Abstract. It’s well known that large differences commonly exist between a computer based original design shape and the resulting flying shapes of offwind sails. Fluid-structure interaction codes based on CFD and FE techniques are nowadays under development and they represent appealing tools useful to close this gap: in fact potential improvements to the offwind sail design process could be provided by developing an offwind sail design database (a collection of baseline designs appropriate for different applications) based upon representative flying shapes rather than present style based upon design shapes. Up to date numerical codes still need a massive validation work and both wind tunnel tests as well as on water testing at full scale can give a substantial contribution, supposing that reliable flying shapes are provided reflective of the realistic sailing and trim conditions. This paper presents a new tool based on noncontact methods which allows for measuring sail flying shapes in the wind tunnel environment as well as at full scale in real life conditions. The proposed method has been validated during a wind tunnel campaign on both symmetric and asymmetric spinnakers conditions. The combination of all these factors leads to a virtually infinite number of flying shapes and, this is especially true considering offwind sails because of the lightweight construction materials and their relatively unconstrained nature.

Several factors contribute to determine the “flying” shape of a sail under real sailing conditions. Some of the most important are, for example, pressure distribution acting upon the sail, which is not dependent only on wind strength and direction but also on structural properties, sail trim controls acting upon the edges and corners of the sail, and on forces applied by the rig and sail leading to the actual fluid structure interaction problem. The combination of all these factors leads to a virtually infinite number of flying shapes and, this is especially true considering offwind sails because of the lightweight construction materials and their relatively unconstrained nature.

Several contributions can be found in literature aiming at assessing sail flying shapes. One of the first attempts in measuring the resulting shape variation of a design shape focusing on downwind sail in different wind conditions using wind tunnel tests, has been made by Razenbach and Kleene in [1]. An asymmetrical reaching sail flown from a conventional pole was evaluated in the GLMWT tunnel. An asymmetrical reaching sail flown from a conventional pole was evaluated in the GLMWT at three Apparent Wind Angle (AWA) in optimal trim and the three resulting flying shapes were found using a Coordinate Measuring Machine (CMM) and a photogrammetry based technique.

Photogrammetry has also been used at Politecnico di Milano Twisted Flow Wind Tunnel by Fossati et al. ([2]) where an in house near IR-camera camera measurement system has been developed to recover sail flying shapes during wind tunnel tests. An experimental database concerning the relationship between upwind flying shapes geometry and aerodynamic performance is provided at different apparent wind angles and sail trim settings.

The photogrammetric technique has been exploited also at the YRU-Kiel Wind Tunnel, and in [3] Graf and Muller presented some tests on a set of spinnakers for an IMS600 custom design, comparing flying and design shapes, wind velocity and wind twist impact on flying shape. More recently, in [4], results of wind tunnel tests on two different asymmetric spinnakers have been reported. During these tests, forces and flying shapes were recorded by a 6dof balance and photogrammetry and a dataset is provided for validation of downwind sail FSI simulations comprising incident flow conditions, sail trimming and sail structural information.

As a general comment, it can be said that the photogrammetry based technique was judged accurate and relatively fast during the tunnel occupancy phase, requiring only that digital images were recorded from at least three vantage points. Its chief disadvantages are that it requires an intensive data post-processing and that suffers from occlusion problem (mostly occurring in downwind configuration due to the sail overlapping). This means that sometimes some grid points are not properly recorded by the cameras. To overcome the problem, a large number of cameras is required, leading to relevant difficulties in system set up in the wind tunnel.

The CMM process requires a longer period during the tunnel occupancy phase (about ½ hour per
configuration), but yields results within moments after the digitizing process is complete. Its principal disadvantage is that the CMM and operator can potentially influence the shape of the sail and it requires the user to accurately select points directly upon the surface of the sail with the digitizing arm’s stylus. As far as the flying shape recovering at full scale are concerned, a valuable research activity concerning sail shapes and performance measurements at full scale using a sail dynamometer boat called Fujin has been presented in [5], [6], [7] and [8]. The Fujin is a 34-foot sailing cruiser, in which load cells, Charge-Coupled Device (CCD) cameras and sailing condition measurement system were installed to obtain the sail forces and shapes, and the boat attitude, simultaneously. The sail shape was recorded using pairs of CCD cameras: horizontal stripes were drawn on the mainsail and jib at different heights and the image processing software calculated the curvature of the sail sections providing some sail shape parameters in these sail sections like maximum camber, maximum draft and twist angle values. The same procedure is used by several computer programs, which are nowadays commonly available on the market aiming at analyzing sail pictures taken onboard by means of a standard camera and providing some sail shape parameters in a certain number of sail sections. For instance, North Sails has developed a proprietary software called ASA (Advanced Sail Analyzer) to digitize pictures deriving synthetic parameters for each section that has been marked by (horizontal) stripes on the sails. Upwind sails aerodynamics with flying shapes measurements at full scale have been also provided by the 33-Foot dynamometer boat DYNA ([9]): for that project a system based on photogrammetric methods was used. The hardware, which mainly consists of a set of six digital cameras installed in fixed position on the boat, is described in details in [10] and a grid of discrete markers applied to the sails forming a grid of horizontal and vertical lines is used to define their flying shape. More recently, in [11], a method called Visual Sail Position and Rig Shape (V-SPARS) aimed at measuring also downwind sails has been presented. It is based on cameras that capture fluorescent colored stripes on the sail and on an image processing software that produces the global coordinates of each stripe relative to a fixed datum position on the yacht. This method has been used for downwind sail aerodynamics investigation at full scale combining pressure and sail shape measurements ([18], [19]). The above mentioned background is extremely useful not only for use while racing but also for sail design tool development which rely on a reliable validation process. One of the main drawback is that these systems can recover only few horizontal sections, deriving the relative angle between them but not being able to describe the tridimensional position of the leading edge, therefore not being able to reproduce with accuracy the entire sail surfaces, which represent respectively the reference or the input in case of FSI or CFD calculations. Moreover, these systems rely on the assumption that the stripes remain in a horizontal plane, which is questionable for downwind sails especially when a large range of AWA is considered. Fluid-structure interaction codes based on CFD and FE techniques ([20], [21], [22]) are nowadays under development and they represent appealing tools useful to close the gap between a computer based original design shape and the resulting flying shapes. In fact, potential improvements to the offwind sail design process could be provided by developing an offwind sail design database (a collection of baseline designs appropriate for different applications) based upon representative flying shapes rather than present style based upon design shapes. Up to date numerical codes still need a massive validation work and both wind tunnel tests as well as on water testing at full scale can give a substantial supposing that reliable flying shapes are provided reflective of the realistic sailing and trim conditions. North Sails has developed its proprietary set of software to design and analyze sails known as NDS – North Design Suite. This suite is capable to produce a tridimensional design shape (known as “Spiral”), over which laying out a fiber structure with “3DLayout” tool. Those two outputs together are used in the CAD/CAM 3D manufacturing process which is known as 3DL/3Di. Those outputs can as well serve as starting point for FSI analysis which NS is carrying out with its proprietary CFD and FEM tools (known as “Flow” and “Membrain”) to predict flying shapes over a vast number of wind and sailing conditions. This paper presents a new tool that allows for measuring sail flying shapes in the wind tunnel environment as well as at full scale in real life conditions, based on the time of flight technology. The innovative tool developed by the authors has been designed within the frame of the Lecco Innovation Hub Sailing Yacht Lab Project ([12]), a new generation sail dynamometer boat that is currently under development at Politecnico di Milano. The Lecco Innovation Hub Sailing Yacht Lab is fitted with instruments for acquiring data on the behavioural variables of the boat and its components at full scale to support a scientific approach to design and research activities related to sailing yachts design and their performance; in particular in order to acquire sail shape data in dynamic situations a sail shape measurement system has been developed based on the laser scanner technology which has great measurement accuracy and speed. The proposed method has been validated by means of a wind tunnel campaign on both symmetric and asymmetric spinakers carried out at Politecnico di Milano during an Offshore Racing Congress project aimed at revising offwind sails aerodynamic coefficients and ORC VPP aerodynamic model ([13]). In the present paper, after a methodology description, some results are presented comparing design shapes
versus flying shapes and potential improvements to the
offwind sail design process by developing an offwind
sail design database rather than upon design shapes is
discussed.

2. METHODOLOGY DESCRIPTION

2.1 Time of flight technology

The proposed tool for the flying shape detection relies on
Time Of Flight (TOF) technology. It can be enclosed into
the category of the active noncontact instruments that
provide the geometry of an 3D object by projecting
energy sources (generally light in the visible or near
infrared range) onto the inspected surface and observing
either the transmitted or reflected energy. The geometric
data for the object are calculated by using triangulation,
time intervals, wave-interference information, and image
processing algorithms. Figure 1 presents the different
noncontact methods.

![Figure 1. Noncontact method](image)

The absence of contact between the hardware and the
object during data acquisition was considered of
particular interest for the application studied because
noncontact instruments ensure no load effect onto the
high deformable and extremely light sail surface. In
particular, with reference to the full scale situation,
taking into account the great dimensions of the sails and
the uncontrolled environmental situations, a device
presenting a wide measuring range insensible to the
weather conditions is necessary.

The principle behind all time of flight (TOF)
implementations ([14] [15]) is to measure the amount of
time (t) that a laser pulse (i.e. laser electromagnetic
radiation) takes to travel to the object and return.
Because the speed of light (C) is known, it is possible to
determine the distance travelled (D):

\[
D = C \times \left(\frac{t}{2}\right)
\]

(1)

Figure 2 illustrates how a time of flight laser scanner
works.

![Figure 2. Time of flight technology](image)

2.2 Flying shapes detection using TOF technology

For all practical purposes, the angle \( \theta \) is very small and
thus has no effect on the accuracy of the TOF distance
measurement. The high velocity of the light allows
scanners to measure hundreds of points per second.

There exist different types of TOF laser scanner. The
range of acquisition goes approximately from half meter
to a kilometre. The accuracy is roughly between few
millimetres and two or three centimetre for long-range
devices. It depends on the output diameter of the laser
beam and its divergence, on the speed of the detector and
on the target surface properties.

The 5-echo technology used in TOF laser scanners
ensures the reliability of the measurements even in
outdoor bad weather conditions such as rain, fog and
dust.

The selected TOF device provides information about the
points measured in terms of polar coordinates: in
particular, for each detected point a radius \( r \) and an angle
\( \alpha \) are provided with reference to the origin of the
coordinates system located on the internal mirror
rotational axis (Figure 4).

![Figure 3. Operating range](image)
Due to its intrinsic characteristics, the laser scanner is able to measure only points lying in the same plane while in order to detect the sail flying shape detection the entire sail surfaces has to be measured.

Figure 4. Polar coordinate (r, \(\alpha\)) sensor system and Cartesian coordinates sensor system (Xs, Ys)

To this aim, a purpose built handling unit based on a brushless motor and an epicyclical gear has been developed to enable the controlled rotation of the measurement device around an axis perpendicular to the TOF mirror rotational axis. Then, a proximitor is used to identify the initial scanning position for each data acquisition. Figure 5 shows the complete measurement system.

Figure 5. The TOF Flying Shape Detection System

An in house computer program has been developed allowing for the handling unit control strategy: the brushless motor is controlled via serial port and the data acquisition is managed via Ethernet connection through a scanning user interface. Measured data are received via TCP/IP protocol and saved onto a personal computer hard disk.

The described technology and the previously mentioned tool, which will be referred to in the following as “TOF Flying Shape Detection System”\(^5\), are able to provide the sail shape 3D geometry in terms of point cloud where the 3D coordinates in an absolute frame are measured for each individual point.

2.3 Flying Shape analysis software

For the shape finding process a custom-built in house post-process software has been developed. The system is able to detect automatically the sail corners and edges; criteria to eliminate bad points from the cloud are implemented and for every shape acquisition a check on each sail edge length is carried out comparing the luff, leech and foot measured values with the reference ones. First of all the full 3D coordinates of each individual point belonging to the sail surface are stored for IGES file creation.

Then, the post process software automatically finds 8 strips considering sail surface sections at different heights as shown in Figure 6.

Figure 6. Selection of sail surface sections

For each sail section, an automatic analysis is performed providing stripe camber, draft, entry, exit, front, back and twist relative to yacht centerline which are output to file and displayed on screen interface as shown in Figure 7.

Figure 7. Example of sail surface design parameters

The software can be run on a low-power PC eventually using an iPad as a remotes screen. In case of need, the resulting flying shapes can be averaged by selecting multiple shapes.

\(^5\) Patent application n° PD2014A000249
3. METHODOLOGY VALIDATION

TOF Flying Shape Detection System has been validated considering both metrological issues and post processing capabilities. Validation procedures are summarized in the following paragraphs.

3.1 Metrological validation of the measurement unit

In order to estimate the measurement precision and accuracy of the TOF laser scanner, several preliminary tests have been carried out varying the distance, the orientation and the material of a planar target surface. The TOF scanner was considered as a distance meter and 1000 scans were acquired for each scenario. Reference distances are taken by means of a Total Station, whose accuracy is one order of magnitude higher than the TOF sensor one. Figure 8 shows an example of the measurement distribution that could be approximated as Gaussian functions. Figure 9 presents trend of the mean values (blue crosses) and the standard deviation (red dots) of the measurement error for the tests regarding the influence of target to sensor distance variation: relative error exponentially decreases while increasing the target distance.

According to the results above, the accuracy of the system fulfills the application requirements. Moreover, tests to verify the influence of the target material properties have been performed using different planar targets made by cardboard, plastic and sail tissue, but no significant influence was observed.

The last series of tests aimed at estimating the influence of the incident angle of the laser ray onto the target surface. The scanner performs the best when the laser hits perpendicularly the target surface (incident angle equals to 90°). Beyond 160° the scanner is not able to perform a reliable measurements, in fact the uncertainties increase at least of two orders of magnitude.

3.2 Metrological validation of the reconstruction

The polar coordinates obtained from the laser scanner are transformed into 3D information considering the TOF unit geometry. To evaluate this transformation, object with known regular geometry were acquired. A flat plate was initially considered, and then, to mimic the shape of a spinnaker with a certain approximation, a cylindrical object with known diameter was scanned. Reference shapes are reconstructed once more starting from point cloud acquired by means of the Total Station. These tests led to satisfying results: distances of the acquired points from the reference surface are uniformly distributed for the whole scan and did not exceed the uncertainty values previously presented. Thus, the proposed methodology actually revealed to be promising for sails shape measuring purposes.

3.3 Sail shape detection methodology validation

In order to test the ability of TOF Flying Shape Detection System post-processing software, design shapes of several symmetric and asymmetric spinnakers have been analysed: more in details, the sails surface design parameters have been provided by North Sails using the North Design Suite and compared with the same parameters evaluated using the TOF Flying Shape Detection System post-processing software.

As an example, with reference to a 50’ cruiser racer A1 gennaker design shape, in Figures 10-11 the surface design parameters are reported for every sail section in terms of camber and twist. In particular, red dots refer to North Sails provided data and blue dots are the same parameter values extracted on the same shape using the TOF Flying Shape Detection System post-processing software.
4. EXPERIMENTAL RESULTS

In the following, some results will be shown with reference to a wind tunnel campaign carried out at Politecnico di Milano during an Offshore Racing Congress project aimed at revising offwind sails aerodynamic coefficients and ORC VPP aerodynamic model.

The design focus for the required sails to be tested was on asymmetric, masthead, centerline tacked gennakers. Two shapes were produced, an A1 with focus on tight angles for light wind reaching or downwind, and an A2 with focus on broader angles for stronger breeze downwind. For each shape two sizes were produced, a “max” version with the maximum reasonable area possible on sail plan, and a “small” version with shortened foot and leech, with area around 87% of the “max” version.

During the tests, forces are measured in a model-fixed coordinate system by a six-component balance and gennaker flying shapes measurements are taken with the proposed TOF Flying Shape Detection System while the mainsail shapes are obtained using the currently available Wind Tunnel photogrammetric system described in [16]. More details on the wind tunnel facility, measurement procedure and experimental set-up are provided in [17].

4.1 Design-flying shape comparison

In this section the results of sail scans at 95° AWA are shown and compared with design shapes in correspondence of the sail trim generating maximum driving force for the given AWA. Figures 12-13 show the comparison between rendered design shape (blue grid) and the rendered flying shape surface (red) obtained by the sail scan measurements. As previously mentioned, using the proposed TOF tool sail surface design parameters can be extracted. For the present case, although several section parameters have been derived for each curve, in Figures 14-17 only camber (profile depth in percentage of chord) and twist (related to boat centerline) are drawn for both sails (mainsail and gennaker), being the most significant for aerodynamic forces.

In addition, two significant vertical curves are analyzed with synthetic parameters: LUFA, that is projection of luff curve on a plane defined by sail corners, and LUSW, that is projection of luff curve on a plane defined by tack and head and perpendicular to the previous one.
difference in tack height relies on the search for maximum driving force – the flying shape is related to the best trim achieved in wind tunnel – for the given wind condition. The tack trim adds vertical curvature, which necessarily ends in a reduction of horizontal, being the total curvature approximately constant; twist has a similar effect on horizontal curve reduction.

Mainsail shows a similar behaviour, while opposite as concerns vertical and horizontal curvature. More intuitively, the mast is much straighter than design luff curve - being the latter targeting a mean upwind condition, while in downwind test condition it is allowed to straighten - thus resulting in fuller horizontal sections. The resulting flying shape can be better understood looking at tridimensional rendering resulting from sail scan (Figure 12-13). In the following, the much different tack trim for gennaker as well deeper luff curve and added twist are clearly visible, as long as added twist at main. It is appreciable how the mast effect (and possibly low luff tension) result in a deeper main in spite of twist increase.

In addition, it is interesting to compare rendered shape with picture from wind tunnel, illustrating the capability to capture irregular shapes such as on the luff in this case (Figure 18).
Such a comparison between design and flying shape might be thought of interest in the contest where tridimensional design shape is intended as an approximation of flying shape aimed at generating building (2D) parameters (sail panel and edge curves- the ones influencing the final flying shape, together with control lines trim). Therefore, aiming the design shape at realistic (or even optimal) flying shape should be possible, even leaving unchanged the building parameters, thus producing the same design shape. This in turn leads to the possibility of introducing parametric changes to 3D design shape, which may be expected to represent more closely the expected variation in flying shape.

In the following, focus is on the relationship of trim manoeuvres on gennaker control lines - primarily tack - with sail shape and sailplan forces. Test was carried out at 80° AWA and the trim manoeuvre consisted in easing the tack line starting from an all-down position and trimming the sheet as needed. Images from 3D rendering, in Figure 19, show in detail tack easing, clew movement and overall shape change, in three subsequent trims.

Synthetic parameters describe this process in detail, showing how at each step the sail loses depth in the upper part while becoming deeper in the lower.
Interestingly, the first trim manoeuvre (from step 0 to step 1) does change a little the luff curve, while the twist is increased due to sheet easing. The second trim, from step 1 to step 2, instead, results in a big increase of luff curve associated with lower twist, apparently due to little sheet trim.

![Figure 20. A1 max sail. Camber values for different trimming steps](image)

![Figure 21. A1 max sail. Twist values for different trimming steps](image)

Pictures taken in the wind tunnel (Figures 23-25) do confirm in particular the similar luff curve between the two first steps, with a bigger difference in the third. Sail forces evaluation (Figure 22) is well correlated with gennaker shape variation. While the driving force is increasing almost linearly with tack ease, confirming the "best practice" in use in sailing regattas, the lateral force at step 1 decreases with twist increase. Step 2, instead, associates more side force with less twist.

![Figure 22. Driving and side forces for different trim](image)

![Figure 23. Picture from wind tunnel test- Step 0 –](image)

![Figure 24. Picture from wind tunnel test - Step 1 -](image)
A deeper analysis can be carried on each curve, being horizontal section or luff curve, for which synthetic parameters have been derived. As an example, in the following diagram all parameters for horizontal middle section are interpolated by a spline allowing an intuitive shape evaluation. A vertical line representing camber and its longitudinal position is drawn, to show how profile depth not only diminishes but also moves forward.

The analysis carried out in this paragraph suggests for each design shape a set of possible flying shapes and associated forces can be derived, under parametric control lines variation, identifying reasonable trims. This would make it possible to identify an envelope of possible coefficients to feed a VPP with a complex set of coefficients for each different sail candidate, better showing behavior under trim variation and relative crossover. The availability of a set of trims and flying shapes for a given design could be also of great help in setting up CFD investigations with the purpose of finding forces and analyzing flows, saving a lot of computational time usually dedicated to this activity, and bypassing the subjective human factor.

### 4.3 Mainsail flying shape and force variation with trim

A similar analysis has been conducted on mainsail trim and its association with sail shape and forces. With reference to tests carried out with the small A2 at 90° AWA, starting from an optimum drive trim, mainsail has been progressively trimmed with less twist by a combined use of sheet and traveler. Starting from step 0, sheet has been trimmed to step 1, than traveler to step 2 then again sheet to step 3. Figure 27 shows the rendered mainsail flying shape surfaces obtained by the corresponding sail measurements, which can be compared with the pictures taken in the wind tunnel (Figure 28).

The effect on twist (Figure 29) is clear and well correlated with manoeuvres: step 0 to 1 the high sheet angle contributes in reducing twist more at foot than at head; step 1 to 2 traveler is brought to windward contributing to an even twist reduction; 2 to 3 sheet is tightened ending close to vertical therefore tensioning leech and reducing twist much more at head than at foot. Forces diagram (Figure 30) do show a slight reduction in drive associated to an increase in lateral force, probably due to an increased portion of mainsail being stalled.
CONCLUSIONS

In this paper, a new tool (referred as “TOF Flying Shape Detection System”) which allows for measuring sail flying shapes is presented. It is based on the time of flight technology and provides the sail shape 3D geometry in terms of point cloud where the 3D coordinates in an absolute frame are measured for each individual point of the sail surface.

The developed “TOF Flying Shape Detection System” is designed also for full-scale applications and it can be installed onboard aiming at detecting sail flying shapes directly in real life environment.

Tool validation procedures, with reference to both metrological issues and post processing capabilities, are briefly summarized and some results obtained from sail scans performed during wind tunnel experiments aiming at revising ORC VPP offwind sails aerodynamic coefficients are reported.

In particular, some comparison between flying and design shapes are shown and differences produced by different sail trims on the actual flying shape and relevant sailplan aerodynamic performance are presented and discussed from sail designer’s perspective.

Potential improvements on current sail design process and techniques are discussed, regarding both design shape intended as 3D shape generating building curves, and the opportunity to associate each design shape to a set of possible flying shapes and their related aerodynamic coefficients. Such an approach is intended to both directly interacting with VPP by evaluation of a selected list of design candidates, and possibly inversely letting the VPP identify the best sail design among a database, by match with one or more optimum criteria.

From this point of view a remarkable amount of data is indeed available from the above mentioned wind tunnel campaign, also with reference to additional offwind sails (symmetric and asymmetric on pole), and further work is currently in progress in particular with reference to numerical tools benchmarking purposes.

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