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Photogrammetric Investigation of the Flying Shape of Spinnakers in a Twisted Flow Wind Tunnel

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1 ABSTRACT

This paper describes a method for the acquisition of the flying shape of spinnakers in a twisted flow wind tunnel. The method is based on photogrammetry. A set of digital cameras is used to obtain high resolution images of the spinnaker from different viewing angles. The images are post-processed using image-processing tools, pattern recognition methods and finally the photogrammetry algorithm. Results are shown comparing design versus flying shape of the spinnaker and the impact of wind velocity and wind twist on the flying shape. Finally some common rules for optimum spinnaker trimming are investigated and examined.

2 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

3 Introduction

Design and flow analysis of spinnakers for contemporary sailing is one of the most challenging topics of sailing yacht technology. One of the reasons for this: the design shape of a spinnaker – the shape defined by the sail designer using sail lofting programs – varies significantly from the flying shape, the shape of the flying spinnaker under wind load, trimmed by sail trimmers on board or in the wind tunnel. Since the flying shape of the spinnaker generates the thrust and heeling forces and moments of the yacht, it is obviously the shape to be optimized. Hence a

3D-description of the flying shape is a quite valuable, if not indispensable information for the sail designer and sailing yacht flow analyst.

YRU-Kiel has developed a technique to acquire the flying shape of the spinnaker in the wind tunnel. It is based on photogrammetry, a method to generate a three-dimensional description of the sail from a set of images taken by digital cameras. This technique is used in our Twisted Flow Wind Tunnel.

Initially the motivation was, to develop a technique for the validation of CFD-investigations of flow around spinnakers, taking into account fluid-structure interaction - the deformation of the sail under wind load by combining CFD with a Finite Element structural investigation, see *Renzsch, H., Müller, O. and Graf, K., 2008*. However since establishing this technique tunnel, it has not only been used by the CFD flow analysts but also by sail makers and sailors to assess sail design and to get trimming hints for optimized sail trimming under racing conditions.

This paper describes the sail shape acquisition technique from a practical view. Hard- and software is described as well as the general setup in the wind tunnel. Operation of the system is given in detail. Results are shown, comparing flying and design shape, wind velocity and wind twist impact on sail shape. Finally some widely accepted advices for proper spinnaker trimming are investigated.

4 The Twist Flow Wind Tunnel At YRU Kiel

The Twist-Flow Wind Tunnel of YRU-Kiel has been described by *Mueller, O. and Graf, K. (2005)*. The open-jet wind tunnel is powered by two axial fans for a maximum wind speed of 10 m/s at the measuring area, Fig. 4-1. 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.

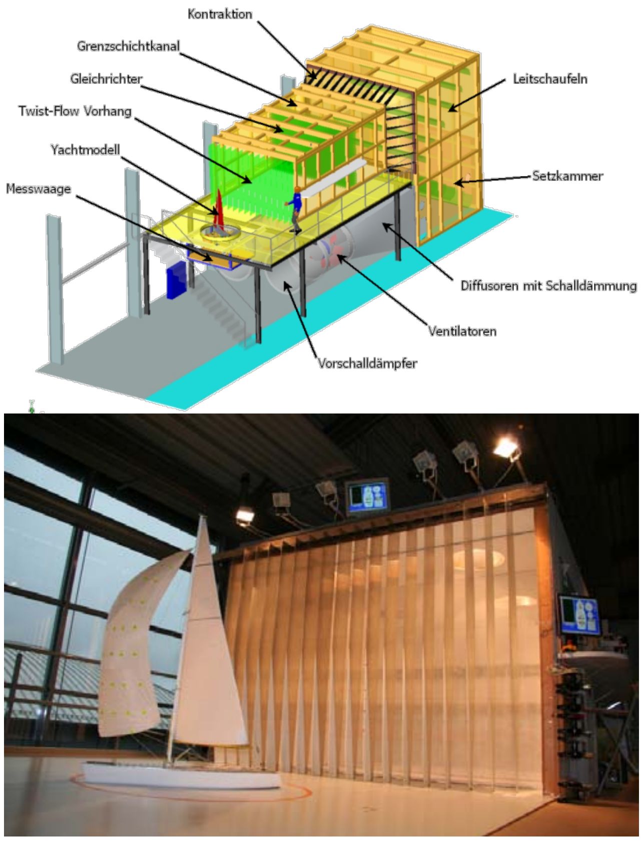
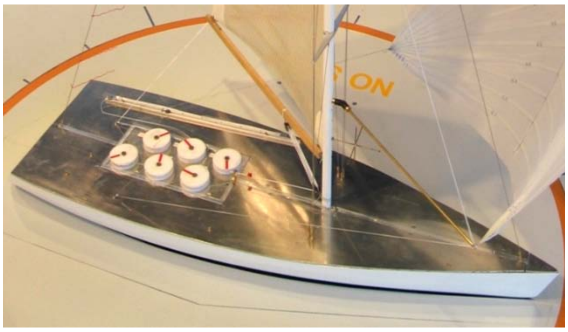


Fig. 4-1:TFWT of the YRU-Kiel

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

A PC based data acquisition system and virtual instruments are used to acquire, filter and convert flow force measurements from the force balance. The entire wind tunnel instrumentation, the fans, any servo motor for trimming and adjusting apparent wind angle and for the visualization and storage of the flow forces and moments is implemented as an integrated PC-based software system based on *National Instruments LabView* © virtual instruments.



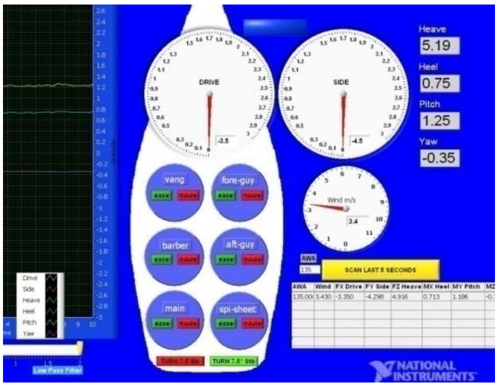


Fig. 4-2: Trimming servos at the model and virtual instruments

Virtual instruments allow the measurement engineer to online review time histories of data signals, select segments to be used for further analysis and assess measurement quality with the help of standard deviation of any signal. In addition trim settings are recorded and can be reproduced at any time. This allows reproducibility tests and precise comparisons of smaller variations of a sail without any human factor.

5 Photogrammetry

5.1 Principle Method

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.

5.2 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. 5-1 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.

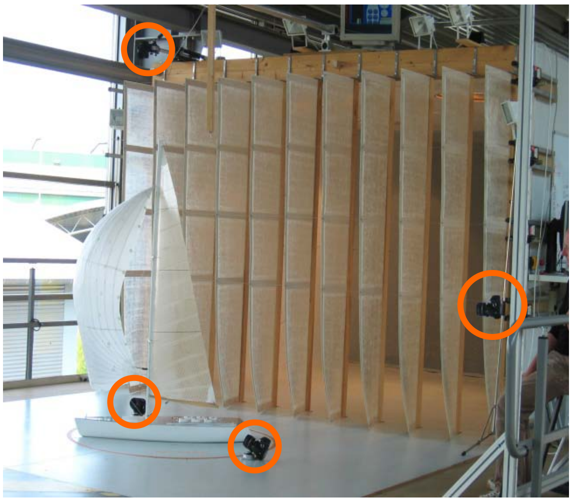


Fig. 5-1: Camera arrangement in wind tunnel

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. 5-2. These markers are 12 bit coded allowing a theoretical number of 4096 different markers.

Fig. 5-2: 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. 5-3 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. 5-3: 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.

5.3 Photogrammetry algorithm

The fundamental physical principle of photogrammetry is the colinearity condition, which states that any object point, the corresponding point mapped on the image, and the point where the light is focused by the sensor, the perspective centre, are located on the same straight line, Fig. 5-4.

From the colinearity condition the coordinates of an image point can be calculated, if the coordinates of the corresponding point in the object frame, the perspective centre and its mapping on the image are known, equation (1) and (2). While the mapped perspective centre in the image plane can be estimated to be identical with the geometric centre of the image, the perspective centre in the object frame has to be calculated.

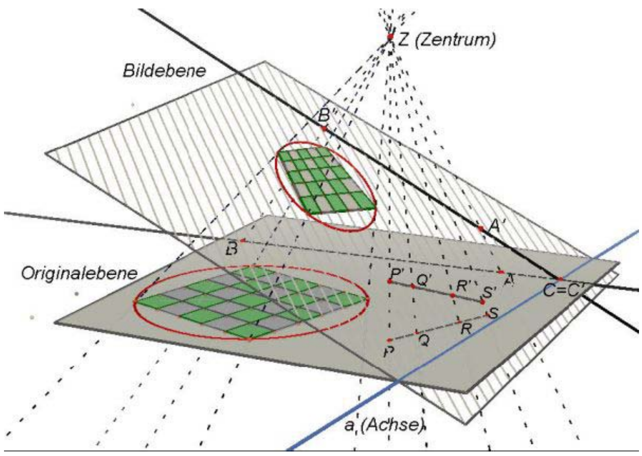


Fig. 5-4: Colinearity of object and image plane

$$x = x_0 - c\frac{R_{11}(X - X_0) + R_{12}(Y - Y_0) + R_{13}(Z - Z_0)}{R_{31}(X - X_0) + R_{32}(Y - Y_0) + R_{33}(Z - Z_0)} \qquad (1)$$

$$y = y_0 - c\frac{R_{11}(X - X_0) + R_{12}(Y - Y_0) + R_{13}(Z - Z_0)}{R_{31}(X - X_0) + R_{32}(Y - Y_0) + R_{33}(Z - Z_0)} \quad (2)$$

where x,y are the photo-coordinates in the image frame, X, Y, Z are the 3-D coordinates in the object frame, c is the focal length of the camera, X_0, Y_0, Z_0 are the 3-D coordinates of the camera's perspective centre in the object frame, x_0, y_0 are the photo-coordinates of the perspective centre to the image plane and R_{ij} is the rotation matrix between the image and object frames.

The general idea of photogrammetry is to calculate the object point coordinates X, Y and Z as well as the perspective centre X_0,Y_0 and Z_0 from known image coordinates x and y of a larger number of images. Three images are sufficient to solve the respective linear equations, however if more than 3 images are available, this results in an overdetermined system of equation, allowing some averaging to increase accuracy.

5.4 Photogrammetry software

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.

Points in the sail can be manually identified in any image (using the mouse on the screen showing the image), for example the sail head, the tack, the clew, intersection of seams or any other conspicuous point in the sail. However here a PMP plug in is used which automatically detects the coded targets. This pattern recognition algorithm is even able to detect a restricted number on non-coded markers arranged between coded targets. This is quite helpful for sails with low smoothness or wrinkles. For a standard spinnaker a detection rate of the coded targets of approximately 75% has been achieved.

Prior to the integration of images into PMP some image processing is carried out to adjust brightness of the images, increase contrast and do some clipping in order to focus on the subject of interest, the spinnaker and the model of the hull of the yacht. For this purpose any image processing software may be sufficient, however here *Canon Digital Photo Pro* is used. This software allows working with raw uncompressed camera images.

5.5 Surface generation

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. Imported points are connected using NURBS curves which then are lofted using NURBS surfaces. Points have to be arranged as a grid, to allow identifying columns of points. If a scattered point arrangement is available only, some grid interpolation techniques have to be applied. Fig. 5-5 shows a surface, constructed of NURBS curves based on imported points.

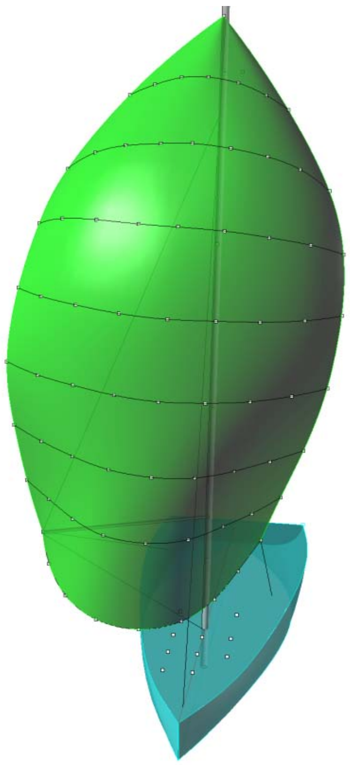


Fig. 5-5: Gridded points, NURBS curves and NURBS surface

5.6 Validation

For validation the surface of a known regular geometry has been acquired using the described technology. To mimic the shape of a spinnaker at least to a certain degree, a cylinder with a circle base surface has been used, Fig. 5-6.

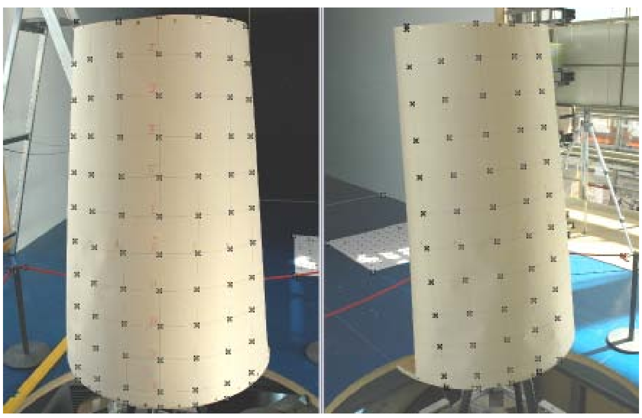


Fig. 5-6: Validation geometry

The result of the photogrammetry process is shown in Fig. 5-7. A quantitative comparison of source geometry and generated surface shows quite good agreement. Average deviation is approximately 1 mm. Maximum deviation of up to 10 mm has been observed at locations where the surface normal points almost rectangular to the line of sight of any camera. Using four cameras in the setup this can usually be avoided by proper placements of the cameras.

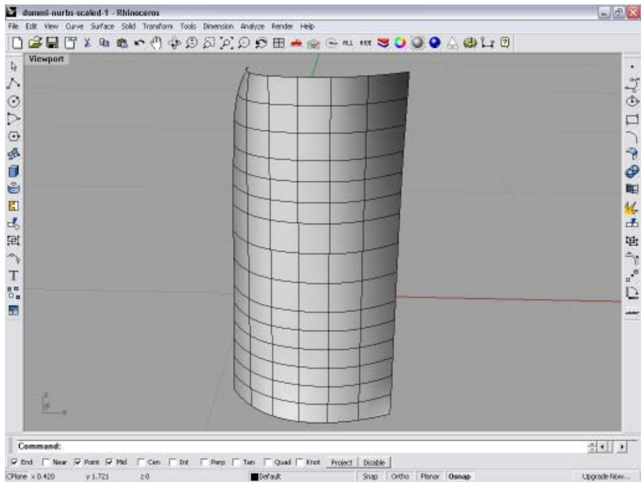


Fig. 5-7: Validation surface

5.7 CAD Geometry

Fig. 5-8 shows the final result of the entire shape finding process. Note the markers on the model sail and corresponding points in the CAD geometry.

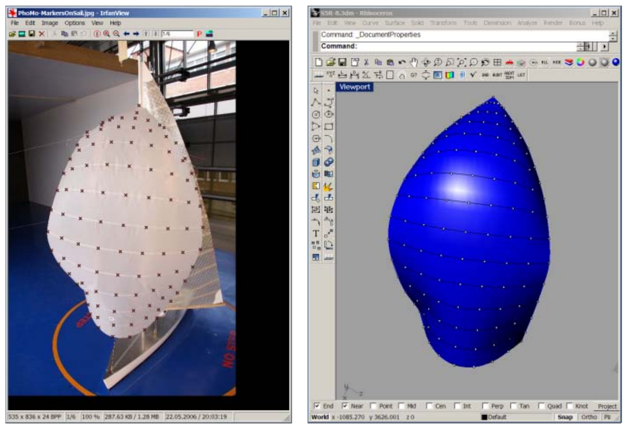


Fig. 5-8: Spinnaker in wind tunnel and as a NURBS representation in a surface modeler

At the current state only the flying shape of the spinnaker can be detected during the force measurement period. Synchronous shape detection of the main sail necessitates additional cameras, which have to be arranged on the windward side of the model. This will be realized in the future.

6 Test Cases

The following test cases show some examples where photogrammetry has successfully been used to study wind tunnel phenomena. A set of spinnakers for an *IMS600* custom design has been developed. Model sail scale factor has been λ=10. Table 6-1 and Table 6-2 show rig dimensions and main dimensions of the spinnaker and main sail which have been used for the following investigations. Note the quite small value of the J-measure, which is a typical characteristic of these types of boats.

S2_A1	
Type	Symmetric runner
SL [m]	1.415
SMW [m]	0.742
SF [m]	0.730
$Area_{Aero.}$ [m²]	0.627
$Area_{Meas.}$ [m²]	0.983
Sailmaker	Faber & Münker
Date	12/05
Sign	S6X
Commentary	Crosscut
Target	110°-180°

Table 6-1: Spinnaker main dimensions

P [m]	1.496
HB [m]	0.022
MGT [m]	0.123
MGU [m]	0.216
MGM [m]	0.353
MGL [m]	0.456
E [m]	0.547
IM [m]	*1.434*
J [m]	*0.408*

Table 6-2: IMS 600 Main and Rig dimensions

6.1 Design shape versus flying shape

Today it is common practice to design sails using PC-based sail lofting programs. As a consequence the sail designer is able to generate a three dimensional view of the design shape of the spinnaker. Fig. 6-1 shows a screen-dump from the *SailMaker©* sail lofting program, which has been used for this study.

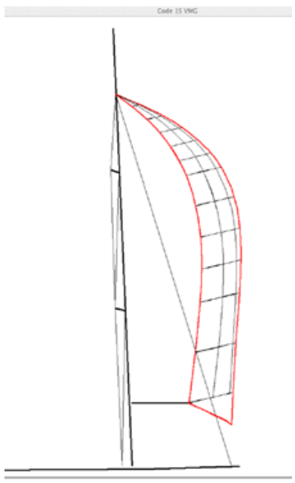


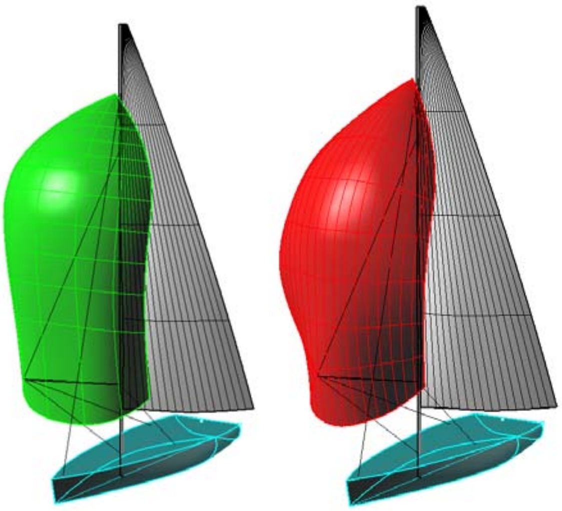
Fig. 6-1: Design shape of spinnaker from *Sail Maker©*

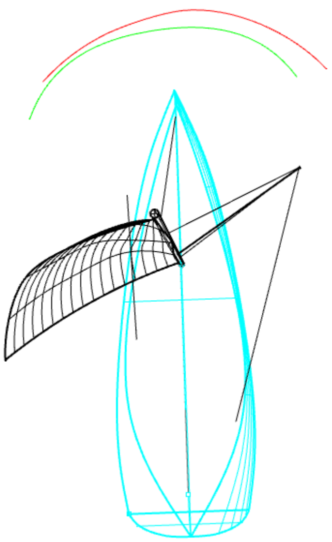
To compare the flying shape from photogrammetry measurements with the design shape, *SailMakers* ability to export the sail design in a *Relax* file format has been used. The *Relax* file format includes a description of the surface shape in *AutoCAD's* .dxf format, which can be imported into a surface modeler.

The spinnaker has been tested at a wind speed of AWS_M=5m/s and a twist of approximately 15° from deck to mast top. A range of apparent wind angles of 80°<AWA<170° has been tested in increments of 3.75°. For each apparent wind angle the spinnaker has been trimmed for maximum driving force.

Fig. 6-1 shows design shape and flying shape of the spinnaker at an apparent wind angle of AWA=158°, which corresponds to a quite deep downwind run.

The differences of design and flying shape are obvious. The design shape is symmetrically with pronounced shoulders and an elliptical horizontal profile being relatively wide and shallow. In contrast to this, the flying shape shows less pronounced shoulders and an asymmetric profile with flatter entrance angle. It can also be detected, that this spinnaker could gain from a longer spinnaker pole (which is fixed to the J-measure under the IMS rules). It seems that the spinnaker head could be placed a bit further away from the mast.





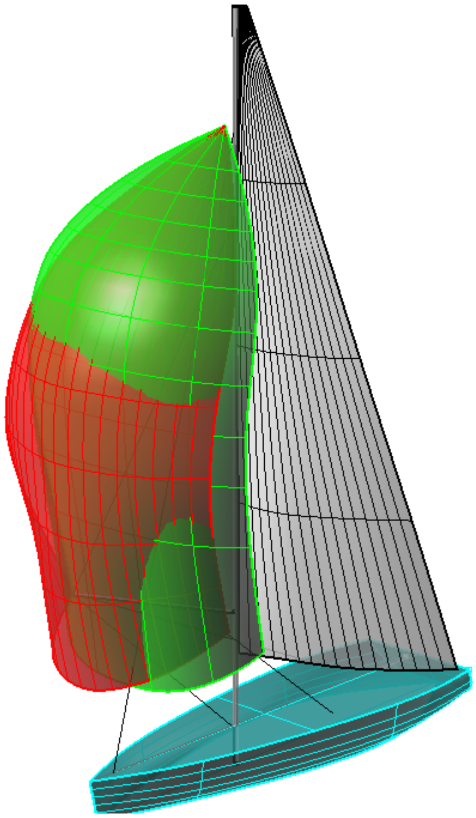


Fig. 6-1 *Design Shape* (green) and *Flying shape* (red) at 5.0 m/s

It has to be realized that the sail designer does not generate a design shape as an aerodynamic profile. He just generates a design shape which results in a flying shape having the desired properties. For this process most sail designers use their experience and intuition.

6.2 Twist Variation

A yacht encounters twisted flow if it moves diagonally to a wind with increasing speed with height over sea level. Consequently it is common practice to test sails, in particular downwind sails, in a twisted flow. This resembles the real flow a sail encounters quite better than a constant flow direction.

The following comparison of spinnaker driving forces is carried out by investigating a spinnaker encountering twisted and non-twisted flow. In both cases the wind velocity was height dependent following:

$$AWS(z) = AWS(z = 10m)\left(\frac{z}{10m}\right)^{n} \qquad (3)$$

where n has been set to 0.1. Boat speed has been set to 8kts. Twist angle from deck level to mast top has been set to 0° (no twist) and 15° (twisted) by adjusting the twist vanes in the wind tunnel.

Fig. 6-2 shows the effect of twisted flow on driving force area AX. Wind speed at mast top was set to 5m/s. The sail has been trimmed for maximum driving force in twisted flow. For the non-twisted flow test case, twisted flow trim has been revived using stepper motor settings. No adjustments have been carried out afterwards to establish maximum driving force trim once again.

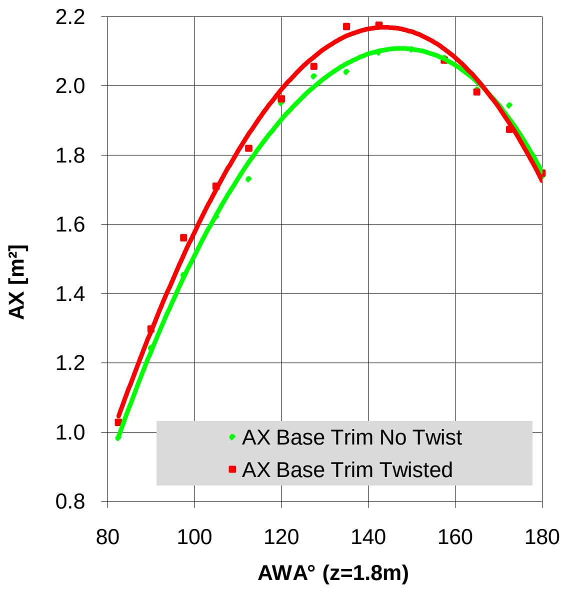


Fig. 6-2: Comparison of driving force area in twisted and non-twisted flow

The result shows that the spinnaker performs better in twisted flow with an increasing gain as AWA increases.

The reason for this can be detected by comparing the shape of the spinnaker for twisted and non-twisted flow, Fig. 6-3, which shows only very small differences in shape even though the angle of incidence has changed dramatically for the lower part of the sail. This is quite important since it is the main rationale behind testing of sails in the wind tunnel.

For a maximum driving force trim the mid part of the sail dominates trimming. It seems that for the non-twisted flow the angle of incidence at the lower part of the sail is too large to generate lift.

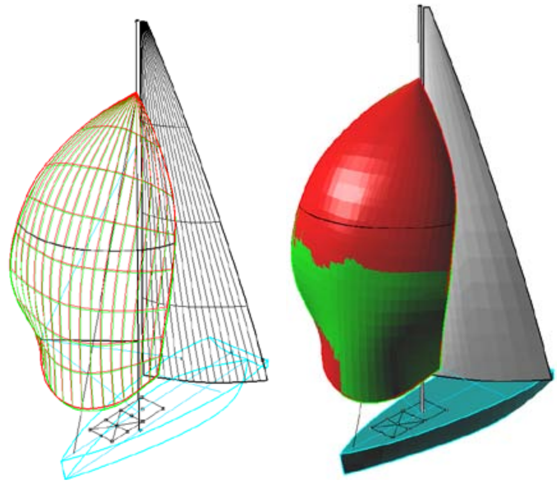


Fig. 6-3: Flying shape of spinnaker for twisted (red) and non-twisted (green) apparent wind, $AWA_{Masttop}$=135°

6.3 Wind Velocity Variation

The description of apparent wind speed in the previous chapter suggest to have a closer look to the wind speed at mast top level, any wind tunnel test of sails have to be based on. Answers to this question are usually derived from laws of physical similitude, of which more than one applies to wind tunnel testing of sails. The most well known, Reynolds law, demanding constant Reynolds number for model and full scale, cannot be realized in most wind tunnels due to wind speed restrictions and structural problems for the model. However due to the deformability of a spinnaker, additional laws of similitude have to be satisfied regarding the weight per area and the stresses of the sail fabric.

In fact most wind tunnels used for sail testing follow the essential rule that any sail testing has to be carried out at a constant wind speed in order to maintain comparability. At our wind tunnel an average wind speed of 5 m/s is used.

A test series has been undertaken to investigate the impact of wind speed on the driving force areas of the spinnaker and on its shape. For this purpose the spinnaker described above has been tested in a range of wind speeds 3.5m/s < AWS < 6.5m/s. Fig. 6-4 shows the driving force coefficient over apparent wind angle for three different wind speeds as a result of these tests. In any case the trim of the sails has been kept constant.

Fig. 6-4 displays that differences in the driving force area AX are quite small for wind speed of 3.5 – 5.0 m/s. However with increasing wind speed, driving force areas decrease. Again the rationale behind this can be found in the flying shape of the sail.

Fig. 6-5 shows the flying shape of the spinnaker at apparent wind speed of AWS=3.5m/s and AWS=6.5m/s. Apparent wind angle is 157°. As expected the displacement of the spinnaker increases with wind speed. However in addition the leeches of the sail have changed quite significantly, opening the sail at higher wind speed, which may result in a loss of pressure in the sail.

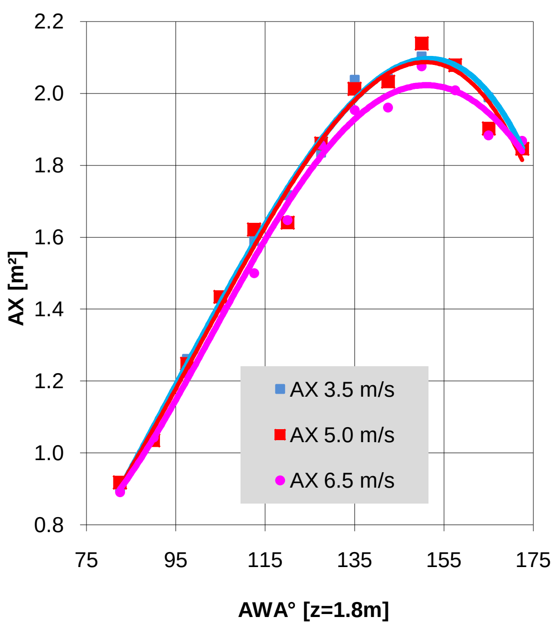


Fig. 6-4: Wind velocity variation

This investigation makes it really clear that the wind speed used for wind tunnel testing should be related to the strains of the material. As a suggestion derived from unity analysis the ratio of dynamic pressure to fabric stresses should be similar for model testing and full scale. However only further research will unveil which rules of similitude have to be applied and are relevant.

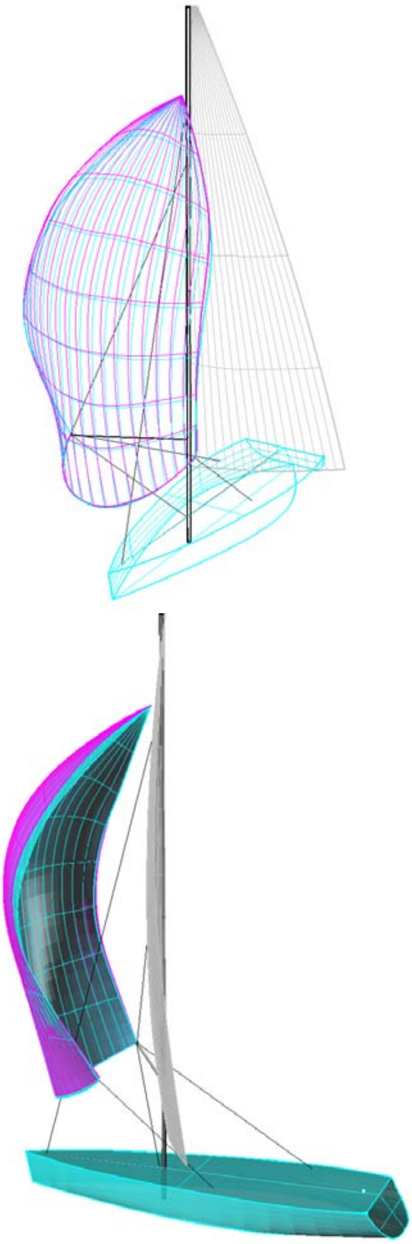


Fig. 6-5: *Flying shape* of spinnaker and mainsail at 3.5 m/s (cyan) and 6.5 m/s (magenta) wind speed and AWA = 157°

6.4 Consent Rules for proper spinnaker trimming

There is a quantity of tuning guides for any boat class. Most if these rules share common specifications for the effective trimming for downwind sailing. The following investigation has been carried out to assess these trimming hints.

As a widely accepted set of trimming hints the authors want to cite the *Speed&Smarts©* newsletter, published by David Dellenbaugh. In Vol. 84/Sept. 2004 he suggests the following sequence of trimming actions:

1. Set the spinnaker pole perpendicular to the apparent wind at sailing courses > 120°
2. Ease the spinnaker sheet as far as possible near to an occasional collapse of the luff
3. Tune the top lift so that the luff curls from top to bottom
4. Engage the barber to a position that both spinnaker tack and clew are on equal height.
5. Spinnaker boom should be horizontal to the water plane
6. Keep the sail foot away from the forestay

- As a secondary rule the middle seam should be vertical to the water surface

Many sailors including the authors agree that these trimming guidelines are very helpful to set up a spinnaker, in particular if they are seen as a starting point, from where a permanent fine-tuning of the spinnaker is carried out to maximize boat speed.

Wind tunnel testing provides an excellent method to assess these trimming guidelines. For such an investigation the spinnaker described before has been tested for a range of apparent wind angles, applying the rules. After taking a measurement additional fine tuning of the trim has been carried out to maximize the driving force. Here the measurement instruments provide an excellent and objective means to check if the trim can further be optimized.

A minor problem arises for consequent realization of the trimming rules. Some of the rules contradict others. In particular, the hint to trim the pole perpendicular to the apparent wind may be incompatible with the rule to keep the foot of the sail away from the forestay. To circumvent this problem, additional test runs have been carried out, where – starting from the initial trim with wind-perpendicular pole – the aft-guy is eased to keep the foot clear from the forestay.

Fig. 6-6 shows the result of these tests. Driving force area is plotted over apparent wind angle at mast top. The diagram shows clearly that additional fine tuning of the trim can significantly increase the performance of the sail. As a limitation of the result it has to be kept in mind, that the trimming in the wind tunnel maximizes the driving force, while trimming on a boat targets the maximization of the boat speed, the latter one needing quite different trim if side forces have to be restricted due to stability constraints of the yacht.

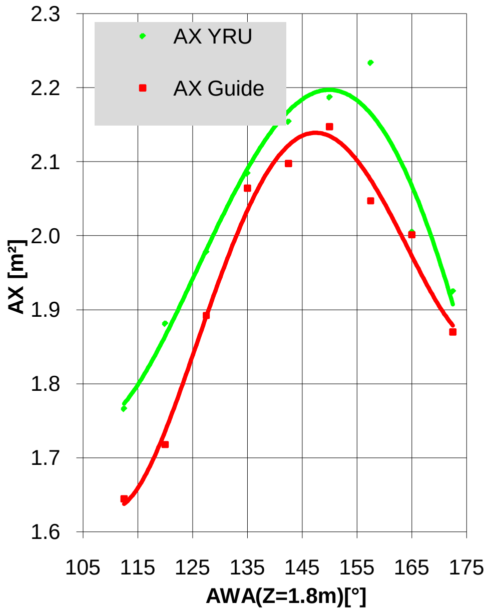


Fig. 6-6: Trim variations

Photogrammetry helps to understand how the refined trim generates more driving force. Fig. 6-7 shows flying shape of the spinnaker at AWA=158° and AWS(z=1.8m)=5m/s, the sail trimmed conforming to the guidelines in red, and trimmed for maximum driving force green.

The refined trim is characterized by an increased height of the clew, violating the rule, that clew and tack have to be leveled. In addition the height of the pole is increased (but to a lower degree than the clew). Generally the pole and aft guy are eased to increase the distance of the foot from the forestay.

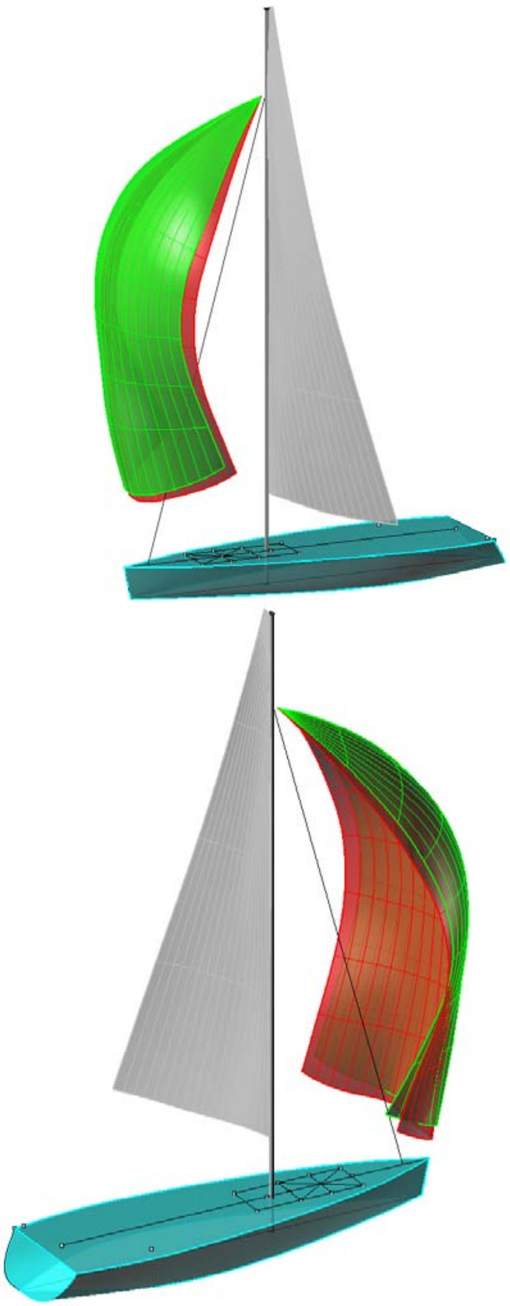


Fig. 6-7: guided trim (red) and YRU-Trim (green) at AWA 158°

7 Conclusion

In this paper a photogrammetric method for the measurement of the flying shape of spinnakers has been presented. It has been used to study flow phenomena observed when doing wind tunnel testing. As such it is not a scientific investigation method by itself but rather a supplement to flow force measurements of sails in the wind tunnel.

The method is quite useful to understand how spinnakers perform and how wind tunnel testing should be carried out. It can thus help to decrease one of the mayor drawbacks of wind tunnel testing, the human factor involved because trimming of the sails is done by sail trimmers rather than by algorithms.

One of the main motivations for the development of the presented method is to have a tool for validation of numerical investigations of the flow around spinnakers, taking into account the deflection of the sail due to wind load, so called Fluid Structure Interaction methods. This has been published by the authors in an earlier paper, *Renzsch, H., Müller, O. and Graf, K., 2008*

This paper raises some questions that point to further research. The ignorance of common laws of similitude is a source of erroneous results achieved in the wind tunnel. This problem will be targeted in a future research program carried out at our institute.

8 References

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