paper.
Great job, I found it very informative and helpful.

I do have some comments and questions on the paper.

Page 3, Table 1: I would suggest adding a Mid girth # or mid girth % to the table (See page 5 comments).
3.3: It would be good to see a close up photo of the pressure taps.
3.3: At a later date it would be good to see the results of (Twisted vanes verses non-twisted).

Page 5, Figure 4: I found it interesting that the A-3 Cx SA forces does not increase at 10 degrees of heel like the other sails. I can only think the reason for this is that the wider mid-girth (reason for adding it to Table 1) may interfere with the mainsail/Slot/up-ward flow?

Page 7: One good addition would be add the timing of the flaps eg below. This will give a sail trimmer some practical guidelines and consistency.

Kite out(1) –in (7)	# of flaps per 10 sec's	Cx	m/s	Comments
1	10	0.95	3.5	Sail very un-stable
2	5	1.0	3.5	Sail just flicking
3	1 (Curling)	1.05	3.5	Sail curling
4	0	0.9	3.5	Sail stable
5	0	0.8	3.5	Start to be over-trimmed
6	0	0.6	3.5	Over-trimmed
7	0	0.3	3.5	Over-trimmed

Page 8, 4.5: "*In the present investigation it was found that with the A1 and the A2 the same maximum drive force could be achieved both by flapping and non-flapping luffs. For instance, in Figure 9 and Figure 10, trims #1 and #3 show a similar drive force but the luff was flapping in trim #1 and not in trim #3.*"

I suspect that this could be explained with the red items above. I had originally thought that the reason for this may have been, that the wind speed was set too high. But at 3.5 m/s (6.80 TWS) I don't think this is the case.

Conclusion: I would believe your findings and conclusions based on real world on the water and wind tunnel experience.
It would be interesting to further investigate the following.

a) Twisted vanes verses non-twisted.
b) Flicking luff verses curling luff

c) Keep the same sail area and increase/reduce the mitre depth at 400 to see if there is a sweet spot.

Thank you

William Lasher

The authors present a very nice investigation of asymmetric spinnakers by providing detailed surface pressure measurements and analyzing them from both a flow and overall force perspective. Their discussion regarding the effect of luff flapping on the pressures and forces was particularly interesting, as this has an important impact on sail trim. I am curious as to why the flatter spinnakers produced a higher drive force when over trimmed (trim #2), whereas the fuller spinnaker did not. Is it due to a higher peak suction pressure for sail A3, or a larger delay in trailing edge separation compared to sail A1? Perhaps an overlay of the Cp difference from sail A1 onto Figure 11 would help to answer this question.

Also, was there anything in the pressure measurements that explains the results shown in Figure 4? Specifically, why does the drive force increase for sails A1 and A2 at 10 degrees heel, and decrease for sail A3? I recognize that this may be difficult to determine from pressure measurements alone, but any comments from the authors would be appreciated.

Robert Ranzenbach

The authors are to be congratulated on their meticulous effort to obtain pressure measurement data on a flexible membrane like an asymmetric spinnaker. As noted in the paper, much of the experimental evidence collected to date has been focused on global aerodynamic forces and this additional data will prove invaluable to our understanding of the underlying physics of asymmetric spinnakers and to anyone interested in validating their CFD predictions of this complex, three-dimensional, separated flow.

Not only does it appear that great care was taken to collect data, it is clear that the authors took great pains to present the results in a compact but meaningful fashion as evidenced by Figure 6 which is an especially good qualitative representation of the pressure results and provides an excellent template for any subsequent CFD validation efforts that might follow.

I do feel compelled to comment on one additional element of the paper. I understand that Figures 9 and 10 are an amalgam of results, Cx and leeward side pressure from sail A1 but windward side pressure from sail A3. The presentation may have been better served if the leeward side A1 and windward side A3 pressure results had been shown on different graphs rather than relying upon the undocumented assertion that the windward side pressures are very similar for every trim setting. In addition, greater comment might be offered by the Authors on the important differences that are evidenced on the windward side between trim condition #1 which shows the windward side Cp varying greatly from the nearly constant value of 1 that dominates the results for nearly every other trim condition. It also seems that these results are not consistent with a claim made earlier in the paper regarding the Cp maximum being equal to or less than 1.0 everywhere.

I am sure that like me, others in the sail testing/design community will look forward to the next installment promised by the authors to discuss how twisted flow changes the pressure distribution on the spinnaker. I personally hope that they will not limit their data collection

and analysis to only one uniform and one twist profile so that the impact of varying twist profiles may also be illuminated.

Michael Richelsen

I would like to applaud the authors for their work and bringing it into the public.

The measured pressure sections help understand the amount of attached flow on the sails. This is valuable not just for feeding back information from a test to the sail designer, as it also allows for more detailed comparison with CFD results. Without the pressure measurements CFD results can only be compared on the basis of total forces whereas now, given measured section pressure values, one can get a better understanding of how well the simulated flow field in the CFD matches the tunnel flow. This is a valuable aid in improving CFD based predictions, which is becoming another tool for evaluating the performance of a sail design.

Obviously to do such a tunnel versus CFD comparison one will also need to obtain an accurate 3D geometry of the flying shape corresponding to a set of pressure measurements. Presumably the tunnel at the Auckland University already has capabilities in this field, either by laser scanning or photogrammetry ?

Ignazio Maria Viola & Richard Flay

Thank you for the generous comments and the very interesting points highlighted. The sail aerodynamics is still far from being fully understood and we hope that this paper answered some questions, but we are conscious that it also raised many other questions.

The large amount of data collected in the presented experiments couldn't be fully discussed due to the restricted space available. Hence, a new manuscript titled Pressure Distributions on Modern Asymmetric Spinnakers has been submitted to the Journal of Small Craft Technology, where the pressure distribution on five sections of the three sails is discussed.

In particular, the effect of the twisted flow is discussed. The pressure measured on three horizontal sections of the sail A3 sailing at 55° AWA and 10° heel, both with and without the twisted flow, is presented. With regard to the question raised by Robert Ranzenbach, only one twisted flow profile was tested due to the time demand of the test.

The effect of the heel on the pressure distribution over the five sail sections is discussed, which shows the strong three-dimensionality of the phenomena. For instance, heeling the A2 by 10° causes the pressure to increase on the highest sections, and to decrease on the lowest sections. Some hypothesis and some possible interpretations are highlighted. With regard to the comment by Grant Spanhake, the different behaviour of the three sails can be due to the mid-girth interference with the mainsail. The mid girths of the A1, A2 and A3 are 1.21m, 1.35m, and 1.61m respectively. Hence, the A3 has the maximum absolute mid girth and also the maximum mid-girth/foot ratio. However, the deeper mitre and the longer sections can significantly affect the complex three-dimensional phenomena, which can explain the opposite trend of the A3 compared to the A1 and A2. Moreover, heeling the model, the spinnaker sheet can be eased without causing the sail to collapse. The sheet ease changes the sail geometry, which is correlated with the force increase. Hence, the way the geometry changes can also explain the trend differences.

Some clarifications are necessary about the flapping and non-flapping trims. With regard to the comment by William Lasher, the non-flapping luff leads to a significant force reduction in the A3 because it is correlated to a significant increase in separated flow. In fact, figure 11 of the paper shows the separation point of the A3 moving from roughly the 60% of the chord to roughly the 50% of the chord, when the sheet is tightened to stabilize the luff. The anticipated trailing edge separation leads to a significant reduction of the suction after the turbulent reattachment. Conversely, the flapping and non-flapping trims of the A1, named trim #1 and #3 respectively in figure 10 of the paper, show similar pressure suction and trailing edge separation. In particular, with regard to the comment by Grant Spanhake, the luff flaps at 1.4 Hz in trim #1, while does not flap in all the other trims. Figure 1 shows the auto-correlation of the pressure signal measured on the leeward side at the leading edge for the three trims #1, #2 and #3.
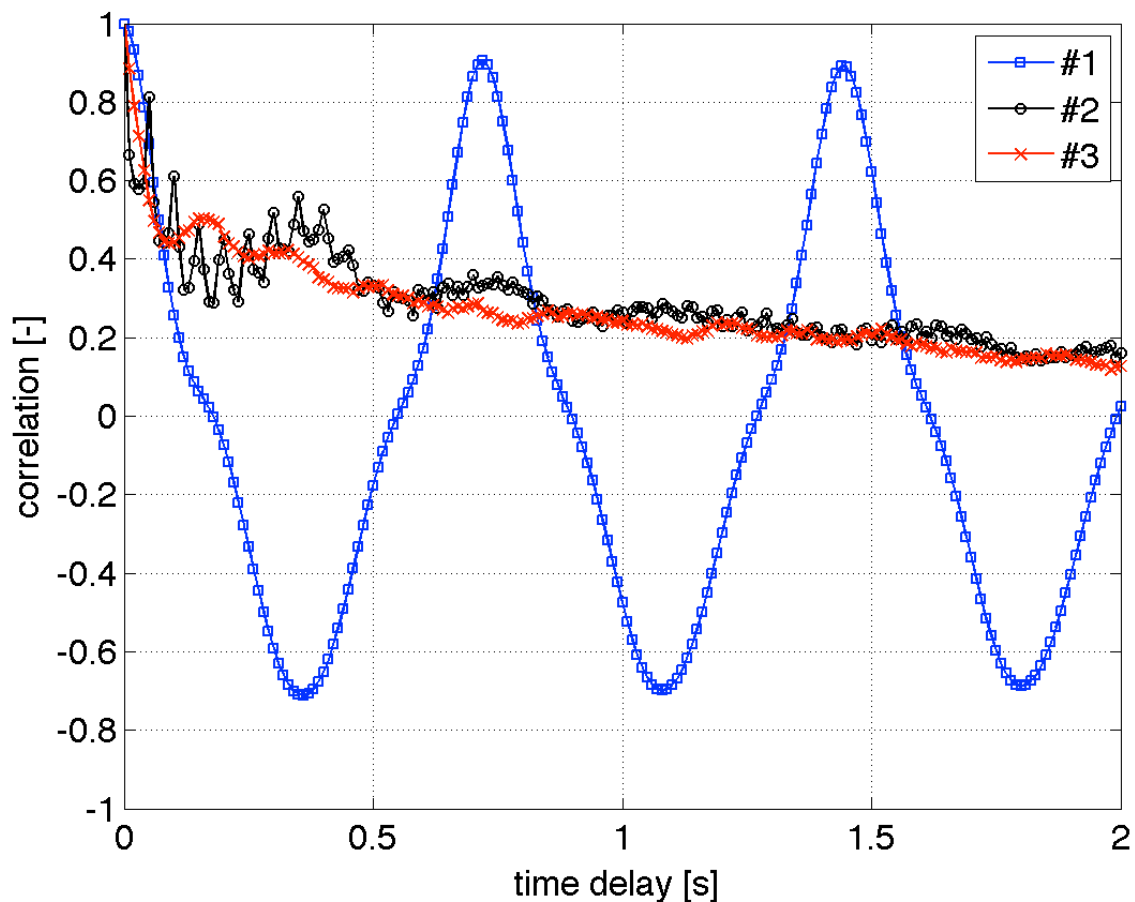

Figure 1: Auto-correlation of the pressure signals for three trims.

The drive force achieved by trim #1 is lower than the drive force achieved by trim #2. However, in the unstable full-scale condition, trim #2 and trim #3 might be unrealistic, because to stabilize the luff, the sheet has to be tightened significantly (as in trim #4). Hence, in full-scale condition the flapping trim would result in a larger drive force than the non-flapping trim.

With regard to the comment by Robert Ranzenbach, the pressure coefficient measured on the windward side of the A3 is presented on figure 10 of the paper for four trims, named #1, #3, #5 and #7 respectively. The luff is flapping in trim #1, while the sheet is tightened enough to stabilize the luff in trim #3, and it is over-trimmed in trim #5 and #7. When the luff is not flapping, the pressure coefficient is almost one over the whole section, id est at

the same pressure of the stagnation point. When the luff flaps, the stagnation point moves from the windward to the leeward side and vice versa repeatedly. When the stagnation point is on the leeward side, the pressure coefficient over the windward side should be lower than one, due to the higher velocity of the flow. Hence, a flapping trim leads to two values of the pressure coefficient: one when the luff is straight the pressure coefficient is almost 1.0, and another when the luff is curled the pressure coefficient is lower than 1.0. The pressure coefficient during flapping trim results in the average of these two values, which would be lower than 1.0. In fact, the pressure coefficient correlated to trim #1 is roughly Cp=0.7.

With regard to the comments by Michael Richelsen, the test was performed also with the aim to provide suitable CFD benchmarks, and cameras recorded each trim from many points of view to allow the flying shapes to be post-processed with photogrammetric technique. The Yacht Research Unit is consistently investing in flying shape detecting systems, and is developing a real-time photogrammetric system named VSPARS, which is already used for commercial testing, and increasing the capabilities of an existing devoted laser scanner.

With regard to the comments by Grant Spanhake, figure 2 shows one of the pressure tap adopted. The tap is a truncated cone with a rectangular base, the base of which is 17x10 mm^2. The transparency of the material allows the hole on the base to be seen, and is connected with a stainless steel tube to a plastic pressure tube.
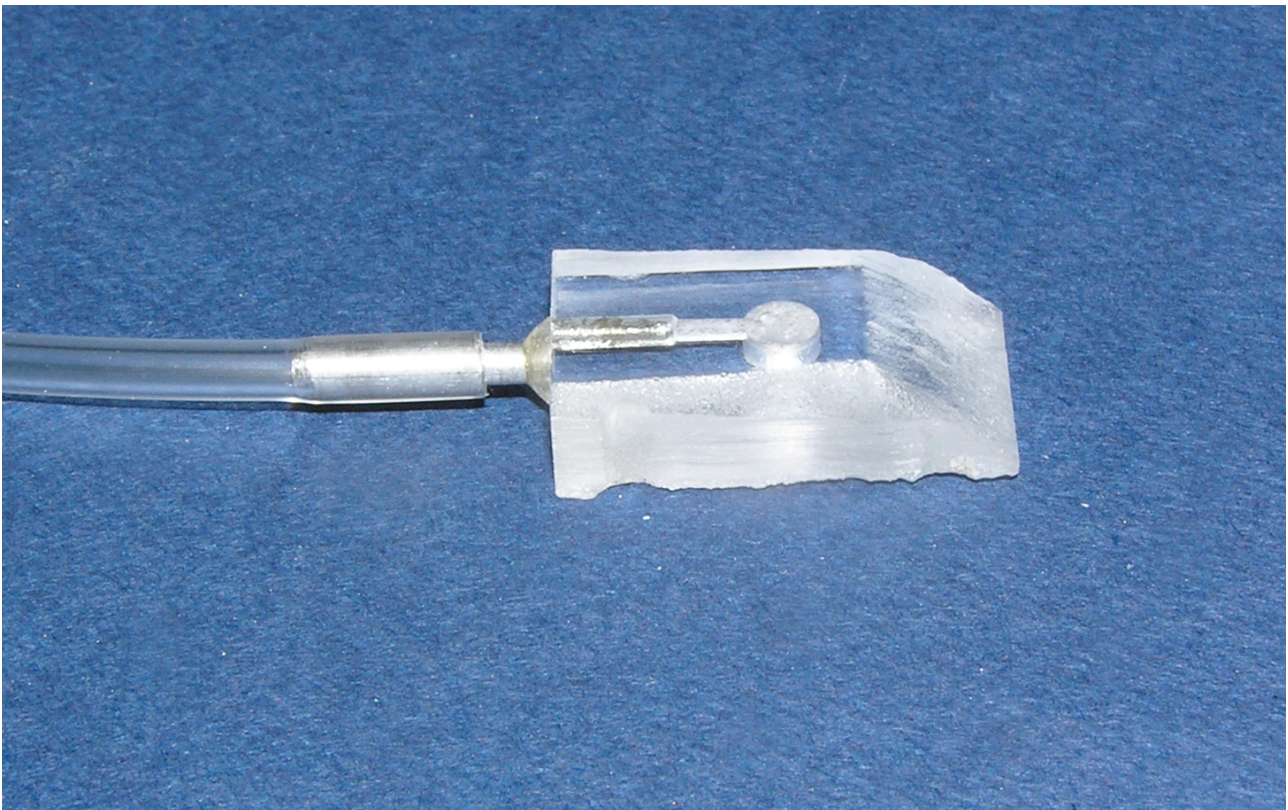

Figure 1: Photograph of the pressure tap.

We thank the reviewers for their insightful and interesting comments about our paper. We will take note of their input in our future research on this topic.