Photogrammetry Based Flying Shape Investigation of Downwind Sails in the Wind Tunnel and at Full Scale on a Sailing Yacht

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ABSTRACT

This paper describes model and full scale measurements of the flying shape of spinnakers that have been developed for a 38' c/r yacht. The flying shape measurement principle was based on photogrammetry. Motivation behind this study was to investigate and compare the flying shape as obtained in the wind tunnel and at full scale. While flying shape measurements in the wind tunnel are straight forward to do providing quite accurate results, respective measurements at full scale in natural, stochastic environment turned out to be challenging. As a result of the comparison it can be shown that flying shape at full scale and model agrees well for given trim settings of the spinnaker, while trim settings for driving force optima where quite different.

NOTATION

Abbreviations:

DOF:	Degrees of Freedom
TFWT:	Twist Flow Wind Tunnel
NURBS:	Non Uniform Rational B-Spline

Symbols:

AWA:	Apparent Wind Angle
AWS:	Apparent Wind Speed
TWA:	True Wind Angle
TWS:	True Wind Speed
AX	Driving Force Area
AY	Side Force Area
x, y	Image Coordinates
x_0, y_0	Coordinates of perspective centre of image
X, Y, Z	Object coordinates in space
X_0, Y_0, Z_0	Coordinates of perspective centre in 3D space
n	Exponent for boundary layer power law
SL	Spinnaker Luff and Leech Length
SMW	Spinnaker Mid Width
SF	Spinnaker Foot Length
P	Main Luff Length
E	Main Foot Length
IM	Jib Head to Deck distance
J	Foresail triangle base length
$MG[LMUT]$	Main Girth Lengths
HB	Main Headboard Length
z	Height above water plane

INTRODUCTION

Wind tunnel testing of downwind sails is widely accepted as an efficient tool for spinnaker design for contemporary sailing yachts. It is conducted to generate aerodynamic information for subsequent sailing yacht velocity prediction, actually to generate the set of aerodynamic coefficients, describing the flow forces the sail generates. In addition, wind tunnel testing allows obtaining the flying shape of spinnaker, i.e. the shape the spinnaker will take under wind load and trimming, see for example (Graf and Mueller, 2009). Flying shape measurements provide a means to analyze the aerodynamic properties of a spinnaker in detail. It helps to understand the conversion from design shape – the shape the sailmaker actually defines – to the flying shape and thus helps to design better sails. It also helps the sailors to understand how to trim the sail to obtain maximum performance.

As ever model testing has severe drawbacks. In the case of wind tunnel testing of sails a couple of rules of similitude are violated. Beside a far too small Reynolds number (typically Rn=4.5e6 for a 38' sailing yacht versus Rn=0.3e6 for a model of span 1.85m), usually neither the ratio of fabric weight to wind pressure nor the ratio of membrane stresses to wind pressure in the wind tunnel matches those values in reality. Since all these characteristics have an impact on the flying shape of the sail, some doubts arouse, whether or

not the flying shape in the wind tunnel matches the one obtained in full scale.

This paper reports about a study, trying to enlighten this problem. In cooperation with a sailmaker (Holm Sailmaker GmbH, Germany) a series of symmetric spinnakers for a 38' c/r yacht has been investigated in the wind tunnel. For the one showing best properties, a full scale replica has been build. Flying shape measurements of this spinnaker in model and full scale have been conducted under various wind conditions. The measurement principle is based on photogrammetry. Comparisons of model and full scale results will be presented.

FLOW FORCE AND FLYING SHAPE MEAS-UREMTS IN THE WIND TUNNEL

The wind tunnel of YRU-Kiel and procedures for spinnaker tests including flying shape measurements have been described by (Graf and Mueller, 2009). YRU-Kiel's Twist-Flow Wind Tunnel is an open-jet wind tunnel, powered by two axial fans for a maximum wind speed of 10 m/s at the measuring area, Fig. 1. Rectifiers, screens and twist vanes are used for proper flow conditioning, realizing the height dependent flow speed and direction, a sailing yacht encounters on a downwind course. Maximum mast height of the model is about 1.8 m. The model is mounted to a turntable, allowing arbitrary apparent wind angle of 0° to 180°. A 6-DOF force balance is fixed to the turntable.
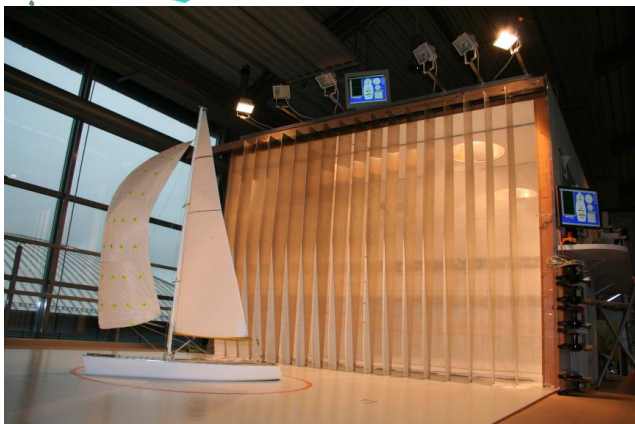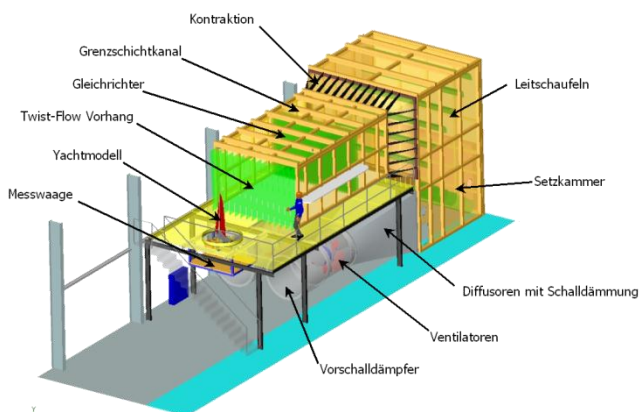

Fig. 1: TFWT of the YRU-Kiel

The model is equipped with stepper motors controlled by PC-based virtual activators in order to trim the sail. The following sheets and haulers are available:

- Main-Sheet
- Boom vang
- Spinnaker-Sheet
- Spinnaker-Aft guy
- Spinnaker pole vang – Top lift
- Spinnaker-Barber hauler

Photogrammetry

The principle method of photogrammetry to obtain the 3D-shape of a flying spinnaker in the wind tunnel is based on four components: a couple of images are taken from the sail simultaneously by digital cameras. The sail is equipped with a larger set of markers at discrete points in the sail. A chain of software tools are used to improve brightness and contrast of the image, to automatically detect the markers in the sail and finally – the kernel algorithm of the photogrammetry – to convert 2D coordinates of individual points in the images into 3D coordinates in an absolute frame. Finally these points are lofted to create spline curves, which in turn are lofted to create a NURBS surface.

Setup in the wind tunnel

The method presented here uses four digital cameras *Canon EOS 350D* with a resolution of 8 million pixels and a zoom lens 17-85 mm focal distance. Fig. 2 shows arrangement of the cameras in the wind tunnel measurement section. Usually the camera location has to be adapted to a range of apparent wind angles of the model. However it can be chosen freely and the actual location of the camera has not to be known for proper shape detection.
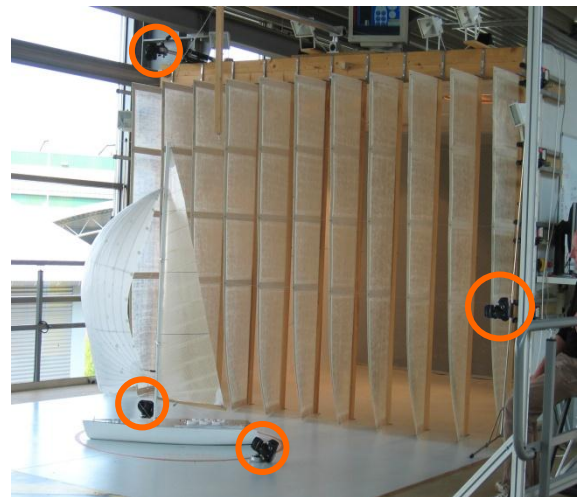

Fig. 2: Camera arrangement in wind tunnel

The cameras are connected to a PC using the USB data bus. In addition they are equipped with a central trigger, allowing simultaneous triggering of any camera. This is

quite important, since the sail vibrates under wind pressure. From an estimated frequency and amplitude of this unsteady motion of the sail a maximum exposure time of 1/80 sec has been derived.

The sail is equipped with a larger number of markers. These markers are distributed over the sail surface such that a smooth surface can be generated from the cloud of marked points. Usually 50 to 60 markers are used. The software system used in this setup allows automatic detection of markers. The pattern recognition algorithm behind this automatic detection needs so called *coded targets* as markers, having a diameter of approximately 25 mm, see Fig. 3. These markers are 12 bit coded allowing a theoretical number of 4096 different markers.

Fig. 3: Coded Targets

In addition to the markers on the sail, some markers are fixed to the model in order to define a local coordinate frame. Fig. 4 shows a symmetric spinnaker of an IMS 600 model, equipped with coded targets. Note the markers for the coordinate frame on the foredeck of the model.

Fig. 4: Symmetric spinnaker equipped with 55 coded targets

This setup has successfully been used for a large number of different spinnakers, among them runners for very deep courses as well as flat asymmetric spinnakers for quite low apparent wind angle.

The measurement of the flying shape is well integrated into a standard measurement run: a particular apparent wind angle is chosen, the sails are trimmed for maximum driving force and then the forces and moments generated by the entire sail set are scanned. The photos are taken within the force scanning period, which usually lasts approximately 10 sec. The cameras are equipped with 1 GB memory cards, allowing to take images for an entire range of investigated apparent wind angles.

For the shape finding process *Photo Modeler Pro* (PMP) of *EOS Systems Inc.* / Canada is used. PMP is a MS-Windows based software with a graphical user interface. It includes the kernel photogrammetric algorithm which generates a 3D point cloud from identical (2D) points in a couple of images taken from the sail from different views. PMP can take into account an arbitrary number of different views / images. Two images are the minimum, if camera positions are known a priori, three images are the minimum, if the camera position shall be calculated automatically by the system. Any additional image increases accuracy. Tests show that for our purpose four images of the sail are sufficient.

PMP generates a set of points in 3D space. This set can be exported as tabulated data or as IGES file, and in turn imported into a surface modeling system. For this purpose *Rhinoceros 3D* of *McNeal Inc.* is used.

FLYING SHAPE MEASUREMENTS AT FULL SCALE

For the full scale flying shape measurement the same measurement principle has been used. Four cameras take images simultaneously while the spinnaker is set on the sailing yacht. These cameras are located on four tenders sailing around the yacht at predefined positions, moving with the same speed as the yacht. Attempts to place one or two of the cameras on the yacht itself have been abandoned after some tests. It was simply not possible to take camera shots from aboard showing a reasonable large number of markers on the sail. With respect to camera positions at full scale the main difference to the wind tunnel testing was that all cameras obviously have to be located close to the water surface.

Transformation from the wind tunnel situation was used to define a general setup for the distribution of the tenders around the yacht, see Fig. 5.
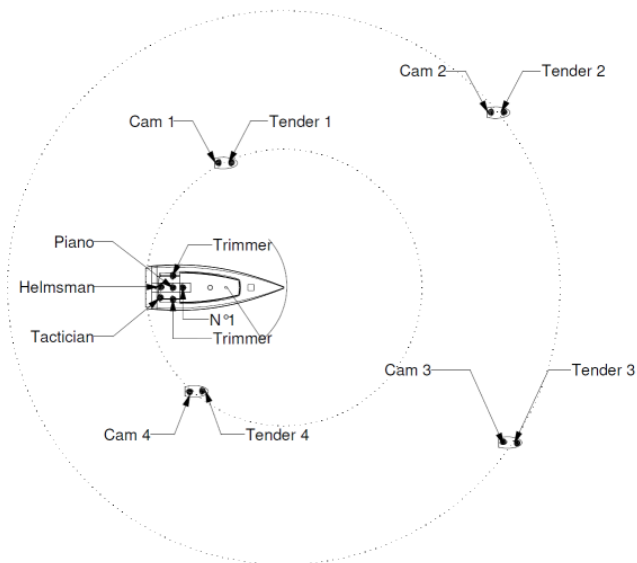
Fig. 5: Arrangement of tenders around the yacht

The PMP-method allowing taking images from arbitrary position as long as at least three images are used for shape finding provides some freedom in the actual position of a tender relative to the yacht. In general the photographers were told to watch for a particular image contents to obtain a particular position.

For the full scale tests only conventional markers rather than coded targets were used for the sail surface, simply because coded targets are complicated to apply to the spinnaker. However due to good light conditions in full scale even simple markers were detected automatically by the pattern matching algorithm of PMP.

Fig. 6 shows the yacht sailing at apparent wind angle of AWA=120°, image taken from camera position 3 as to Fig. 5, Fig. 7 showing the same from camera position 2 and 4. Note markers at the guardrail for reference coordinate system.

Fig. 6: Spinnaker with non-coded markers, camera pos. 3

Fig. 7: Images from camera pos. 2 and 4

The main challenge of the field measurements has been to cope with the stochastic behavior of wind conditions in natural environment. While in the wind tunnel constant laboratory conditions prevail for some time and accurate flow force measurements allow to find an optimum, in full scale field tests the amount of time to trim the spinnaker for optimum driving force is limited, wind conditions change frequently and finding of what is regarded to be an optimum trim has a strong human factor.

Measurements took place in the inner part of the Kieler Förde where flat water could be expected. The following procedure has been applied:

- Move to the starting point of a measurement run, where constant wind conditions prevail.
- Set spinnaker, find an apparent wind angle that can kept constant for a couple of minutes. Trim the spinnaker for optimum boat speed.
- Call the tenders to obtain their intended position around the yacht.
- Trigger a simultaneous shot of all cameras with an acoustic signal, read wind conditions, boat speed and heel from nautical sensors and define a qualitative assessment of this measurement ("good", "sufficient", "instationary", …)
- Repeat the triggering up to four times.
- Find a new location and a new apparent wind angle and repeat entire procedure.

Following this procedure, a total of 80 test runs were done successfully, which were distributed over a range of apparent wind angle 80°<AWA<160° and 1.5 m/s<AWS<5m/s according to Fig. 8. The duration of the measurement campaign was 9 h, divided over 3 days, not taken into account some initial tests to develop the measurement setup.
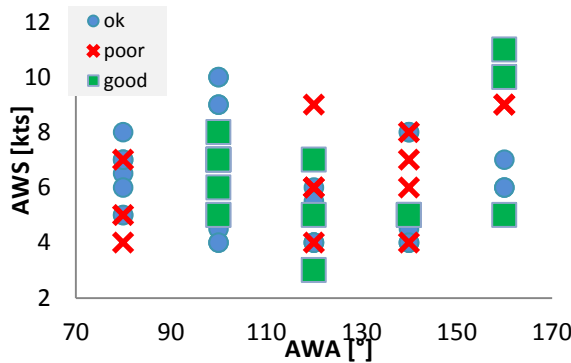
Fig. 8: Test conditions at full scale

SPINNAKER MODELS

Two series of 8 symmetric molds have been developed for this investigation. The first series focuses on the total size of the spinnaker for given leech/luff and foot length, leaving the spinnaker maximum width as the variable parameter. Shape A4-mod emerged from A4 by manual manipulation after visual inspection (fixing wrinkling using scissor and tape).

The second series consists of only small variations of A4-mod. A generic mold has been developed for A4-mod in order to make use of it in full scale within a sail lofting program (A5). Variations of A5 differ only very marginally in the topmost part of the spinnaker. When designing these alternatives, the target was to have a very flat, as

broad as possible head without the tendency of the spinnaker to collapse early.

	Name	SL	SF	SMW	Area$_{Holm}$	Area$_{Calc.}$	SMW/SF
		[mm]	[mm]	[mm]	[m²]	[m²]	[-]
Serie 1	A1	1430	720	700	0.88	0.948	97%
	A2	1426	808	963	1.15	1.239	119%
	A3	1430	808	808	1.01	1.086	100%
	A4	1430	808	880	1.08	1.159	109%
	A4-mod	1430	808	808	1.01	1.086	100%
	A5	1430	808	880	1.06	1.159	109%
Serie 2	A6	1430	808	820		1.098	101%
	A7	1430	808	820		1.098	101%
	A8	1430	808	820		1.098	101%

Fig. 9: Model Spinnaker Dimensions

WIND TUNNEL FLOW FORCE RESULTS

The spinnaker have been tested in wind velocity of 5 m/s at mast top and a total twist angle of approximately 15°. The spinnakers were trimmed for maximum driving force.

Fig. 10 shows driving force area and side force area AX and AY over apparent wind angle AWA. Here AX is defined as:

$$AX = \frac{FX}{\frac{1}{2}\rho\,AWS^2}$$

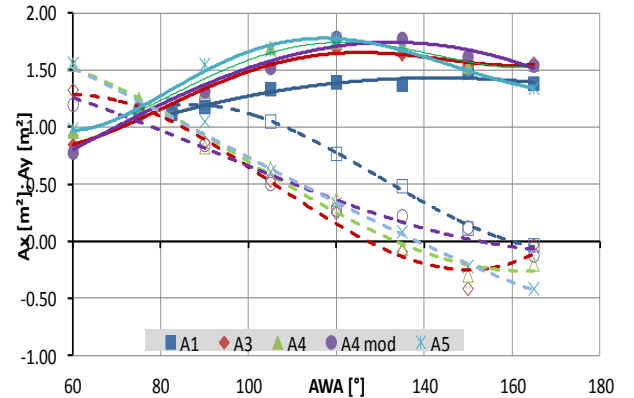where FX is the measured flow force in yacht longitudinal axis.

Fig. 10: Wind Tunnel Force Measurement Results Series 1

The result clearly shows that neither the maximum sized spinnaker gives best performance on deep courses nor the most slender spinnaker on hot course. A4-mod did show the best overall performance. It provided the most driving force on deep courses, while being close to the best spinnaker with respect to driving force on hotter courses, albeit at significantly lower side forces than the spinnaker A5, providing maximum driving force at hot courses.

Variations of A4-mod have been tested in a second series, the result shown in Fig. 11. Here the differences are very

small as expected. The small variations of the topmost part of the spinnaker showed some impact on the dynamic property of the shape, which has been observed visually only.

Finally the shape A7 has been identified as the top-scorer in the test field, providing the best compromise on flow forces and dynamic behavior. This spinnaker then has been produced in full scale (scale factor 11) to be used for the full scale flying shape measurements.
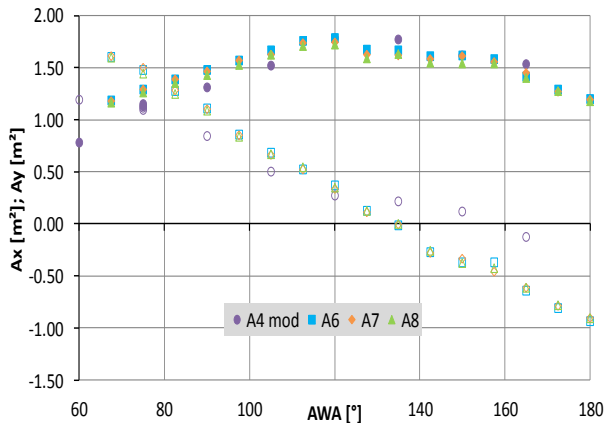

Fig. 11: Wind Tunnel Force Measurement Results Series 2

FLYING SHAPE IN THE WIND TUNNEL AND AT FULL SCALE

Flying shape measurements in model and full scale have been carried out with the spinnaker shape A7 at apparent wind angles of AWA=80°, 100°, 120°, 140° and 160°. The comparison is shown in the following diagrams.

In this study wind tunnel flying shape measurements have been done after completion of the full scale flying shape measurements, in order to maintain comparable conditions. Here it turned out, that there are actually three modes of comparison:

Mode I comparison: In the wind tunnel spinnaker pole height and angle with respect to yacht center line is set to the respective values at full scale. The same holds for spinnaker sheet length and sheet lead position. Spinnaker clew is free to move under sheet constraint.

Mode II comparison: Spinnaker pole is set as under Model I, however the sheet-length is varied to search for maximum driving force.

Mode III comparison: Starting from the trim as in Mode I the model spinnaker has undergone a full optimization, i.e. a full re-trim of spinnaker pole and sheet length.

Fig. 12 to Fig. 22 show the flying shape of model (scaled to full size) and full scale spinnaker for the range of AWA=80°, 100°, 120° and 160° and all three modes of comparison.

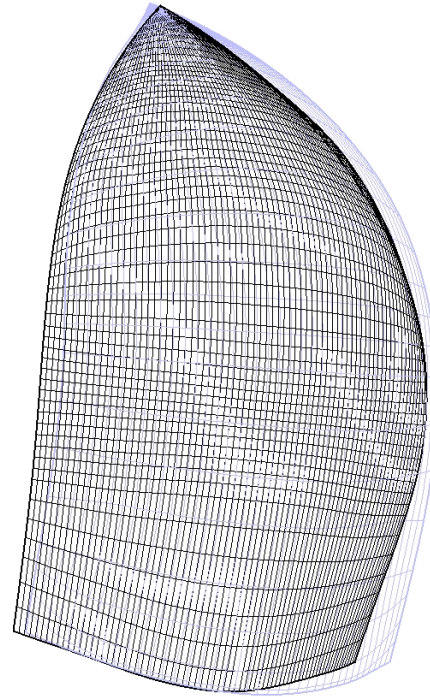Fig. 23 to Fig. 27 show contour plots of the Mode I comparison.

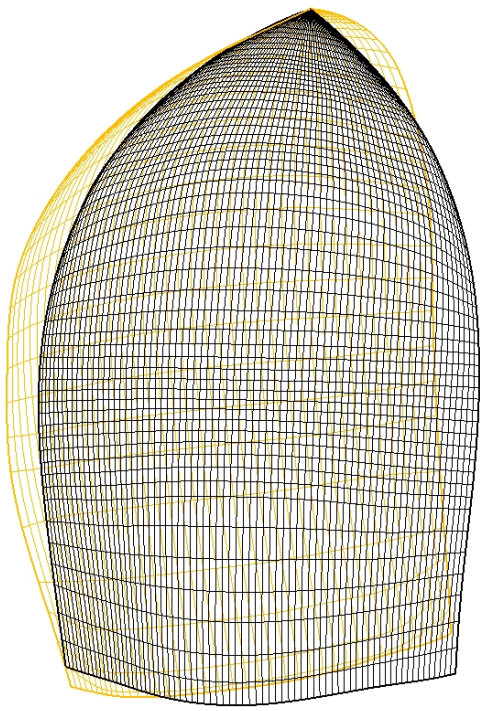Fig. 12: Mode I comparison at AWA80°

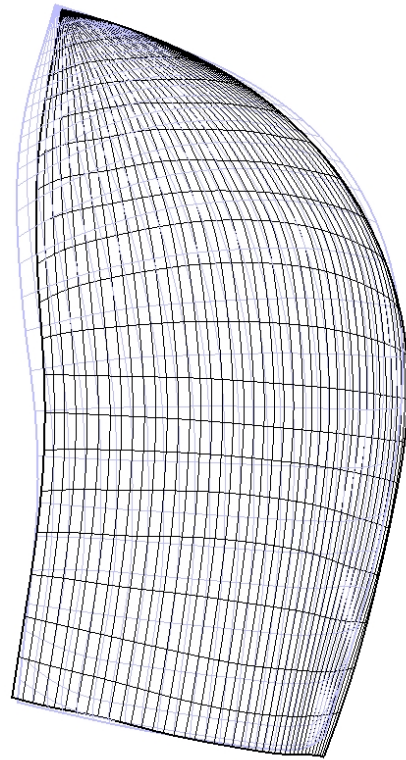Fig. 13: Mode II comparison at AWA=80°
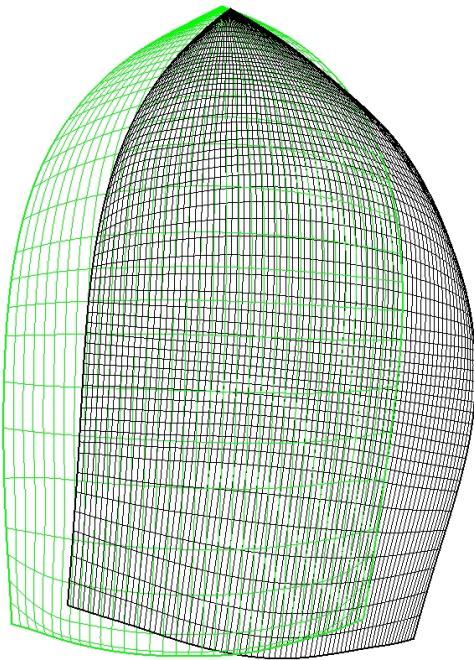

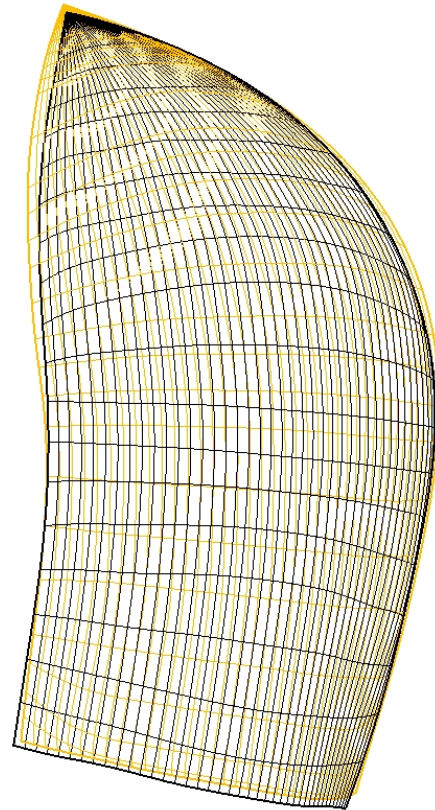Fig. 15: Mode I comparison at AWA=100°

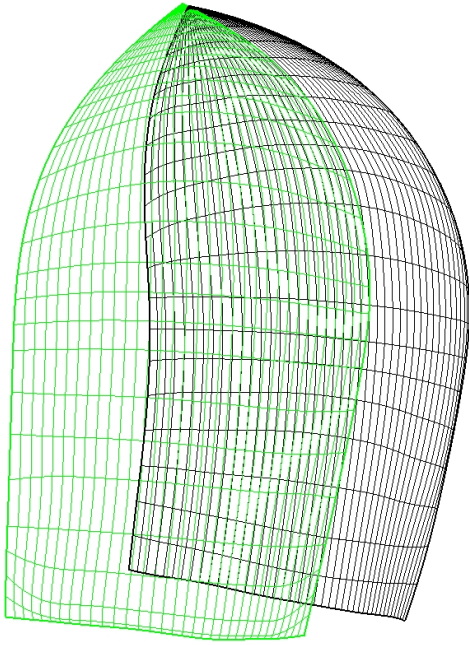Fig. 14: Mode III comparison at AWA=80°

Fig. 16: Mode II comparison at AWA=100°

Fig. 17: Mode III comparison at AWA=100°

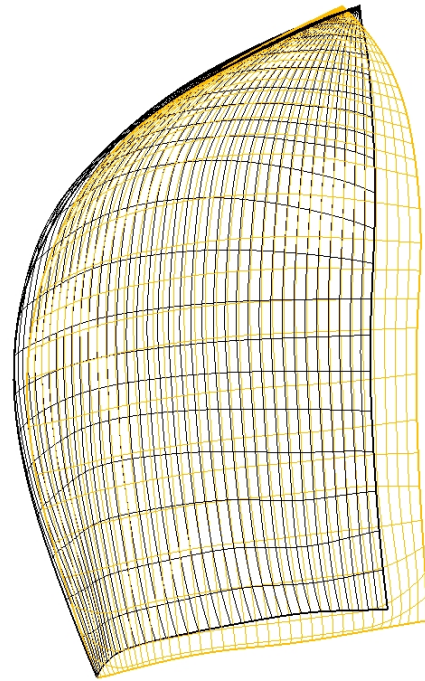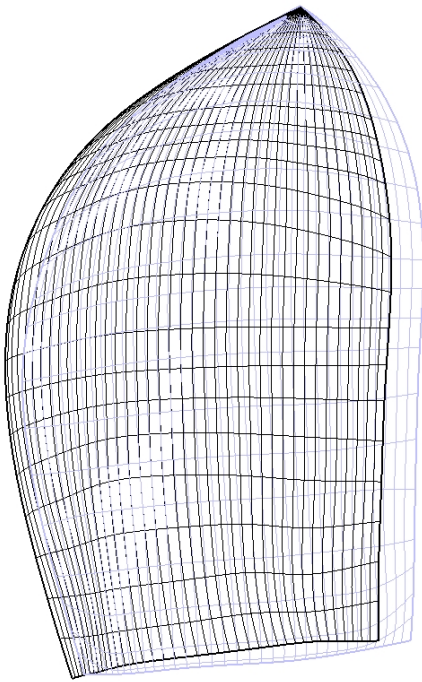
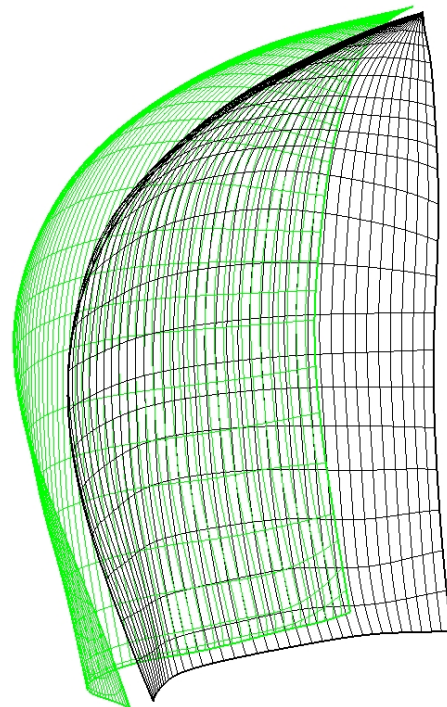Fig. 19: Mode II comparison AWA=120°

Fig. 18: Mode I comparison AWA=120°
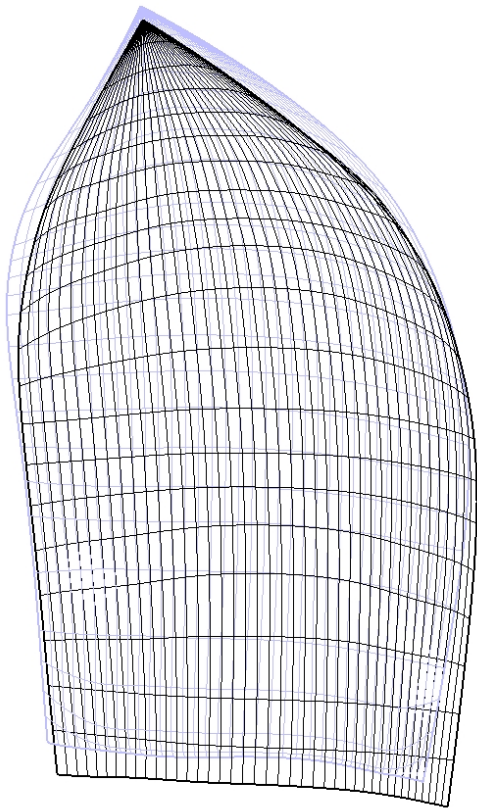

Fig. 20: Mode III comparison AWA=120°
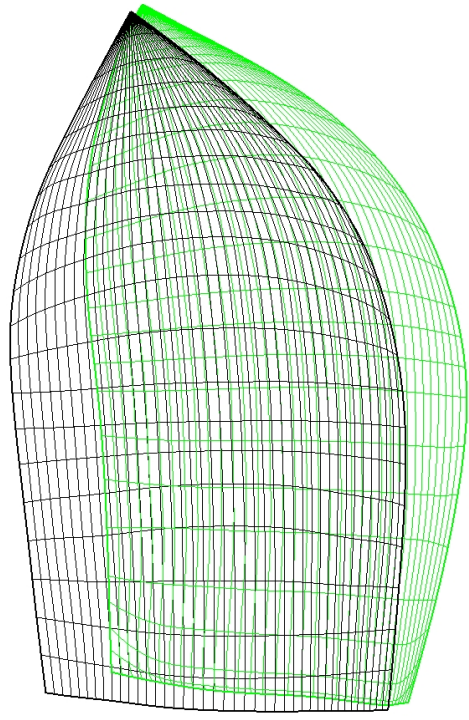
Fig. 21: Mode I comparison AWA=160°

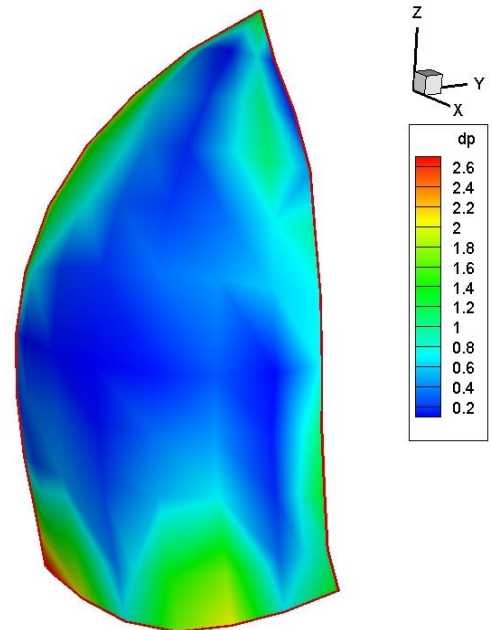Fig. 22: Model III comparison AWA=160°
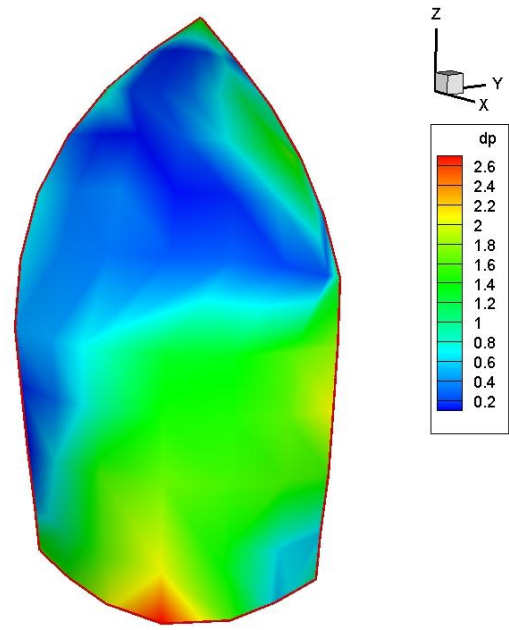

Fig. 23: Mode I, AWA=80°
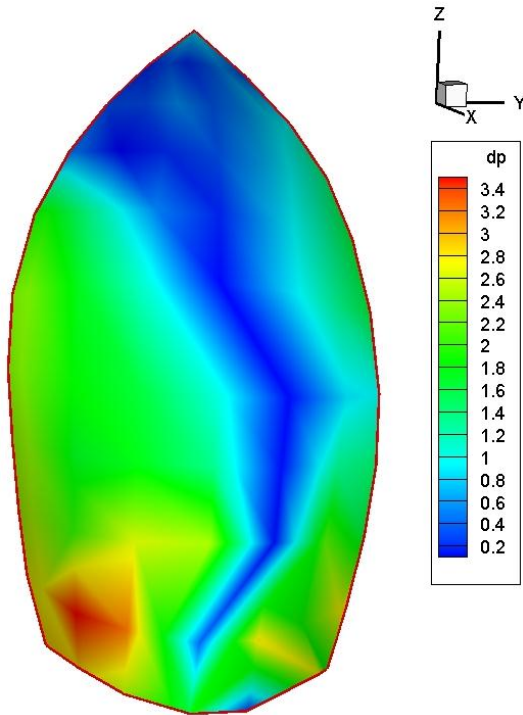

Fig. 24: Mode I, AWA=100°
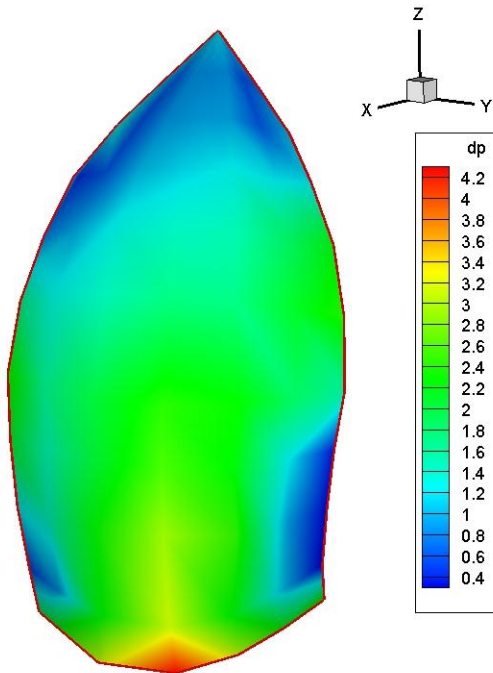
Fig. 25: Mode I, AWA=120°
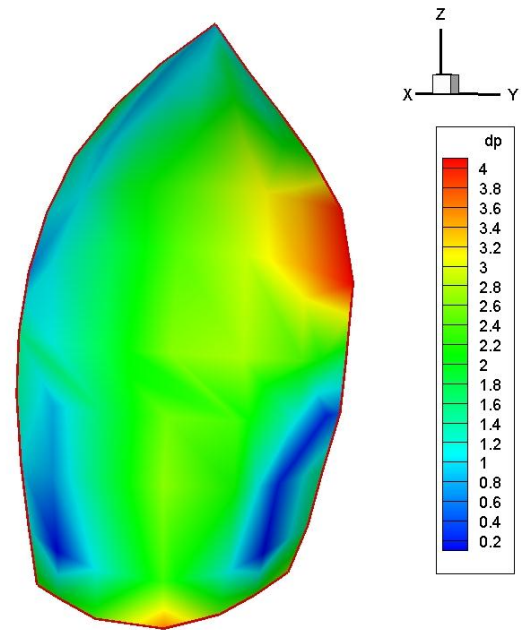

Fig. 26: Mode I, AWA=140°

Fig. 27: Mode I, AWA=160°

Analysis of diagrams for Mode I comparison gives a quite satisfying agreement between model and full scale flying shape. Differences are within a range of 1 to 2% of the leech length for most parts of the surface, with maxima reaching 4-5%, which mainly can be found at the foot of the sail. This has to be seen in the light of potential sources of inaccuracy: elastic deflection of sheets (model and full scale), problems to establish identical sheet lead positions, instationary environmental conditions and so on.

Considering the challenging test condition one encounters at full scale this is a good result. It rectifies the twist chosen in the wind tunnel to properly fit the one found in full scale. It also allows concluding that the violation of rules of similitude as discussed in chapter 1 can be accepted at least to a high degree.

On the other hand the comparison results of Mode II and III raise some doubt in the validity of the optimization procedure in the wind tunnel and at full scale. As a general trend it has been shown that it was possible to ease the sheet much more in the wind tunnel as in full scale and to haul the aft guy tighter, all this with the consequence of higher driving forces compared to the trim that has been regarded to be the optimum while sailing full scale.

There are three possible reasons for this:

a) due to low Reynolds number pressure field close to the luff of the model sail develops in a way that the collapsing of the luff is delayed to much higher local angles of incidence. In this case the optimization procedure as used in the wind tunnel remains questionable.

b) It has to be considered that the trimming of the spinnaker on the sailing yacht (the maximization for driving force in full scale) was done under high time pressure in an in-stationary, somewhat stochastic environment. The trimmers on board have been reasonable experienced sailors but no professional spinnaker trimmers. Consequently it may be possible that the trim for maximum driving force has not been achieved in full scale.

c) Regarding the large difference in Reynolds number between full scale and model separation pattern may be very different. While laminar separation is prevented in the wind tunnel due to large turbulence intensity of freestream, still maximum lift coefficients and corresponding drag coefficients strongly depend on Reynolds number, this to some degree being a consequence of separation patterns depending on Reynolds number. This in turn may be the rationale for different trimming in the wind tunnel and at full scale.

The authors however believe that the main reason for any difference between model and full scale result is simply the human factor on trimming of the sail. At full scale on the water, assessment of an optimized trim is done by the intuition of the sailor and maybe with a look on the speed-ometer, the boat speed itself depending not only on spinnaker trim but on ever changing environmental conditions as well. In contrast to that, trim optimization in the wind tunnel is done with the help of true and accurate metrics, basically the instruments for measuring driving force and other state variables. All this is done with unlimited time resources in a fully stationary environment. Consequently it is much easier to obtain an optimized trim in the wind tunnel than at full scale.

CONCLUSION

This paper describes a study about the comparison of flying shape as found in the wind tunnel and in full scale. The measurement principle was based on photogrammetry.

As a result of the study it was found that good agreements of model and full scale flying shape can be achieved for comparable spinnaker trim conditions. However there are some hints that raise doubt about the comparability of the trim that has been regarded to be an optimum one in full scale and the trim that has been thoroughly optimized with the use of the instrumentation and the constant laboratory conditions in the wind tunnel.

Future research on this topic should try to replicate a trim at full scale that has been found to be an optimum in the wind tunnel (reversing the comparing process). This remains challenging due to the stochastic nature of field tests this can only be done by mass-data investigation and in a sailing environment with very stationary wind and weather conditions.

REFERENCES

Graf, K. and Mueller, O. (2009): "Photogrammetric Investigation of the Flying Shape of Spinnakers in a Twisted Flow Wind Tunnel", Proc. 19th Chesapeake Sailing Yacht Symposium, Annapolis / USA, 2009