Pressure Measurements on Yacht Sails:
Development of a New System for Wind Tunnel and Full Scale Testing

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ABSTRACT

The paper presents an overview of a joint project developed among Politecnico di Milano, CSEM and North Sails, aiming at developing a new sail pressure measurement system based on MEMS sensors (an excellent compromise between size, performance, costs and operational conditions) and pressure strips and pads technology. These devices were designed and produced to give differential measurement between the leeward and windward side of the sails. The project has been developed within the Lecco Innovation Hub Sailing Yacht Lab, a 10 m length sailing dynamometer which intends to be the reference contemporary full scale measurement device in the sailing yacht engineering research field, to enhance the insight of sail steady and unsteady aerodynamics [1].

The pressure system is described in detail as well as the data acquisition process and system metrological validation is provided; furthermore, some results obtained during a wind tunnel campaign carried out at Politecnico di Milano Wind Tunnel, as a benchmark of the whole measuring system for future full scale application, are reported and discussed in details.

Moreover, the system configuration for full scale testing, which is still under development, is also described.

NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \rho )</td>
<td>Density of air ( (\text{kg/m}^3) )</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Pressure coefficient (-)</td>
</tr>
<tr>
<td>( p )</td>
<td>Actual Measured Pressure ( (\text{Pa}) )</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>Reference static pressure ( (\text{Pa}) )</td>
</tr>
<tr>
<td>( V_\infty )</td>
<td>Incoming/apparent wind speed ( (\text{m/s}) )</td>
</tr>
<tr>
<td>LWL</td>
<td>length water line ( (\text{m}) )</td>
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INTRODUCTION

The possibility of knowing the effective pressure distribution over the sail plan is of great interest for the aerodynamic and structural design of sails and for the selection and the optimal use of materials and production techniques. Integral measurements alone may not be sufficient in understanding how a sail plan can be optimized on specific purposes, if any information about the complex local fluid-structure interaction are provided.

In the last few years there has been a revival of pressure measurements on yacht sails and recently several contributions can be found in literature aiming to assess sail pressure distribution detection ([2-9]).

The present paper presents an overview of an ongoing joint project developed among Politecnico di Milano, CSEM and North Sails aiming at assessing a new sail pressure measurement system based on MEMS pressure transducers, connected to strips and pads. These devices were designed and produced with the scope to provide differential measurements between the leeward and windward side of the sails.

The project has been developed within the Lecco Innovation Hub Sailing Yacht Laboratory project, a 10 m length sailing dynamometer which has been the modern reference full scale measurement setup in the sailing yacht engineering research field, in order to enhance the insight of sail steady and unsteady aerodynamics.

An overview of the Sailing Yacht Lab project is provided in [1]: a brief summary of the origin and building steps of the vessel’s design are given, along with a description of principal design and performance criteria. Also the project management and commissioning are described, as well as the measurement capabilities and data acquisition procedure.
Furthermore, an important feature of this project is the availability of measurement systems for pressure distribution acting on the sails at full scale. In the following, the pressure measurement system is described in details, as well as the data acquisition process and system metrological validation is provided.

The pressure measurement system has also been tested in the wind tunnel using a scale model of sailing yacht and compared with a different pressure measurement system already available at Politecnico di Milano Wind Tunnel. For wind tunnel tests were realized strips and pads adequate for the model sails. Some results obtained during a wind tunnel campaign carried out during an Offshore Racing Congress project aimed at revising sails aerodynamic coefficients and ORC VPP aerodynamic model are reported and discussed in details.

In conclusion the pressure measurement system designed for full scale testing is described.

PRESSURE MEASUREMENT SYSTEM

The pressure distribution on the sails is carried out by means of MEMS sensors (an excellent compromise between size, performance, costs and operational conditions) and dedicated pressure strips and pads which have been designed and produced aiming to provide the differential measurement between the sail leeward and windward side. The pressure sensors are designed and built to provide the differential measurement between the measurement point and a reference pressure value which can be supplied by the user.

In the following a detailed description of the pressure scanners will be provided, as well as of the other main components of the system.

Pressure strips scanner description

The scanner CSEM C16 is a miniaturized electronic pressure scanner in a slim, lightweight and waterproof package (Figure 1). It provides 16 differential pressure sensors and a CAN bus interface for the communication. High attention was given to dimensions and shape of the scanner box. The scanner height, of only 6 mm, has minimal impact on the airflow, which makes it possible to place the scanner directly in a custom built sleeve close to the actual measurement section on the sails. Each of the 16 sensors has its own reference input which makes the scanner especially suited for measuring the pressure difference between leeward and windward side.

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The commercial MEMS pressure dies, integrated in the scanner, are a new generation of piezo-resistive differential low-pressure dies to reach very low full scale ranges below 1000 Pa. Despite the die size of only 2 x 2 x 0.5 mm, that is much smaller than traditional low-pressure dies, it provides improved zero-stability, reduced g-sensitivity and reduced sensitivity to humidity. This added stability permits use with added amplification to achieve accurate performance in ranges much lower than its nominal 1000 Pa rating. The key specification of the scanner is given in Table 1.

The MEMS sensors are cost efficiently bonded to a FR4 substrate using innovative die bonding techniques based on elastic adhesives (Figure 5). The sensors are packaged in a sensor array with minimal air cavity to ensure optimal performance in combination with the micro-channels of the pressure strips.

The pressure measurement system has also been tested in the wind tunnel using a scale model of sailing yacht and compared with a different pressure measurement system already available at Politecnico di Milano Wind Tunnel. For wind tunnel tests were realized strips and pads adequate for the model sails. Some results obtained during a wind tunnel campaign carried out during an Offshore Racing Congress project aimed at revising sails aerodynamic coefficients and ORC VPP aerodynamic model are reported and discussed in details.

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Figure 1 - Pressure Scanner C16 with auxiliary parts. 1) Scanner, 2) CAN Cable, 3) CAN connector, 4) Tube Adapter

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Unit</th>
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<tr>
<td>FS pressure range</td>
<td>±1000</td>
<td>Pa</td>
</tr>
<tr>
<td>Number of pressure inputs</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Number of reference inputs</td>
<td>16</td>
<td></td>
</tr>
<tr>
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<td>Maximal CAN cable length</td>
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<td>m</td>
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<td>Internal flash data memory size</td>
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<tr>
<td>Size</td>
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</tr>
<tr>
<td>Weight</td>
<td>50</td>
<td>gram</td>
</tr>
</tbody>
</table>

Table 1 - Pressure Scanner Specification

A dedicated pressure flange system makes the scanner compatible with either the pressure strips or with standard tubing. Three different pressure adapters have been developed, which can be screwed to the scanner. The first adapter provides 32 tubes (2 per pressure sensor, one facing to the front side and one to the reference side of the sensor). A second adapter combines all reference inputs to a single tube, in order to connect all MEMS sensors to the same reference (Figure 2 and Figure 3). Finally, the third adapter provides direct access to the pressure strips without the need of any tubes.
The scanner C16 supports a standard CAN interface (CAN 2.0A) with a proprietary CAN protocol, allowing remote access to the essential commands required when integrating the unit into an instrumentation system. The serial CAN bus topology (Figure 4) allows for up to 128 scanners in a single network. In practice, the number of scanners per network should be below 16 (i.e. 256 pressure sensors) in order to reduce the data traffic on the bus and to guarantee synchronized data sampling.

The CAN interface has been preferred over a wireless solution due to its robust data transmission capability, the guaranteed data rate of 1 Mbit per second and the possibility to directly supply electrical power to the scanners via the flat CAN cable. Thus, no battery is required in the scanner which reduces both, the dimensions and the overall weight of the scanners. All measurement data and configuration commands are sent over the CAN interface. A correctly received command is always acknowledged by the scanner with the transmission of a response message.

Two basic data sampling approaches are supported either autonomous sampling or master sampling. The desired option can be configured and stored in the configuration flash. In auto sampling mode each scanner in the network generates its own sample timing according to a programmed sample rate and transmits the measurement data of each sample to the CAN bus autonomously. The measurement data can be collected on-line or can be stored in the internal flash of the scanner and downloaded off-line after the measurement session.

In master sampling mode the user programmed instrumentation system (SW running on PC or Laptop) acts as sample master and broadcasts each sample start with a SINGLE_SHOT sample command. All scanners in the network receive the sample command at the same time and start the measurement immediately and synchronously. Each scanner writes the measurement data to the CAN bus following a bus collision avoidance protocol. The master collects the response messages of all active scanners in the CAN network, and initiates the next sample according to the desired sample rate. The master sampling mode has the advantage that all scanners connected to the CAN bus are synchronized by the master, even over a long sample period of several hours. The 16 sensors of each scanner are sampled sequentially with an internal scan rate of up to 4 kHz. Hence in master sampling mode all sensors in the CAN network can be sampled nearly synchronous within 4 ms.
Pressure strips technology

The pressure strip system is suited for aerodynamics testing on full scale objects in their natural environment but also for models in a wind tunnel (Figure 6). Its main advantage is the light weight and thin, flexible foil appearance which allows non-invasive application to the test surface. The pressure strips are made of thin polymer films and the strip geometry can be customized for nearly seamless fitting to the test object (Figure 7). Tiny micro-channels in the pressure strip propagate the pressure from the tap to the connected pressure scanner. Manufacturing processes have been developed successfully using laser and micro-milling to produce strips with comparatively deep channels. Laser fabrication has the advantage that it can produce channels in soft materials such as silicone or soft PVC, thus increasing the flexibility of the strip significantly without having to reduce the thickness of the strip. On the other hand, channels can be manufactured approximately 5 times faster using micro-milling (Figure 6).

The base material with milled or laser ablated channels is laminated with transparent adhesive tape in order to obtain sealed channels.

![Figure 6 - 400 μm wide and 400 μm deep laser fabricated micro-channels in a silicone strip (left) and micro-milled in a polycarbonate strip (right).](image)

Pad technology

Pressure pads are a specific form of small pressure strips and provide a simple solution to attach a pressure tube to a very thin structure like a sail or spinnaker. The pads can be individually placed on the test section and connected to the pressure scanner with small plastic tubing (Figure 8). This system has been extensively characterized, in terms of static and dynamic response, which is reported in the following section (Metrological Validation).

The pads provide two pressure taps on one end of the pad and a pressure tube adapter with two metal tubes of 1 mm diameter on the other end. Each of the two taps faces to one side of the sail (leeward or windward). A small hole of 0.8 mm in diameter is made in the sail directly beneath the respective pressure tap to realize a pressure passage to the opposite side of the sail. The pad thickness is between 0.5 and 1 mm and therefore introduces only minor interference to the airflow. The length of the pad depends on the size of the test object. For model sails the length is as short as 30 mm while for real sails the length is up to 150 mm to keep the tube adapter a certain distance out of the air flow of the measurement section (Figure 8). The micro channels are cut in the base layer using the same laser ablation and micro milling techniques as for the pressure strips. The base layer is made of a soft material like PVC soft, silicone or acrylic foam tape and usually has a thickness of 0.3 - 0.5 mm. The cover layer is a transparent adhesive tape of 0.2 mm. The cover layer overlaps the base layer by a few millimeters which results in a smooth transition between the sail and the pad layers after application on the sail.

![Figure 7 – Pressure strip with 40 taps on three sections tailor-made for the jib of a 1:10 scale model yacht](image)

![Figure 8 - Conceptual drawing of the pressure pad](image)

METROLOGICAL VALIDATION

Some preliminary tests were performed to verify the measurement quality of the system in terms of static accuracy of the pressure measurements and dynamic response of pressure strips.

Static accuracy

The analysis of the static accuracy of the CSEM pressure measurement system was carried out in the 1m x 1.5m test section of the close circuit wind tunnel of the Aerodynamics Laboratory of Politecnico di Milano, using a constant section NACA 23015 airfoil model. The model has 0.3 m cord length, aspect ratio 3.1 and it is instrumented with pressure taps along the mid-span section. A dedicated pressure strip has been realized spanning from the 25.5%
chord position of the lower surface to the 87.5% chord position of the upper surface of the model (Figure 9).

The strip is provided with a double series of pressure taps (Figure 9): at the same chord position of each pressure tap on the strip another hole through the strip was created to be connected to proper tubes, so that comparative measurements could be taken both for the novel pressure system with strip micro-channels (CSEM) and the consolidated high accuracy pressure scanner system (PSI) (Figure 9). More specifically, the latter relies on an Esterline Pressure Systems DTC ESP miniature pressure scanner with 1 PSI range, controlled by a Chell QUADdaq System.

Static measurements were gathered for fixed incidence angles, ranging from -2 degrees to 14 degrees, at respectively 2.5 m/s, 5 m/s, 10 m/s, 15 m/s and 20 m/s wind speed.

For clarity, in Figure 10, only the results for the wing model at 6 degrees of incidence, are reported. The data plotted in the graph are reduced in terms of pressure coefficient, defined as

$$C_p = \frac{p - p_0}{\frac{1}{2} \rho V^2_{\infty}}$$  \hspace{1cm} (1)

where $p$ is the pressure on pressure tap, $p_0$ the reference pressure, $\rho$ the air density and $V_{\infty}$ the wind speed of the incoming inflow.

It can be noticed that there is good agreement between pressure taps data and the pressure strip data, except for a few points near the airfoil leading edge, where the airfoil has strong curvature. In this region the strip installation, even though it was executed with particular accuracy, presents some tiny surface deformations - visible as small air bubbles around the pressure taps next to the leading edge - which are the main source of the differences.

**Dynamic response**

Further experimental investigation was also carried out to better understand the dynamic capabilities of the pressure strips. A truck hooter has been utilized as pressure wave generator, driven by a signal generator and an amplifier. The pressure measurements were taken by the means of two CSEM pressure scanners: one with a pressure port connected directly to the pressure wave source by a very short tube (Figure 11), the second with a pressure port connected to the strip channel under test in the same way to be used during the wind tunnel testing, Figure 7.

A special attention was paid to the pressure connections to the source. Two tubes of the same length were adopted to connect the scanner and the strip channel to be tested, Figure 11. In such a way it can be reasonably assumed that the pressure wave measured near the source has the same amplitude and phase of the pressure wave reaching the pressure tap on the strip. The connection and the sealing of the tube on the strip was done by means of modeling clay.

Measurements were carried out on the pressure taps connected with the longest channel of each pressure tap array (bottom, middle, top) both on the mainsail and the jib strip (red circles in Figure 12).
The tests were conducted generating single tone sinusoidal pressure waves and sinusoidal sweeps in the frequency range 0 - 3 Hz the expected frequency range for this phenomenon. The pressure data acquisition was started simultaneously on the two scanners. The choice behind the characterization of the pressure system within this frequency range, is consistent with the interest of investigating the physics of slow varying aerodynamic phenomena connected to the sailing yacht motion, due the combined wind and wave loading. The full-scale cutoff frequency of this range is approximately 2 Hz [10]. Frequencies higher than this range (e.g. turbulence) are not expected to have any relevant influence on the overall dynamics of the boat, in that it represents a mechanical low pass filter.

For the sake of simplicity, only the results obtained for the pressure tap on top array of the mainsail (left) are shown in Figure 13.

Figure 12 – Positions of the pressure taps tested

The obtained results agree with the expected ones for channels with a small section and comparable length. As it can be noticed from Figure 13, the linear trend in the output/input relative phase means a constant shift of the signal in phase (i.e. angular coefficient of the straight line in the frequency graph, Figure 13), so that the time history can be easily and consistently corrected during the post-processing procedures.

WIND TUNNEL TESTS

Test apparatus, program, and procedure

A complete 1:10 scale model of a 48’ cruiser-racer, consisting of yacht hull body (above the waterline) with deck, mast, rigging and sails is mounted on a six component balance, which is fitted on the turntable of the wind tunnel (Figure 14). The turntable is automatically operated from the control room enabling a 360° range of headings. This permit to set desired AWA (apparent wind angle) during the tests.

The large size of the low speed test section enables yacht models of quite large size to be used, so that the sails are large enough to be made using normal sail making techniques, the model can be rigged using standard model yacht fittings and small dinghy fittings without the work becoming too small to handle, commercially available model yacht sheet winches can be used and, most importantly, deck layout can be reproduced around the sheet winch, allowing all the sails to be trimmed as in real operating condition. Moreover, the model yacht drum type sheets are operated through a 7 channel proportional radio control system, except that the aerial is replaced by a hard wire link and the usual joystick transmitter is replaced by a console with a 7 multi-turn control knobs that allow winch drum positions to be recorded and re-established if necessary. The sheet trims are controlled by the sail trimmer who operates from the wind tunnel control room. Figure 14 shows the model mounted in the wind tunnel. Both sides of the main sail and the jib are equipped with tailor-made pressure strips, each providing three test sections and a total of 40 pressure taps. An example of such pressure strip is given in (Figure 7). Wind tunnel pressure set up was realized to measure pressure distributions on both sides of the sails, whereas in the full scale set up only differential pressure could be measured, for the intrinsic difficulty in the definition of a reference pressure signal in the real operating environment: this set up permits to better investigate the flow field around the sail, more in detail than it would be possible for full scale measurements.

A high performance strain gauge dynamic conditioning system is used for balance signal conditioning purposes. The balance is placed inside the yacht hull in such a way that x axis is always aligned with the yacht longitudinal axis, and the model can be heeled with respect to the balance. The wind tunnel is operated at a constant speed after the wind speed profile and optionally wind twist can be properly tuned considering the desired targets, which are previously calculated considering the potential boat performance at different true wind speeds and yacht courses. This allows to reproduce apparent wind speed both in terms of wind magnitude and profile [11]. As previously mentioned, the velocity profile can be simulated by means of independent
control of the rotation speed of each fan joined to the traditional spires & roughness technique, while the twist can be simulated by twisting the flexible vanes by different amounts over the height range. The wind tunnel speed is most usually limited by the strength of the model mast and rigging and the power of the sheet winches.

The model is set at an apparent wind angle and at a fixed heel. An important feature of wind testing procedure is that the model should be easily visible during the tests so that the sail tell-tales can be seen by the sail trimmer. For this purposes some cameras placed in the wind tunnel as well as onboard allow a view similar to the real life situation (Figure 16).

Flying Shape Detection

During the present wind tunnel campaign, a novel sail flying shape detection system, based on Time of Flight technology (TOF), was adopted to perform shape measurements along with pressure and force data, as in the full scale final system [1]; therefore, a master software was programmed to trigger synchronously the acquisition of all devices. A thorough explanation of this TOF novel technology can be found in [12]. Basically, a laser pulse is emitted by the TOF sensor and by measuring the time the pulse takes to hit the target surface and to come back to the receiver, it is possible to estimate the target distance.
Upwind sails tests and results

The usual way to analyze data of this type of measurements is to compare non-dimensional coefficients \([11], [13]\), allowing to compare the efficiency of sails of different total area at different conditions of dynamic pressure. The first useful parameter to be analyzed is the variation of driving force coefficient \(C_x\) versus heeling force coefficient \(C_y\).

Figure 18 shows \(C_x\) vs \(C_y\) curves for the 6 apparent wind angles (AWA) tested in this campaign. It can be seen that there are some settings at the highest values of heeling force coefficients where the driving force is lower than the maximum value (e.g. below the maximum efficiency curve, isolated points in Figure 18). These non-optimum values were due to an over-sheeting of the sails, such that the mainsail generally had a tight leech and the airflow separated in the head of the sail, \([14]\). After having maximized the driving force, the sails were adjusted to reduce the heeling force measuring the reduction of the driving force. The reduction in heeling force was achieved by initially easing the main sheet, to twist the mainsail and minimize flow separation, then adjusting the traveller to reduce the angle of attack of the wind on the main. Envelope curves have been drawn through the test points with the greatest driving force at a given heeling force (e.g. depower curves, Figure 18).

The heeling moment is also measured during these wind tunnel tests and it can be used to determine the center of effort position of the rig. For close hauled configuration, the sail plain center of effort height, \(C_{eh}\), is obtained by dividing the roll moment by the heeling force component in the yacht body reference system and normalized over the height of the mast.

A plot of center of effort height variation with heeling force coefficients for tested apparent wind angles can be seen in Figure 19, in terms of the ratio between center of effort height from the boat deck and the fore-triangle height. As it can be seen, the center of effort height tends to decrease as the heeling force coefficients decrease. This is explained by the way in which the sails are de-powered to reduce \(C_y\): increasing the twist reduces the loading in the head of the sails and then depowering the mainsail leaving the same genoa trim, which has a lower center of effort, tends to reduce it.

Analogously, also the center of effort longitudinal position, \(C_{ea}\), is obtained by dividing the yaw moment by the heeling force component in the yacht body reference system and normalized over the LWL. Its variation with heeling force for all angles can be seen in Figure 20, to be interpreted with reference to the envelope of the points corresponding to maximum driving force at each heeling force are reported (Figure 18).

In Figure 20 \(C_{ea}\) is measured from the origin of the balance which is placed behind the mast. As can be seen \(C_{ea}\) moves forward as \(C_y\) reduces: this is again explained by the way the sails are de-powered, as described above.

As depicted in Figure 18, the points laying on the de-powering curve at maximum apparent wind angle AWA (35°), were chosen for a more thorough investigation in terms of pressure distributions and corresponding flying shapes. More specifically, as it can be noticed in Figure 12, three stations at different height, both on main sail and jib, port/starboard sides, were chosen to put the pressure strips on (Figure 12 and Figure 17). In Figure 12, L1, L2 and L3 stand respectively for the three levels at 25%, 50% and 75% of the sail heights, so the corresponding pressures at the points 1-4 are reported in Figure 28.
Furthermore, in Figure 28, the pressure channels at the L2 level of the main sail, were doubled to get the same measurements with two different pressure systems to cross-check again, during wind tunnel tests, the reliability of the novel CSEM acquisition system (the empty markers are due to the certified old system, PSI).

Figure 28 suggests a few interesting comments about the aerodynamics behind: analyzing singularly the pressure coefficients of the main sails, especially for L2 and L3, it can be easily seen that the trend is of an increase in the pressure coefficient $C_p$ nearby the main sail’s leading edge, where the mast is placed, associated to a separation bubble, which has been documented in the past [14]. Furthermore, moving along the airfoil chord, up to the trailing edge, another greatly negative pressure coefficient is experienced, for points of lower driving force coefficient $C_x$ (i.e. 3-4 of Figure 18), right after the reattachment behind the mast separation, whereas for points with greater efficiency (i.e. 1-2 of Figure 18) this bubble seems not to be occurring: therefore, after the separation due to the mast, a monotonic trend up to the trailing edge is evident, index of a gradually and efficient reattachment of the flux on the leeward side of the sail. Nevertheless, some considerations can be reported when it comes to analyzing comparatively both jib and main sails at the same time, for example at the level L2 (Figure 28). It is clear how moving to less efficient trims of the sail plain (i.e. 3-4 of Figure 18), which were possible by sheeting differently only the main sail, as thoroughly above explained, has an important influence on the jib sail itself, then modifying the overall driving force coefficient $C_x$.

More specifically, for worse trimming of the sail, the aerodynamics of the jib is modified in the sense that the suction effect of the main gets weaker (Figure 28, L2 – jib), leading to a different lifting attitude of the jib as well. Therefore, the higher (less negative) pressure coefficient on the leeward side of the jib, visible in the L2 section of Figure 28, can be interpreted as a consequence of this phenomenon.

Moreover, in Figure 29, a comparative plot of two different AWA (i.e. 20° and 35°), both from maximum driving force coefficient configurations (see Figure 18), are reported. Considering again the section L2 both for jib and for main, without loss of generality for the other sectional airfoils, the following explanations can be drawn: the pressure distributions of the jib have basically the same trends and values, since the related shape is due to the maximum power trim; therefore, the main difference can be noticed in the main sail, where the pressure distribution also explains the lower driving force coefficients $C_x$ AWA 20° (Figure 18), associated to a center of effort that is located upward (Figure 19) and slightly forward (Figure 20) with respect to the higher angle of attack (AWA 35°). This trend is also visible in the Figure 21, where it is clear that the driving force, computed as the integral of the pressure distribution on the corresponding section, is mainly given by the jib. In Figure 21, the blue arrows correspond to positive pressure coefficients (windward), whereas red ones to negative (leeward). The pressure measurements of the whole wind tunnel session reported were referenced to the wind tunnel static pressure signal.

Comparing Figure 28 and Figure 29 is also interesting to notice that a less efficient sail plan (e.g. pt.4 of AWA 35°, Figure 28) is aerodynamically kind of equivalent to a sail plain set to a smaller effective apparent wind angle (AWA 20°, Figure 29), which is something that is also known and commonly experienced in sailing. As a matter of fact, great similitude can be found in the results reported in Figure 28 and Figure 29, with the extensively investigated aerodynamics of airfoils with external airfoil flaps [14].

The same considerations can be drawn analyzing pressure distributions along with the sail shapes detected by TOF system. More specifically, in Figure 22 a comparative visualization of the pressure distributions on the effective flying shape, at the corresponding section (L2), is reported for the apparent wind angle AWA 35° and for maximum and minimum efficiency (i.e. pt.1 and 4 of Figure 18).
The pressure distributions are the same that are also reported in Figure 28: it is evident how basically the same jib’s shape of the section, which was not modified along the de-power curve of Figure 18, turns out in a different pressure trends due to the different efficiency of the main sail, whose suction effect on the jib is greatly lower in a de-powered regulation. Also the different overall lateral forces $F_y$ depicted in Figure 21, computed from integrating the pressures over the L2 section, confirm the integral measurements reported in Figure 18. Furthermore, in Figure 23, the comparison of different AWA results, both in a maximum power configuration, as reported in Figure 29, for L2 section, are shown in terms pressure/shape visualizations. It is easy to notice that the fairly similar pressure distribution on the jib (Figure 29), due to the maximum power based trimming, is associated to different shape, leading to different driving forces on the jib and comparable lateral forces on the main sail (i.e. Figure 18, for approximately the same $C_y$, AWA 20° shows a lower driving force coefficient $C_x$ with respect to AWA 35°). Also Figure 24, in which apparent wind directions are highlighted, supports the consideration above reported: more specifically, the less efficient sail plan at AWA 35° shows similarities with lower AWA configurations in terms of main sail pressure distribution. In fact, it is quite evident a reattachment of the flow right behind the mast combined with the co-alignment of the flow with the luff of the mainsail.

It is worth mentioning that these tests represent, according to author’s knowledge, one of the first systematic wind tunnel set of measurements of the pressure distributions on flexible sails, instead of rigid, which is a testing condition closer to the real navigation (i.e. full scale), whose measurements (forces, pressures and flying shapes) on SYL, will be taking advantages from the present research.

Furthermore, the rationale behind the way the sails were trimmed, corresponds to a procedure which is consistent to the real sailing navigation. However, a systematic investigation on the aerodynamics of sail plains, relying on this experimental setup, could be based on different depowering approaches, aiming at assessing the effect on single trim parameters (involving also the jib) on the local and integral efficiency of the sails.
FULL SCALE PRESSURE SYSTEM LAYOUT

On the Sailing Yacht Lab, the pressure distribution on the sails is carried out by means of specifically designed pressure pads which have been designed and produced aiming to provide the differential measurement between the sail leeward and windward side. So that the above reported metrological characterization on the strips and the wind tunnel tests were mainly to assess the capabilities of the measuring system, in advance with respect the final full scale implementation with pads. However, during the wind tunnel tests some tests on pads themselves were conducted just to verify the expected functioning, Figure 25.

With reference to the SYL sail inventory, Figure 26 and Figure 27 show the proposed sail pressure measurement system, the sections considered and a relevant number of pressure taps for the complete sail plane. The full scale pressure system is being finalized at the time of writing this paper.
CONCLUSIONS

A joint project developed among Politecnico di Milano, CSEM and North Sails, aiming at developing a new sail pressure measurement system is presented in the paper. The system was designed for the specific application of full scale measurements on Politecnico di Milano Sailing Yacht Laboratory.

The capabilities of this system were evaluated through a metrological validation of the system alone (static and dynamic tests) and through wind tunnel tests in upwind configuration. The pressure system was integrated in the existent set up, in particular together with the flying shape detection based on Time of Flight (TOF) technology.

Wind tunnel tests allowed both to check the reliability of the new system and to investigate thoroughly upwind soft sails aerodynamics, with the possibility of carrying out regulation as in real navigation. During wind tunnel test session, each side of the sail pressure distributions were measured with reference to a common static pressure, by means of pressure strips, whereas for full scale implementation, pressure pads for differential measurements were developed.

Wind tunnel results give a promising sight of the potentiality of the system described in explaining the dependency of sail plan aerodynamics on the sails trimming, relying on the combined measurements of forces, pressures and flying shapes.

Furthermore, these measurements will represent a great reference database for validation of CFD codes and can be used to complete the interpretation of full scale results.

Further developments in the visualization techniques (PIV) are expected to be combined with this methodology in the near future.

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REFERENCES

Figure 28 - Pressure distributions on the three stations along the span of the sail plane: points on the maximum power curve for an apparent wind angle AWA of 35°
Figure 29 - Comparison of the pressure distribution of two different apparent wind angles AWA (20° and 35°), both considered at the maximum driving force coefficients.