DIPLOMARBEIT / DIPLOMA THESIS

Titel der Diplomarbeit / Title of the Diploma Thesis

„Performance comparison of a standard and an innovative carbon rig on a 29er sailing skiff“

verfasst von / submitted by

Bakk. rer. nat. Gottfried Gerhard Klampfer

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Magister der Naturwissenschaften (Mag. rer. nat)

Wien, 2018 / Vienna, 2018

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	A 190 482 412
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Lehramtstudium UF Bewegung und Sport UF Physik
Betreut von / Supervisor:	Ao.Univ.-Prof.i.R.Dr. Wolfgang Püschl

Statutory declaration

I hereby declare that the submitted thesis is my own unaided work. I have not used other than the declared sources and I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Wiener Neudorf, ___________________ Gottfried Klampfer

Acknowledgment

It’s not possible to write a master thesis without the help of many people. This is why I use this place to say thank you to everyone who encouraged me during my study and most importantly to finish this thesis. To start I want to say thank you to my supervisor Prof. Dr. Wolfgang Püschl who supported me all the way through the development process with his know how and his patience and gave me input whenever needed.

Second of all I have to thank my partner Elisabeth, who gave me strength and power even in the darkest hours and when things went really bad. A good friend told me: “she’s a keeper” and during this process I realized even more that she is and how important it is, to have someone in the background looking after you when times are difficult. It wasn’t only her but also my parents, Birgit and Gerhard, who supported me since early childhood to follow my dreams.

Apart from family and friends there is one person I have to thank in particular: Julian Bethwaite. He is not only developer and license holder for the 29er and 49er but during this process he has become a friend. Without his trust, to commit his full carbon rig for the 29er to me, allowing me to have and work with this unique prototype and to have insights in the boat building and designing process, this whole thesis would not have been.

My last thank you belongs to Reinhard Dietze and Ovington Boats who allocated a boat and his logistics to help to make everything happen. Last but not least Reinhard Kugler, my dearest sailing companion and all the other sailors who taught me what life on the water actually means and spend their spare time with me, gathering data that is being used in this work.

Abstract

This thesis compares a standard 29er sailing skiff with an innovative carbon 29er skiff. The carbon rig consist of a full carbon mast with a fully battened square top main sail. In this study the boats were tested in a head to head test to gather relevant data on the performance difference. The main objective was to measure the overall speed differences (SOG), the sailing angles (AWA, TWA) and to create a polar diagram. The outcome of this thesis is that there is an advantage of the full carbon rig in terms of consistency of speed but a disadvantage on sailing angels to the wind. Considering the overall VMG it is to say that the carbon rig has an advantage over the standard rig due to the higher speed. The study furthermore showed, that the decreased mass of the carbon mast and the square top main sail have a positive influence on the handling of the boat and therefore better control in gusts and lulls.

Zusammenfassung

Das Ziel dieser Diplomarbeit war es, die Performance eines Standard 29ers, bestehend aus einem Alumasten und einem spitzen Segeltop mit der des Prototypen mit einem Carbonmast und einem „Square Top“ zu vergleichen. Die beiden Boote mit jeweils identischen 29er-Rümpfen wurden in einem eins-zu-eins Vergleich getestet, um Leistungsunterschiede festzustellen. Die Hauptzielgrößen dabei waren Geschwindigkeitsdifferenzen (SOG), Segelwinkel (AWA, TWA) und die Erstellung von Polardiagrammen. Die Studie ergab einen Vorteil des Prototypen in Hinblick auf eine konstant höhere Geschwindigkeit. Als Nachteil zeigte sich jedoch, dass mit diesem Boot weniger Höhe gesegelt werden kann. Resultierend kann man jedoch sagen dass durch die höhere Geschwindigkeit auch eine höhere VMG erzielt wird. Des Weiteren zeigte sich, dass sich das Boot, durch das verminderte Mast/Rigggewicht, bei böigen Windverhältnissen bzw. höheren Wellen, stabiler segeln lässt, als das herkömmliche 29er Skiff.

Contents

Index of illustrations

1. Introduction

Sailing has changed a lot in the course of time. One subject to change is the sailing ability of a sailor, which can only be changed and improved with training and second the boat itself. Sailing a specific type of boat needs specific demands and premises. A trainer once said: *“Practice does not make perfect. Only perfect practice makes perfect.”* (1) What this quote actually means is that only with perfect premises and its training options, it is possible to achieve great success in sport. So the Olympic classes in sailing need training boats for kids and youths and this was achieved with the 29er for the Olympic boat class the 49er.

The project was set up in cooperation with Julian Bethwaite (the builder/designer of the 29er and the 49er) who designed a full carbon rig for the already existing alloy/carbon standard 29er. The main changes are the mast that changed, as already stated, from an alloy mast with a carbon top section and a so called pin head sail (compare appendix chapter 1) to a full carbon rig with a square top main sail. The tests were set up to compare the performance differences of the standard and the prototype 29er in order to figure out if the prototype significantly increases the overall performance in terms of overall speed (SOG – speed over ground) and angle (AWA – apparent wind angle, TWA – true wind angle, VMG – velocity made good). Over a period of 4 months the prototype boat was tested in various conditions, different crews and different locations to gather significant knowledge on how to sail this boat in a way that comparison with the standard rig can be made. In addition 4 days of extensive data collecting with measurements in comparison with the standard rig were done.

2. Theory of sailing

Wind is the driving force for sailing boats and therefore it is important to understand how wind develops and how it can be used to power sailing boats to achieve high speeds for sail boat racing.

2.1. True wind

Wind is an effect that occurs because areas around the globe heat up differently (eg. water and land) and these differences result in different pressure areas. As an effect masses of air move from higher to lower pressure areas on the earths' surface. (2)

Marchaj states five factors to determine the quality of the surface wind: (3)

- The atmospheric pressure gradient (difference between a neighboring low and high)
- The sun's heat input
- The height above water level
- The thermal differentiation of the area
- Wind barriers such as local obstruction etc.

If you look at these factors you can see that the second to fifth point more or less deforms the wind structure and are responsible for local winds. These last four factors are the ones useful for sailors but unfortunately rarely constant in strength and direction.[1]

Sailing is not influenced by these high winds. We have to look at a much smaller area and therefore on a local area. The local winds are roughly created by the points mentioned above. Therefore temperature differences and thus pressure differences move the masses of air or they are being deflected by any local obstacle (i.e. Mountains, landmasses, buildings...). When air flows over any surface friction is the player that changes speeds. At low wind speeds this frictions are little and the wind moves with little turbulences and relatively laminar. With increasing speed the friction rises and the laminar flow becomes turbulent (4). Especially close to the ground this phenomena affects sailing as these different layers, wind speeds and wind angles affect the sail position. This phenomenon is called the wind gradient and is indicated by a function of altitude. The ITTC (2017) describes the wind speed as a function of altitude: (5)

$$v_T = U_{10}(z/10)^n$$

U_{10}… Wind speed at 10m [ms^{-1}]

[1] Wind is named by the direction of origin – northerly wind blows from north to south. Sea breeze comes from the sea. (2)

z… altitude above sea level [m]

n… is a coefficient which is equal to 1/7 for the sea surface (ITTC)

Comparing Fig. 1(4,6) you can see the different directions of wind hitting the ribbons on the mast. This indicates different wind speeds and directions across the sail. As a result sail twist (see chapter 1.6.4.) is the way to compensate these different layers (3).

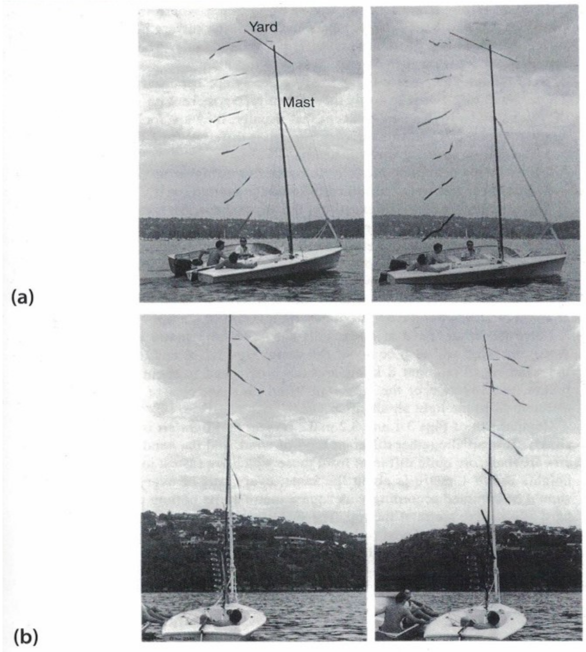

Fig. 1 Behaviour of Ribbons fixed on a Mast of a stationary Boat in light air (about 4 knots of wind). The further up the mast the stronger the breze gets. (4,6)

2.2. Apparent wind

As seen in the chapter above, wind is nothing you can call constant. Many influences change the speed and the direction. But sailing is even more complex as apart from changing wind conditions, the boat itself is also moving. As a result the true wind cannot be considered as "the sailing wind". In his book 'Sail Performance' Marchaj (3) explains 5 factors that are considered to be the apparent wind:

The angle between the yacht's course and the true wind direction

- The speed of the yacht
- Variations in the true wind velocity at different heights above the sea
- Rolling of yacht[2]
- Pitching of the yacht[3]

[2] Rolling is a movement along the longitudinal axis, basically a side-to-side tipping (7).
[3] Pitching is a movement along the lateral axis, a rotation where the bow lifts and falls (7).

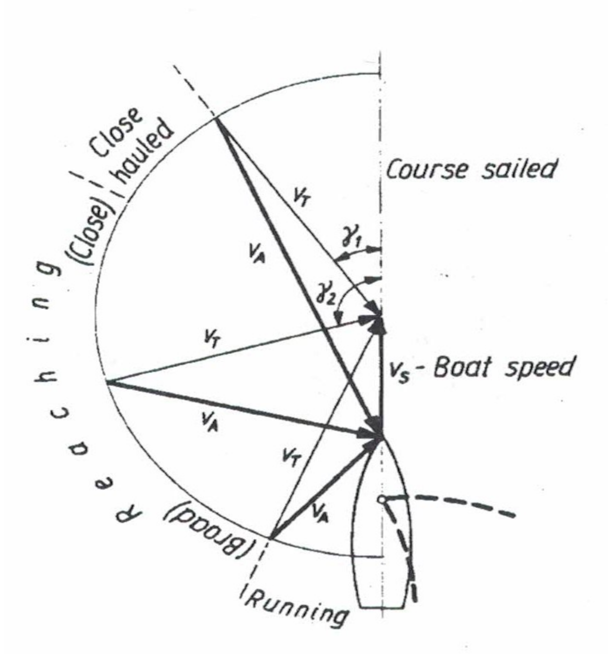

Fig. 2 Wind triangle composed from the true wind (v_T), boat speed (v_S) and apparent wind (v_A) at a constant v_T with its belonging sail positions: close hauled; broad reach; running. (3)

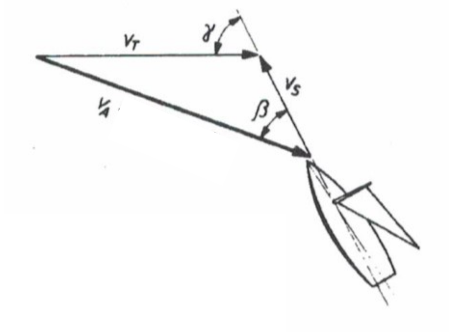

Fig. 3 composition of the apparent wind (3)

v_T… true wind speed

v_A… apparent wind speed

v_S… boat speed

γ… angle of true wind to the course sailed

β… angle of apparent wind to the course sailed

The apparent wind is basically the wind the crew "feels" on board and can be composed by the true wind speed (v_T), the angle (γ) at which the true wind hits the moving boat and the yacht's velocity (v_S). (compare Fig. 2 (3))

Generally seen the apparent wind is much more forward than the true wind as you can see in Fig. 3. Considering high-performance boats like the 29er or in extreme means catamarans or boats with Hydrofoils[4] it can happen that the boat speed exceeds the wind speed. This happens if, for example, the wind comes from behind (reaching or broad reaching), the velocity of the boat increases and at a point the boat speed exceeds the wind speed. What happens is that the wind triangle rotates forward and the apparent wind no longer hits the boat from behind but from the front. As a result the boat sails with the true wind from behind (reaching/broad reaching) but the apparent wind from the front (close hauled). Boat speed and the absolute value of the apparent wind become a multitude of the true wind speed. Because the aerodynamic force is proportional to v^2, the apparent wind exerts a force much stronger on the sail of the moving boat, than the true wind on the stationary sail. (3,9)

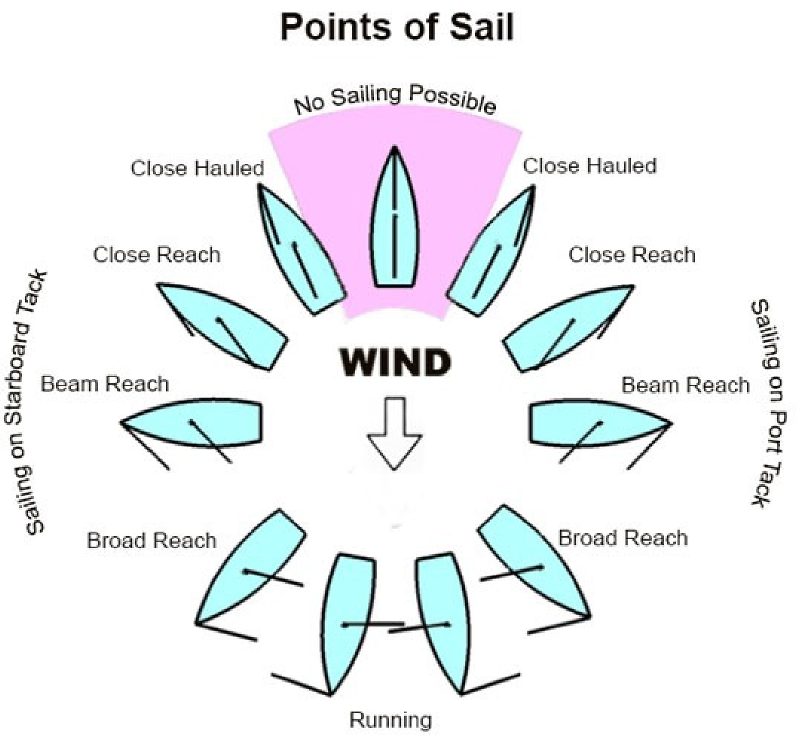

Fig. 48 Courses to the wind with its sail positions. (8)

[4] "A Hydrofoil is an underwater fin with a flat or curved winglike surface that is designed to lift a moving boat or ship by means of the reaction upon its surface from the water through which it moves. Ships that use hydrofoils, or foils, are themselves called hydrofoils. Hydrofoils can lift a boat's hull clear of the water as speed increases, and the resultant reduction in drag yields higher speeds without expending more horsepower."(8)

2.3. Courses to the wind

To sail a boat in different directions a list of terms are standardized to name these directions. Windward and leeward are, respectively, the sides of the boat facing the wind and it's opposite. (Fig. 48 Courses to the wind with its sail positions. (8)Fig. 4) (8)

2.4. Steady movement through water

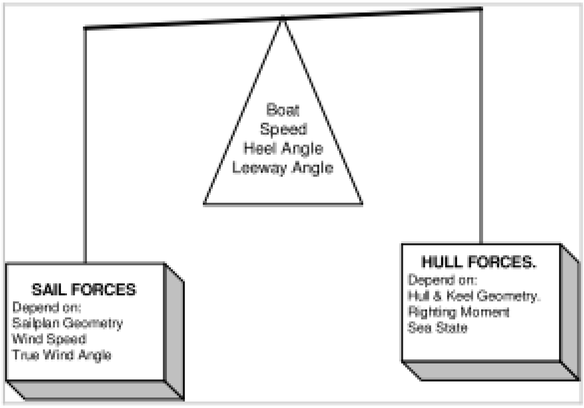

Fig. 5 Force balance on a sailing boat. Two sides influence the structure: a "solution algorithm considering the boat speed, heel angle and leeway angle and the boat model all other factors considering the boat and its forces. (10)

Determining a balanced system one has to define two counter parts to work closely with or against each other. When trying to find an equilibrium in sailing there is, as Milgram 1993 states, a "two-part structure" of a solution algorithm and the boat model, where the solution algorithm must find an equilibrium condition for each point of sailing. (10)

When talking about sailing on a steady course through water it is assumed that you sail without any accelerations or other influences through water. This can only happen, looking at Newtons' first law, if the sum of all forces equals to zero.

$$\sum \vec{F} = 0 \Leftrightarrow \frac{d\vec{v}}{dt} = 0$$

A boat consists of two connected wing-like profiles moving through two different fluids – water and air (9). The direction of the inflow and the fluids' speeds are different and with this information it is clear that a boat can sail/move – even against the wind. Important is not the absolute speed of either fluid but the relative movement between the sailing vessel and air/water. (9)

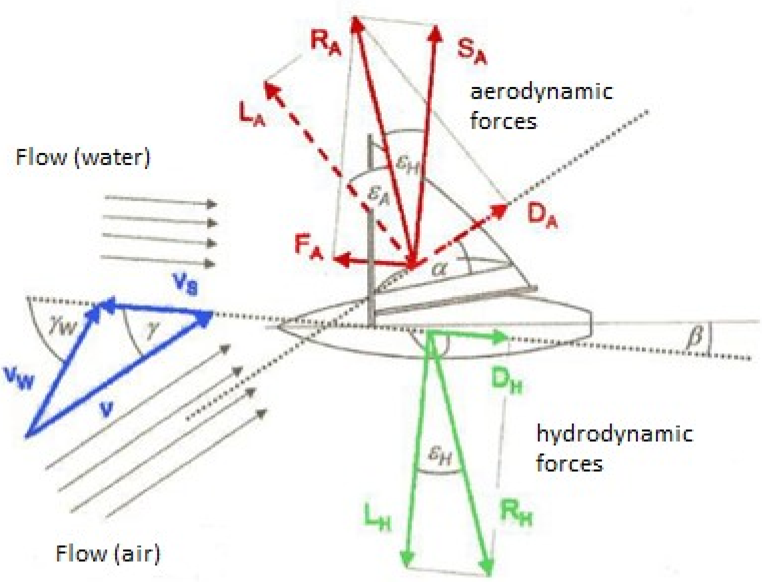

Fig. 6 In steady conditions the aerodynamic and hydrodynamic forces are equalized. (7)

R_H … overall hydrodynamic force

L_H … hydrodynamic lift

D_H … hydrodynamic drag

R_A … overall aerodynamic force

L_A … aerodynamic lift

D_A … aerodynamic drag

F_A … aerodynamic force in moving direction

S_A … aerodynamic side force

v_w … True wind

v_s … boat speed

v … apparent wind

α … angle of the sail to the wind

β … drift angle (= angle of the keel or center board)

2.5. Sailing Downwind

Newton postulated that each one of these “corpuscules”[5] exert a force proportional to its velocity when hitting a surface. Also the rate at which it hits a surface, is proportional to the velocity.(7) When sailing downwind the way of moving is by capturing each molecule with the sails and so being propelled by the mass of the molecule m and its velocity *v*. Newton postulated that when hitting the sail the molecule is stopped at the windward side and the boat is pushed forward, as the molecules exert an equal but opposite force on the boat.

$$F = m * a$$

Multiplying it by the impact time t and $V = at$ ($V\ldots$ wind speed)

$$F = \frac{mV}{t}$$

For the actual (simplified) drag force (F_D)[6] the number of molecules (N)

$$N = A(sail) * [Vt] * \rho(air)$$

have to be added

$$F_D(wind) = \rho\ (air) * A\ (sail) * V^2$$

As stated before, a boat consists of two connected systems of wing like profiles, this equation can be altered to work with water as well.

$$\rho(air) \rightarrow\ \rho(water), A(sail) \rightarrow A(hull).$$

Newton’s theory was generally seen as right but in newer studies (eg. Hoger Babinsky (11)) the area of fluid dynamics treats this phenomena in a detailed way and will just be superficially touched in this thesis. The basic idea is that when sailing in downwind conditions molecules do not only hit a surface and thus propel the boat, but interact with each other. In knowing that the visualization of the flow around a certain plate/wing has to be changed. The main force produced due to any fluid, is mainly induced by pressure difference, called suction (vacuum), which pushes the sail/boat from a region with high pressure on the windward side to the low pressure region on the leeward side. (3,9)

[5] Newton used this word in Volume 2 of Newton’s *Principa* because atoms and molecules were unknown (7)
[6] Drag force is a force in the direction of the fluid motion, opposite the relative motion of a moving object (7).

The modified form of the equation adds an additional “drag coefficient” (C_D) which includes influences outside the wind influence (eg. surface friction of the hull or the sail drag).

$$F_D = \frac{C_D}{2}\rho A V^2$$

F_D is the drag force, ρ is the density of the fluid, A the sail area and V the velocity. (3,7)

2.6. Upwind sailing

To sail to windward (against the wind) a second force has to be added: lift. Lift occurs in a direction perpendicular to the oncoming flow direction. (3,7,9)

2.6.1. Water forces

As the boat travels with a speed v_s on a certain course to windward the drag (D_H … hydrodynamic drag) of the boat is in direction of the moving fluid. In order not to go backwards the underwater part of the boat (keel, hull, centerboard and rudder) has to be on a slight angle (β). The second force created is the lift (L_H … hydrodynamic lift) which can be much larger than the drag. As a result you get the hydrodynamic force (lift). (R_H) (3,12)

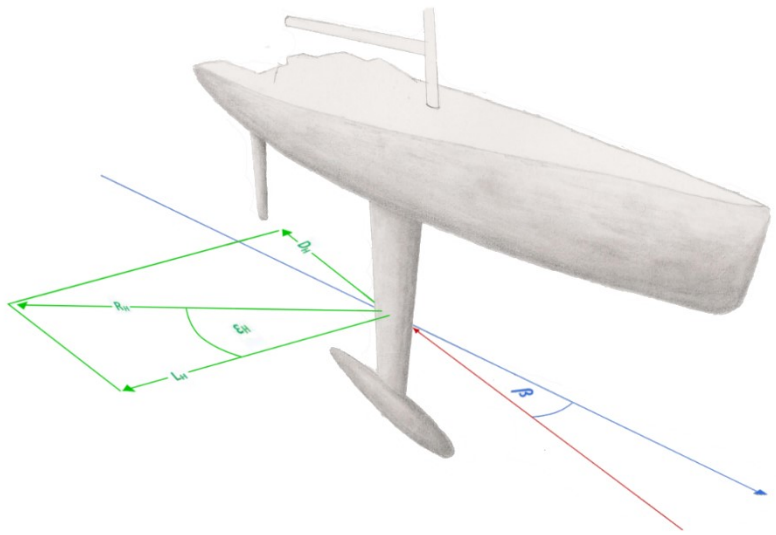

Fig. 7 hydrodynamic forces on the keel of a boat (provided by Georg Bauer)

2.6.2. Wind forces

The same happens to the sails. The apparent wind (v) (compare chapter 1.2.) is the wind as measured in the reference frame of the moving boat. Therefore one has to adjust the mainsail to it, creating the aerodynamic force (R_A) which can be split to a lift component (L_A) and a drag component (D_A). (3,7,12)

As already discussed in chapter 1.4., in a state of steady movement there has to be an equilibrium between the total aerodynamic and hydrodynamic forces.

2.6.3. Lift

When looking at aerodynamic wings in an experiment, one can see, that if a wing is positioned in the right way, the flow line (in ideal liquids) separates at the front tip of the wing and connects again on the trailing end of it, although the time of the upper and the lower stream is different. As H. Babinsky demonstrated (11) there is not only a speed difference but the two streams arrive at different times as well resulting in a pressure difference. Due to viscosity and flow detachment there is a more or less small zone of turbulence at the end of the profile[7].(3,9)

In an ideal liquid with no friction, there would neither be any turbulences nor a dynamic lift. On the other hand surface friction is only significant in a very small distance (boundary layer – very close to a solid surface). (Fig. 7a) (9). When the air particle travels along a wing one can see that the travelling line is close to the wing-profile and thus on a curved track. Because of the changing of direction there must be an additional force (centripetal force) which is generated by pressure differences implemented by the pressure difference on one side of the particle due to friction (adhesive force) (11).

As result of forces, a small vortex is created that detaches with increasing speed creating a counter-rotating flow around the wing (bound circulation) due to the conservation of angular momentum. With the bound circulation the flow is given an additional speed which helps to smooth out the flow at the tail of the wing. According to the Bernoulli theorem[8] this circulation and flow has the effect that the air stream on the lee side of the wing is faster and thus the

[7] For further details see Marchaj 2003 *Sail Performance*

[8] "Bernulli's theorem states the relation among the pressure, velocity, and elevation in a moving fluid (liquid or gas), the compressibility and viscosity (internal friction) of which are negligible and the flow of which is steady, or laminar. It furthermore states that in effect, that the total mechanical energy of the flowing fluid, comprising the energy associated with fluid pressure, the gravitational potential energy of elevation, and the kinetic energy of fluid motion, remains constant."(13)

pressure is lower than on the windward side of the wing – slower and therefore higher pressure (9,12). This pressure difference creates the lift.

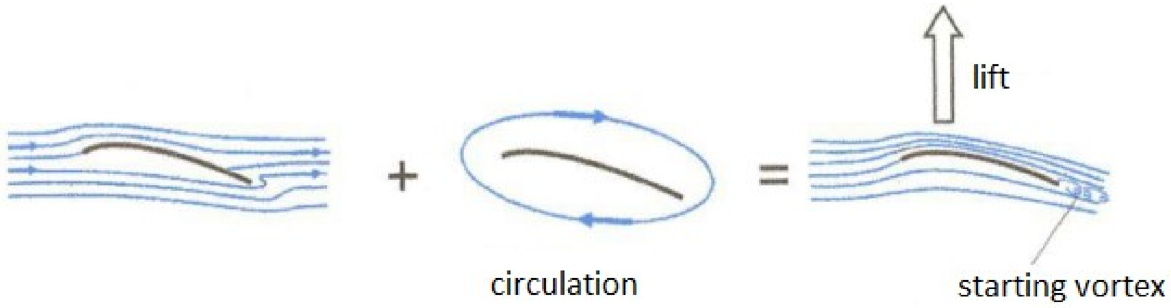

Fig. 8 Surrounding airflow of a wing-like structure through a ideal liquid (a), adding a circulation (b) and in a real liquid with all additional forces as explained in the text. (adapted from 7)

With the theorem of Kutta-Joukowski the lift can be described with the following formula:

$$\frac{L}{b} = -\rho v_0 \, \Gamma$$

L ...lift

ρ …density $[kg * m^{-3}]$

b … wingspan $[m]$

v … streaming velocity $[m * s^{-1}]$

Γ … circulation

The minus sign is necessary because in the coordinate system chosen, the undisturbed flow is in the positive x direction, the bound circulation is assumed to be clockwise, which is mathematically negative, and the lift is supposed to be in the positive y direction. This an essential 2D formula, referring to a section of wing e.g. in a flow channel. (9,11)

To sum up, with some additional corrections[9], the lift can be described as:

$$L = \frac{1}{2}\rho v_0^2 c_L A$$

L… lift

ρ …density $[kg * m^{-3}]$

v … streaming velocity $[m * s^{-1}]$

c_L… properties of the profile design, Reynolds number and dependence on attack angle

A… wing area [m^2]

[9] Further informations compare Püschl 2012 *Physik des Segelns*

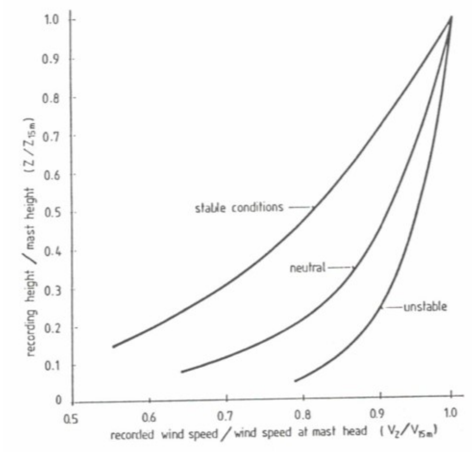

Fig. 9 wind speed as a function of height (over ground) in different meteorological conditions and sea state (stable, neutral and unstable conditions). The height is to be seen as a fraction of the mast height (15m above water) and the wind speed as fraction of that at the masthead. (6)

2.6.4. Twist

As already stated in the sections above, the wind changes speed and direction with increasing height above the water surface. This happens because of friction on the surface that slows the lower true wind down. The wind speed gradient is also influenced by convection resulting from temperature differences between water and air because it favors vertical momentum transfer. This effect is stronger the more unstable the layers are (Compare Fig. 9). For sailing this is important because the apparent wind meets the boat from a more forward direction than the true wind. (4,9)

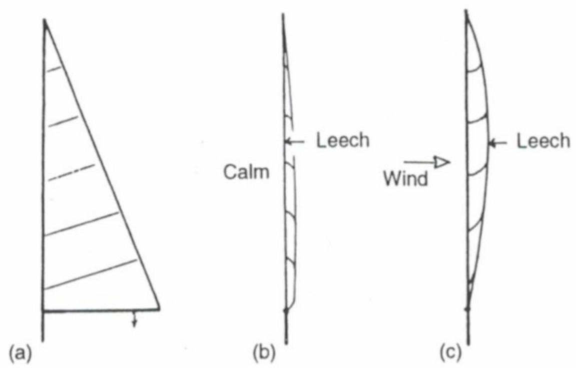

Fig. 10 In calm weather conditions the leech – the free part of the sailcloth - lies straight down and shows no twist (b). As soon as the wind effects the sail, the leech is forced to leeward resulting in a twist in the

Due to these effects sails have to adapt and therefore the shape of the sail has to change. As already discussed a large lift/drag ratio does not ensure a good windward ability (12). As Garrett states there are three factors that produce lift in the sails:

- Angle of attack
- Sail shape
- Chord length

Fig. 11 A 29er sailing skiff in a gust. The twist in the sail can be seen as the upper end of the leech is much further to leeward than the part fixed to the boom. (Author)

All of these factors vary with the position up the sail and the important thing is to find the best position/setting for each section along the sail. As for sailing this twist affects the total drag, as the angle of attack and hence the lift distribution is altered.

> *"Twist is measured by comparing the angle of a straight line between luff and leech with that of the boom. It is best estimated in practice by positioning oneself directly behind and in line with the boom and comparing the line of the leech with that of the mast."*(12). (Compare Fig.10)

The main criteria is that the higher from the surface you get, the stronger the true wind gets. As a matter of fact the apparent wind changes (speed and direction) and therefore the angle of attack increases. If not altered, the lift would increase resulting in a heeling momentum and a loss of speed or capsize. Therefore the sail should twist to keep the angle of attack constant. To alter and control the twist, a boom vang[10] is installed to tighten the leech and therefore to bend the mast aft. This tightening allows the sail to flatten (reduce camber[11]) and especially in a stronger breeze twisting the sail more open as seen in Fig. 11 (6,12).

[10] A system to pull down the boom to flatten the sail and to control the leech tension. (4)

[11] Camber describes the depth/curvature of the sail (4)

"So whether twist is wanted or not there is no escaping it. The consequence of this is that much handling lore reduces to ways of optimizing performance in the presence of twist which is not wanted but which cannot be avoided" (6)

In sailing the best performance is obtained when maximizing the forward drive whilst keeping the boat as flat as possible with as little heeling moment as possible. Basically maximizing the driving force for a given heeling force (12).

2.7. Planing

When placing an object in the water a certain amount of the object is under-water, displacing water and creating a buoyancy which is equal to the weight of the displaced volume of the water. (14,15) When that object moves, it creates 3 forms of drag: form drag, induced drag and skin friction. When sailing, this drag is directly proportional to the total wetted area of the hull. Further influences on the drag are: smoothness of the hull surface and the viscosity of the water (12). Especially at low speeds the skin friction drag effects the sailor at a much larger scale than in higher speeds.

2.7.1. Friction drag

As already mentioned in chapter 2.6.3 a particle that touches the surface of the sail/hulls experiences a certain breaking effect and affects the adjacent particles. This process repeats itself so that the layers of particles have different speeds. These so called boundary layers have a strong effect on the flow around a solid object (ie. sail or hull). The speed difference between those layers can reach from zero (at the surface) up to the flow velocity outside these boundary layers. What can be said is that the areas, like the bow of the boat or the leech of sail, have a small boundary layer thickness, in contrast to a further aft position where the layer becomes thicker but a lot more turbulent. With increasing speed the friction drag and the layer thickness becomes thinner. Marchaj states *"that thinner laminar boundary layer absorbs less energy from the external flow than thicker turbulent boundary layers, the friction drag of foils (and hulls too) subjected to laminar flow is lower than that experienced when boundary layer is turbulent."*(3) Friction drag can therefore mainly be influenced by the form of the hull /sail or even more important by the smoothness of the surface but is not directly proportional to the wetted area of the hull. Generally seen the smoother a surface is the lesser the drag. (3,9)

2.7.2. Wave drag

The second hazard for a planing boat is wave drag. Producing waves (from the boat) is in need of energy generated by the moving hull. The wave produced by the moving boat depends vaguely on the size of the bow/stern of the hull and the shape and speed. Ross Garrett describes a bow wave: “a bow wave can be thought of as a pileup produced by the hull forcing its way through the water.” (12) with this explanation it implicates that a certain “hole” is created at the stern of the boat that has to be compensated. Depending on the speed of the moving boat the bow and stern wave have a wave length lesser than the boat length. The faster the boat sails, the higher the bow and stern wave becomes, the longer the wave length gets the more drag is generated. With increasing wave drag a certain point is reached which is called hull speed – when the wave length is the same length as the boat. This hull speed does not mean that a boat cannot sail faster but after this point the boat experiences a significant increase of drag. Compare Fig. 12 and 13 a heavy keelboat and a 49er hull. (4,9,12,16)

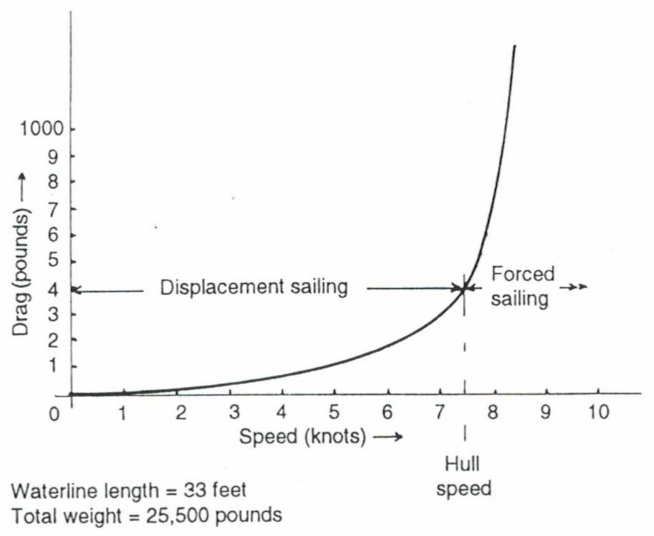

Fig. 12 Drag curve of a heavy keelboat (3)

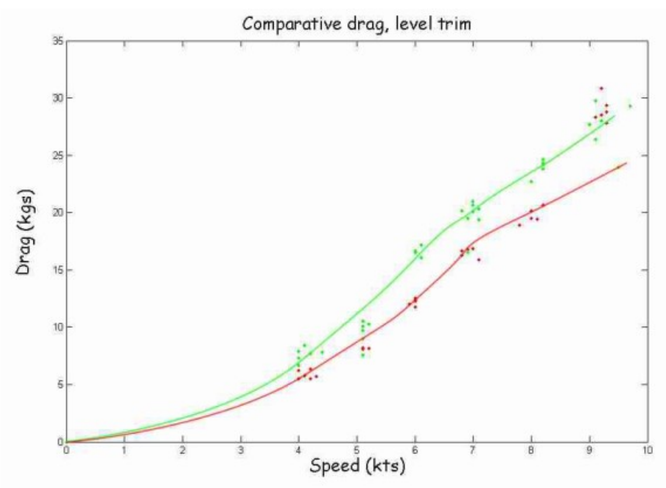

Fig. 13 drag curve of a planing 49er hull (the bend at around 6 kts is the point when the boat starts planing. (13)

When sailing a yacht in displacement mode[12] , especially with larger yachts, the drag increases as the wave length also increases to a length greater than the boat length and the aft sinks deeper in the water than the bow until the boat has to sail "uphill" – up the wave (Fig. 14). (9,14)

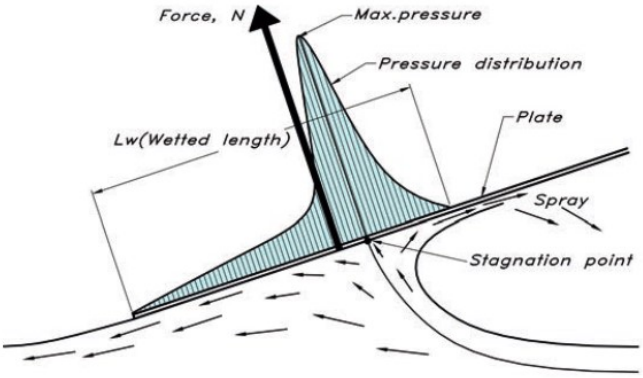

Fig. 14 Model of a planing plate with a pressure distribution graph (10)

Smaller boats, such as skiffs, reach a state where they overtake this "wave", leaving the wave behind creating an effect with very little hydrodynamic drag although the boat has to be "carried" by another force – hydrodynamic lift created by the excess pressure under the hull. In Fig. 14 the velocity vectors underneath the planing plate are shown in direction of the flow relative to the plate. At the stagnation point it can be seen that the vectors hit the plate at a right angle. This point indicates the highest pressure since the kinetic energy is converted into pressure. Further back along the plate the vertical component of the pressure is reduced but still creating lift, balancing the weight of the boat, relative to the pitch angle.(14)

Generally seen it can be said that short but wide plates plans better, faster and better than boats with a deep hull. Therefore fast planing boats, like skiffs, have a very flat but wide hull (9,16).

Fig. 15 Picture of a 29er Hull with the flat but wide transom and a very pointy and narrow bow. (Author)

[12] The displacement of water of the boat is equal to its own weight. Displacement mode or hull speed is the speed at which the wave length of the bow wave is equal to the boat length.((17)

Püschl 2012 defines three characteristics for a good planing boat:

- Light weight to easily overcome the bow wave.
- A wide but flat transom with a sharp edge where the flow may easily be separated.
- Enough propulsion force like big sails to create enough aerodynamic lift. To handle these large sails the crew can trapeze to create more righting moment.

High performance boats like skiffs reach their high speeds only when planing. With extremely large sails areas in comparison to their displacement they have to rely on their crew to stabilize the boat. Therefore when planing, sailing upright in means of heeling is prerequisite to go fast, but even more important is the pitch. Especially when sailing downwind with a large gennaker the bow has to be lifted out of the water to avoid pitch poling[13].Both forces have to be equalized the crew in the trapeze. Viola et al.2013 investigated with planing skiffs and found that at low speeds the weight has to be shifted forward to help to get the wide transom out of the water to reduce the suction of the wide transom. The faster the boat sails the weight can be shifted further aft to reduce the resistance (18)

a)

b)

c)

Fig. 16 Towing test of a 49er hull at below (a), exactly at (b) and over (c) hull speed. The black line along the wave patterns indicate the wave systems at various speeds. (13)

---

[13] Burring the bow in the water ahead of the vessel and the aft is lifted clear of the water up and rotates over the bow (18)

3. Carbon fibres

Carbon fibre is a long, thin strand of material with a micro graphite crystal structure. These carbon atoms are aligned parallel to the longitudinal axis of the fibre.(19)

There are a various benefits of carbon fibre and reasons why it's the choice of material in the sailing industry:(19)

- Lightweight: carbon fibre has a very high strength to weight ratio, which makes it more attractive than aluminium or steel.
- High tensile strength: Carbon fibre has a high tensile strength[14], which makes it one of the strongest fibres in the commercial industry.
- Resistant to corrosion: due to the strength of carbon-carbon bonds, it is very resistant to oxidization (e.g. salt water).
- Low CTE (Coefficient of thermal expansion): A low CTE means, that carbon is very unlikely to change its shape when being exposed to heat or other outer influences.
- Exceptional durability: Objects made of carbon fibre don't easily deteriorate under the stress of daily use.

In these days about 90% of the commercial carbon fibres are made either of PAN (polyacrylnitrile). The remaining 10% are either made of rayon or pitch. These raw materials, also called precursors, are all organic polymers. Their chemical structure are long string shaped molecules, which are tied together by carbon atoms. Fibres derived from PAN are used for a wide array of applications such as aircraft brakes, space structures, lithium batteries, sporting goods etc. Pitch is known to have an ultra-high elastic modulus[15] and an ultra-high thermal conductivity[16]. (19)

These physical characteristics are the reason why Pitch is extremely useful for any field of application where stiffness and heat removal is important – such as critical military and space applications. (19)

3.1. Production of Carbon fibres

[14] Tensile strength is "…a measure of the resistance that a material offers to tensile stress. It is defined as the stress, expressed as the force per unit cross-sectional area, required to break it".(20)
[15] "The Young modulus of elasticity, named after the British physicist Thomas Young, refers to longitudinal stress and strain" (20)
[16] "Thermal conductivity is a measure of the ability of a substance to conduct heat". (20)

The production of carbon fibres is partly chemical and partly mechanical. It includes the following steps: (19)

- Stabilizing

Before the fibres are carbonized, they need to chemically change their form from a linear atomic bond to ladder bond, which is chemically more stable. To reach this they have to be heated up to about 200-300°C for 30 – 120 minutes. In this period of time the fibre picks up oxygen molecules from the air and alters its atomic bond. The chemical reactions of stabilization are a complex process and several reactions occur simultaneously. They also tend to produce heat. This is why overheating of the fibres must be prevented.

In the commercial industry stabilizing includes a variety of steps and techniques, which differ from company to company.

- Carbonizing

After stabilization the carbon fibres are placed in a furnace filled with a gas mixture (without the presence of oxygen) and heated up to 1000 – 3000°C for a few minutes. During this heating process the fibres lose their non-carbon atoms and a few carbon atoms in form of gases, such as water vapour, ammonia, carbon monoxide and carbon dioxide, hydrogen and nitrogen. The remaining carbon atoms realign in tightly bonded carbon crystals.

- Treating the surface

After carbonization the fibre surface does not properly bond to the epoxies and other materials used in composite materials. Therefore the surface is slightly oxidized by dipping it in gas, such as air, carbon dioxide, ozone or in liquids, such as sodium hydrochlorite or nitric acid. As a result better chemical and mechanical bonding properties are achieved.

- Sizing

During the process of sizing the carbon fibers are coated by an adhesive to protect them from damage by wind or water or during weaving. Typical coating materials are epoxy, polyester, nylon, urethane and others.

3.2. Carbon fibres in Sailing

The two biggest advantages of carbon are its mechanical strength and its fatigue strength. In sailing this means being able to perform greater strength with lower weight. The result is greater boat speed and a more stable boat. Due to a greater impact strength and reduced weight sailing has become safer as well. (21)

The biggest benefits in performance can be found in carbon masts, carbon hulls and building ballast fins out of carbon, starting from the top down to the bottom.

3.3. Carbon Masts

Carbon masts have following benefits:

- During sailing the carbon mast is generally seen stiffer and therefore it doesn't need as many additional add ons to stabilize the mast (eg.: spreaders or diamonds) and therefore makes it easier to sail the boat with a shorter crew. As a result of the lighter weight the pitching and heeling is being reduced.
- Especially on larger boats, carbon masts reduce rolling when standing still (during mooring) as the center of gravity is lower than with the heavier alloy masts.
- The outer influences of carbon are a lot less than with aluminum. Especially saltwater doesn't affect the carbon as much and therefore its lifespan is much longer. (22)

3.4. CST - Compsites

Being an Australian company working with Julian Bethwaite in projects before, CST-Composites were the first to agree in the process to create a new mast for the 29er. The company founded in 1995 *"have focused on the manufacture and design of cost-effective, yet high quality, filament wound tubing. CST Marine is a division of CST Composites focused on providing high performance products for a variety of boat classes."* (23)

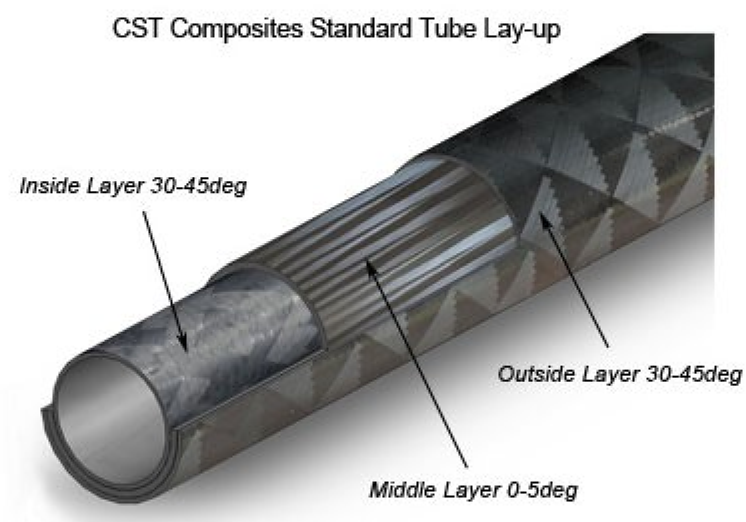

Fig. 17 construction of a carbon mast with different layers. (38)

The used technology for the mast is a filament wound technique to create tubes that are stiff but flexible at the same time. *“Filament winding is an automated process of wrapping resin impregnated filaments (called rovings or towe’s) over a rotating male mandrel in a geometric pattern. This is then cured under high temperature and pressure.”* (24) Advantage of this method is the accuracy of the automatic process resulting in a strong and reliably product with little weight.

A standard mast is wound with three different layers of carbon fibres. The inside layer is wound in an angle of 30 to 45 degrees. The middle layer 0-5 degrees and the outside layer 30-45 degrees again. (24)

4. The 29er (2)

In 1996 the 49er was introduced as an Olympic class for sailing. This class was completely new and had nothing to do with classical dinghy sailing.

Not only the tactical decisions for winning races are extremely demanding, but mainly the technique of sailing these boats is not comparable with any other boat. Only the 18 Footer has similarities to the modern 49er but sailing a big boat with three people is even more demanding than sailing a boat with two.

> *"This used to be called the X^2 law, one person reacts perfectly with her/himself because he knows what he is about to do. 2 people, is 2^2 so 4 times as hard because they have to know what each other is about to do, and that's not given, add a 3rd and its 3^2, so 9 times as hard to make it work."* (25)

The problem was that learning how to sail these boats was only possible when sailing a boat that behaves exactly like this.

> *"This all has to do with hard wire reaction times. You really need to start sailing a boat of the same genre by about the age of 12-13, very similar to learning a 2nd language, yes you can do it latter, but it so much harder and less complete."* (25)

The main differences to a classical 470 or a Laser, that Frank Bethwaite found, are (4):

- Sailing to windward at speeds well in excess of hull speed.
- Tacking downwind is faster than the wind with the apparent wind forward of the beam.
- Helming from the trapeze
- Carrying a wing-like asymmetric spinnaker which calls for a different handling skill from handling a parachute spinnaker
- Tactical decisions on which side is best is a new component that no other class has got. Looking at a lot larger areas of distant wind is a criteria to win or lose.

Looking at these criteria it is obvious that sailing on "planing-trapeze helmed-huge sails carrying-apparent wind boats" (4) has to be trained differently than other classes. Especially the young sailors are not able to sail the 49er as the rig is just too big and the change from a 420 or a Laser II to the 49er is simply not possible at a young age.(4)

4.1. Development and early tries

Developing a new class is always a matter of trial and error.

„Superficially they all look like a cross between a brick and a skiff, because to look something like a skiff is what they were designed to do. But at the performance level, none of them could tack downwind faster than they could run square in most winds. […] They cannot deliver fast, reliable, apparent wind sailing, and to contemplate using this sort of contraption as a serious youth trainer was irresponsible" (4).

Mistrials were always part of the game. The first prototypes just couldn't tack downwind and furthermore wouldn't sail faster than the wind. Frank Bethwaite – the mastermind behind the 49er in the 1990s – tried to adapt a Laser II[17] – a youth training boat for learning to sail 470s or other boats – to create something like a skiff. Soon Frank Bethwaite and his son Julian Bethwaite agreed that these adapted Laser IIs were just a partial solution to the problem of creating a youth trainer for the 49er. Sketching different styles of rigs only made them look like "Twelve foot skiffs" which led to the conclusion they had to start completely new to create a "skiff to train for a skiff"(1) . In order to create a boat like this Julian and Frank decided they had to ask the people that had to sail these boats – the youth sailors – what they actually needed. (4)

As Frank Bethwaite had two sons that sailed boats like the 18 Footer he knew that it is extremely important to have youth boats in order to create training possibilities for young sailors. The main problem especially today is, that sailing gets "boring" if sails and boats are too slow. This is why you need a boat that is fast but not too dangerous as the 49er or the 18 Footer (25). Looking at the financial side of the 49er it was funded by a consortium of a Japanese, an American, a Brit and the family Bethwaite. This worked very well for some time. Later on with the 29er Frank Bethwaite and his wife Nel decided to finance this new project by themselves. (4)

At the time Julian Bethwaite was one of the best international skiff sailors either on 18 Footer prototypes like the B-14 or the B-18 (Fig. 18) or the 49er and in addition he was a student of Industrial Design so he started applying ID techniques to boat design. The general idea for the 29er concept was his. Scaling down an existing boat to the needs of a youth is difficult. Looking at medical data for average weight and limb length at various ages was part of the research that had to be done to create a boat like this. Taking the B-18 Mk IIIC hull – probably the fastest 18 Footer hull at the time – and looking at the proportions and forms of the boat Frank and Julian Bethwaite decided on how the new boat had to look. Considering the limits of transport on land, wing width and the gunwale beam was fixed by the Traffic Authority's to make them easy to transport. The underwater shape minimum limb length and flotation needs were decided on basis of the measurements from the B-18. The only difference was that the

[17] For further informations look at the International Laser 2 class association. (26)

29er concept was meant to helm the boat sitting on the gunwale in the cockpit and the forward hand on trapeze in contrast to the 49er and B-18, both of them helmed from the trapeze making it easy to “run” from one side to the other. As a result the deck had to be redesigned with something like a cockpit. (3)

Fig. 18 B14 1988 (3)

> *“I wanted to keep the freeboard and profile low for least aerodynamic drag, but too-shallow cockpit is uncomfortable. I checked existing designs and observed that an 8in depth was regarded as acceptable by young crews”*(4).

It took 4 prototypes to get the best prototype[18] of the standard 29er.

4.2. The Standard 29er (27)

Fig. 19 schematic representation of the 29er (27)

[18] Prototype development and descriptions are to be found in the appendix.

weight (with complete rig)	90kg
Length	4.45m
Width	1.77m
mast height	6.25m
main and jib area	13.19m^2
genacker area	16.83m^2
Designer	Frank and Julian Bethwaite
Year of final design	1998
Hull	Glass reinforced polyester
Mast	Upper part: carbon Lower part: alloy
Sail	Main and jib fully battened Mylar foil from McDiarmid Sails. Gennaker: triradial, asymmetric

4.2.1. Standard 29er Sail plan (28)

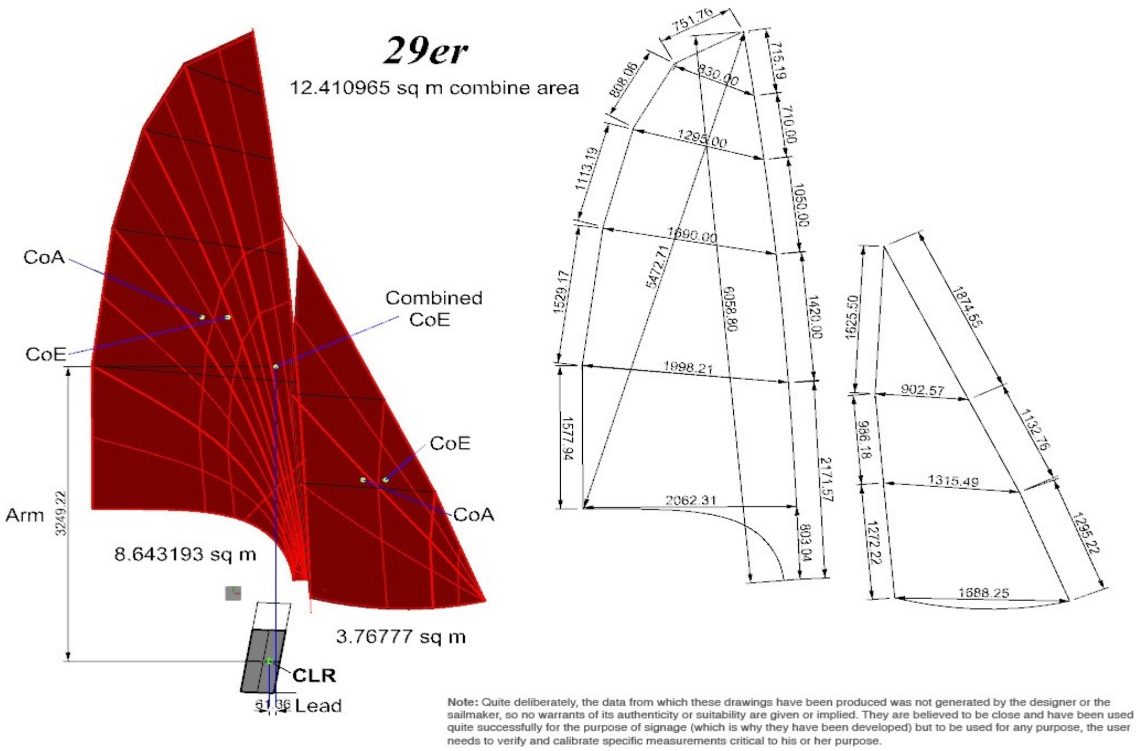

Fig. 20 standard 29er sail plan (not officially from the designer) (28)

5. Analysis Methodology

The aim of this thesis is the comparison of two different rig and sail styles: an old-style 29er rig using a conventional alloy-carbon mast with a pin head sail with an innovative carbon mast and a square headed main sail.

The experiment took place in Austria on two different lakes where different advanced 29er teams sailed, equipped with measuring wind-, GPS- and Speed measuring systems, against each other to analyze the differences of the two rig concepts. As part of the investigation the speed (only the progression during a tack) was analyzed as well as sailing angles to the true wind.

5.1. Influencing factors

The analysis is conducted on test data that is collected via test runs of two similar boats, equipped with either one of the two sailing rigs. The boats are each sailed by experienced sailors that are competent to sail this boat class.

Based on the data, which has been collected within this work, the conclusions are based on the following evaluation criteria are on-water performance criteria, which are defined as follows:

- speed gains in gusts
- stability in lulls
- boat handling and seamanship

Generally speaking it is known (compare e.g. Watin 2007) that the square headed main sail, with a proper carbon mast, is faster and is to be sailed smoother in gusty conditions, but as this rig is a prototype of its kind, no one knew how it would behave in real-live situations on a 29er or other skiffs as there is hardly any real data on the performance of high performance skiffs, although it can be assumed that the results are quite similar to those of the 49er. A general comparison can be made with other boat classes that changed already to square tops (eg. The big America's Cup catamarans (AC45[19]) or the 49er[20])

The focus of the thesis is to find out if the speed-gain in gusts and lulls is that significant, to change the class of the 29er to a full carbon mast system.

[19] Compare (29)
[20] Compare (16)

The second objective was to create a polar diagram for both rigs in order to make them comparable.

In order to conduct a representative performance test of two test objects, the equipment, the sailors as well as the environment have to be taken into account. As environmental factors, the following influences have been

- wind speed, gustiness, wind angles and shifts
- wave height and length

More complex factors like water depth, salt water versus freshwater (density), as well as temperature, air pressure and other external influences are neglected during the test runs in order to keep track over the data and not getting lost in too much detail as they do not make a difference in the intended outcome. All test runs take place at the Austrian Lake “Attersee” (compare chapter 4.3.) to sustain comparable results.

The underwater part of the boat – centerboard and rudder – is ignored as both boats have the same.

	Standard 29er	Carbon 29er
Material	Alloy /Carbon	Carbon fibre
N° of parts	2	2
Overall mast length	6276	6323
Weight of the rig (Sails and Mast)	10.4 kg	7.8kg
Bend [%]	Approx. 5.5-6%	Approx. 3-4%
Mainsail area	8.643m^2	9.134m^2
Jib area	3.76m^2	3.76m^2

Fig. 21 Picture of the Standard 29er Rig with the pin head (Author)


Fig. 22 Picture of the Carbon 29er Rig with the square top (Author)

As factors for equipment, the most important ones are the rig configuration. The rig configuration is influenced by the tension of the shrouds and the compression of the mast. The listed parameters have been controlled in order to create comparable results during tests:

- the shroud tension according to the wind speed
- the correct setup of the mast, the compatible sails

To provide similar and comparable testing conditions the shroud tension has been measured with a PT-1 tension gauge[21]. The standard mast has just one shroud, while the prototype mast has two shrouds. The only difference considering the shrouds is, that the D1 shrouds (the lower ones to adjust the lower bend) on the prototype were made out of dynema chord and therefore do not have to be adjusted as exactly as the main shrouds. (Annotation of the boat builder: This is a safety decision. The D1 shrouds on the 29er are very low and there is not much space for the sailors. In order to keep the young sailors safe and not cutting themselves with the wires the dynema was used.)

The shroud tension has been adapted to the wind conditions according the following table.

Wind speed [kn]	main shrouds	forestay
7-9	27	18
10-15	28	19
18+	31	21

Wind speed [kn]	D1 shrouds (dynema)	main shrouds	Forestay
7-9	No tension	27	17
10-15	No tension	28	18
18+	No tension	30	20

The test boats are sailed by experienced but not professional 29er sailors:

Sailor 1	Helm	60 kg
Sailor 2	Crew	71 kg
Sailor 3	Helm	62 kg
Sailor 4	Crew	58 kg

[21] Loos&Co., INC. Cableware Division (30)

Sailor 5	Helm	74 kg
Sailor 6	Crew	70 kg
Sailor 7	Helm	80 kg
Sailor 8	Crew	60 kg

5.2. The measuring system

The measuring system was mounted on two similar 29er skiffs. One with the standard alloy mast with the pin head main sail and one carrying the full carbon rig with the square top main sail. Both boats had similar jibs (compare chapter 3.).

Fig. 23 The wind measuring system „IQ“ developed by Julian Bethwaite. (Author)

To measure the on-water performance a wind measuring system was used, which was newly developed and built by Julian Bethwaite. This newly developed system is called “IQ” and according to the manufacturer and programmer (defined by the hardware inside) the accuracy is:

Wind speed: 0.8 – 125 km/h ± 0.5%
Wind direction: 0-360° ± 0.5°

To get GPS data and to save the collected data an IPhone SE was used. The IPhone uses an assisted GPS[22] and GLONASS[23] technology and a digital compass (31) The IPhone was placed in a sail pocket next to the boom, recording speed, heading, position and time. The wind sensor (Fig. 23) was placed at the mast top, recording, true wind speed and true wind direction (with a digital compass). As we do not look at maximum speeds the accuracy provided by the IPhone was regarded as sufficient. It is clear that testing in real life situations – on water– loads of influences occur whilst measuring (heeling, pitching,…) that won't be taken in account but will be considered during the discussion. Circumstances like waves or human errors – sailing mistakes – can be seen in the outcome but will be neglected.

To cross check the wind data a standard anemometer[24] and a standard compass was used, taking its readings from an inflatable powerboat at a distance, less than 200m from the sailing boat.

5.3. Experiment process

The first stage was about test setup and handling. Within a testing-period of 4 months different crews have evaluated the two test objects. In the first phase the test objects have been adapted to the two test boats in order to have representative results within the test phase. Focus of this phase was to determine rig tensions for testing conditions. Within this period, the sailors learned handling with both test objects, in order to be able to sail steady angles for the testing phase.

In the second stage of the experiment the differences on water with 2 different crews during 3 days of sailing on the Austrian "Attersee" lake and 2 crews on 1 day at the "Neusiedlersee" lake. During the tests on the "Attersee" the conditions were quite challenging as we had moderate but gusty winds on the first day and hardly any wind on the corresponding days and very strong winds on the "Neusiedlersee". Though these days were difficult we got a good set of data. The third stage was to analyze some of the sailors' subjective feeling on the boat in comparison to the standard rig.

Location	Morning	Afternoon
Attersee (1st day)	5-8 knots (gust 12 knots)	8-10 knots (gusts 15 knots)
Attersee (2nd day)	4-6 knots	2-5 knots
Attersee (3rd day) (no relevant data)	1-3 knots	1 knot

22 GPS – Global Positioning System
23 GLONASS – Global Navigation Satellite System
24 Windmaster 2, Kaindl electronic [± 4%]

Neusiedlersee	18-25 nots	

5.4. Use of Polar diagrams

A polar diagram basically shows the velocity (SOG – Speed Over Ground) for a course to the true wind (TWA – True Wind Angle). These diagrams (compare Fig. 24 and Fig. 25) show what course is the fastest to reach a certain point while sailing. This is also known as the VMG – velocity made good.

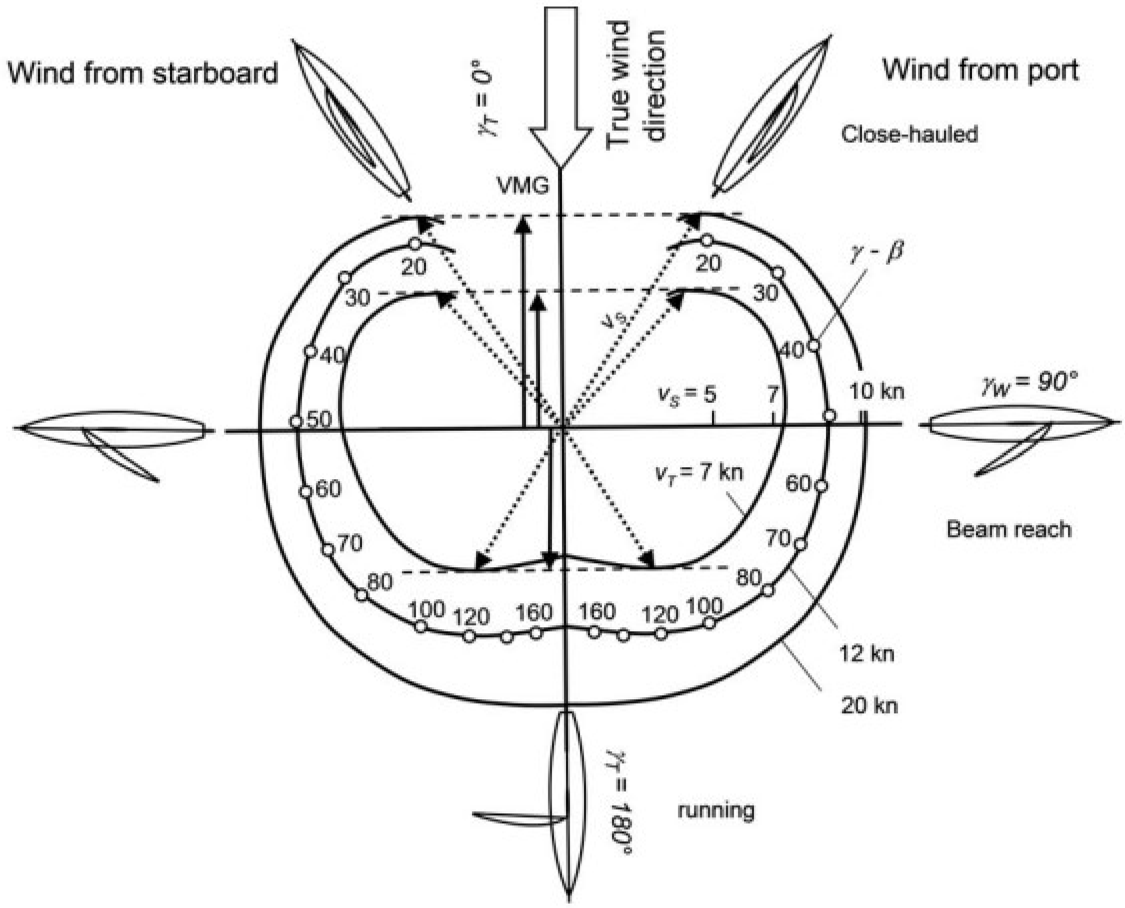

Fig. 24 Speed Polar diagram for a conventional keel boat. Dottet lines indicate the classical racing angles for maximum VMG at given true wind speeds (7, 12, 20 knots). (adapted from (7))

5.4.1. VMG – Velocity made good:

When sailing it is obvious that sailing directly against the direction of the wind is impossible (compare chapter 1.4.). This is why tacking upwind is necessary to get to a mark to windward. VMG is basically the progress you make directly to this windward mark (with downwind tacking boats like the 29er also to the leeward mark) considering the SOG and the TWA. In most cases the SOG is higher than the actual VMG due to the angle one is sailing to the true wind.

As mentioned sailing on a straight line directly against the wind is impossible. Comparing Fig. 24 Speed Polar diagram for a conventional keel boat. Dottet lines indicate the classical racing angles for maximum VMG at given true wind speeds (7, 12, 20 knots). (adapted from (7)) one can see that there are two possibilities to sail to windward: either very closed hauled with less speed but a small angle or fuller, sailing a smaller relative component to windward but with more speed. Which one of these possibilities is better is mostly dependent on the boat class. Skiffs tend to sail with more speed and a not so favorable angle, Laser for example tend to sail a lot higher as the speed cannot be increased to a similar extent by sailing a fuller course.

When sailing downwind it is important to know which sails a boat has. A Spinnaker, a gennaker or none of these additional sails. When running dead before the wind the boat is driven by drag alone and therefore cannot sail faster than the true wind. As already discussed for modern boats it is possible to tack downwind and thus reach a VMG even in excess of the true wind speed. Looking at the polar diagram (Fig. 24) it is easy to see that a running boat is slower than the one that is tacking downwind (with now additional sail). This can be seen on the concave part of the diagram when comparing it with the convex part on each side. The speed on the convex part is higher than the one right when running flat. (Fig. 25)

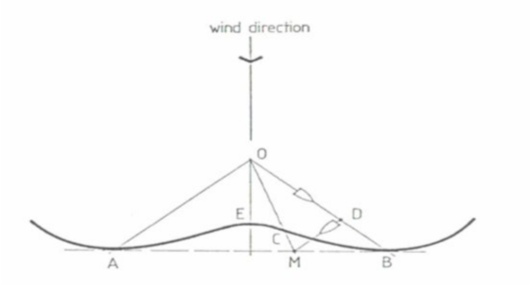

Fig. 25 Downwind sailing Polardiagram with no additional Sail. The course OD and DM indicate the downwind tack to maintain the maximum VMG (9).

This can even be exceeded when using for example an asymmetric gennaker. In the diagram shown Fig. 26 you can see the difference between an 18 Foot skiff and a Tornado. The 18 Foot skiff for example, but also most of the planing boats as well, have an asymmetric gennaker which is used when sailing downwind. As the sail is extremely big it needs a strong air stream to fly properly. The problem is when running the boat speed is almost as high as the wind speed and therefore the sail would not be of any use. Therefore the boat has to tack downwind. There are two advantages: First the speed advantage on a broad reaching course is much greater than the angle advantage and second the faster the boat sails the more the apparent wind rotates forward. As a result the boat can sail a much lower angle and therefore increase its VMG to the bottom mark. In Fig. 26 it is also to be seen that with increasing VMG it is possible to reach speeds faster than the true wind.

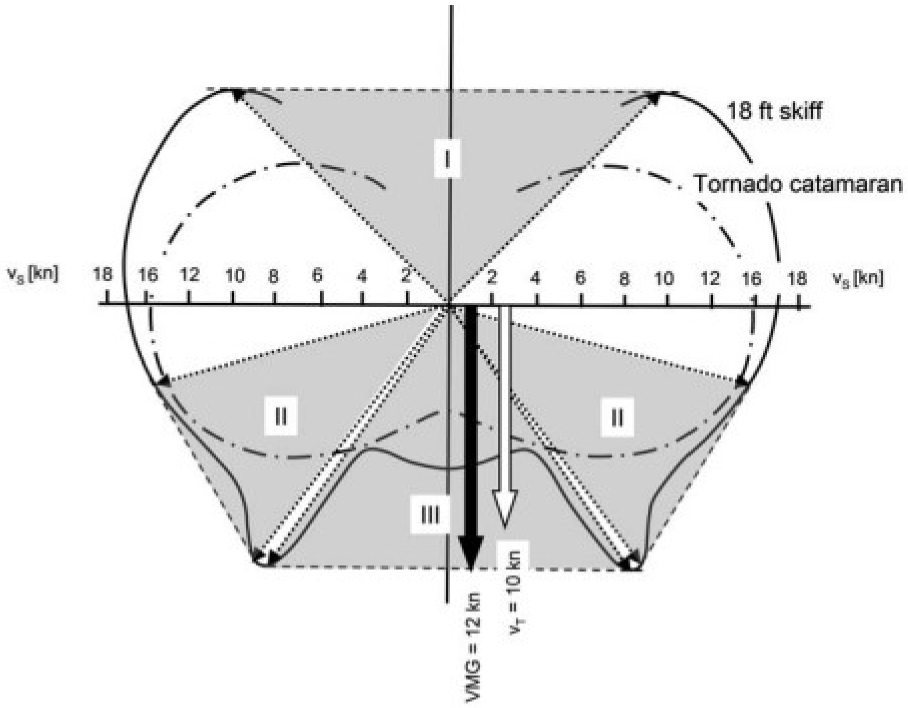

Fig. 26 Polar diagram for a 18 Foot skiff with an asymmetric Gennaker and a Tornado catamaran. (adapted from (7))

6. Results

In this chapter the acquired data is processed and the analysis results are summarized.

The aim is to show the advantages/disadvantages of the two rigs in means of SOG and angles weather the advantages of the carbon mast are significant. For the analyzing process only parts of the whole data will be used. The used data was chosen by the fact when two boats sailed close to each other experiencing almost the same wind. (This will be explained more detailed in chapter 6.1.).

What is already known from previous studies of eg. Simon Watin 2007 (16) and other authors is, that with the combination of the carbon mast and the square headed main sail the overall speed will be slightly higher than on the standard 29er. The expectancy on the sailing angles was, at that stage unknown as many influences affect the outcome.

6.1. Comparison in terms of speed

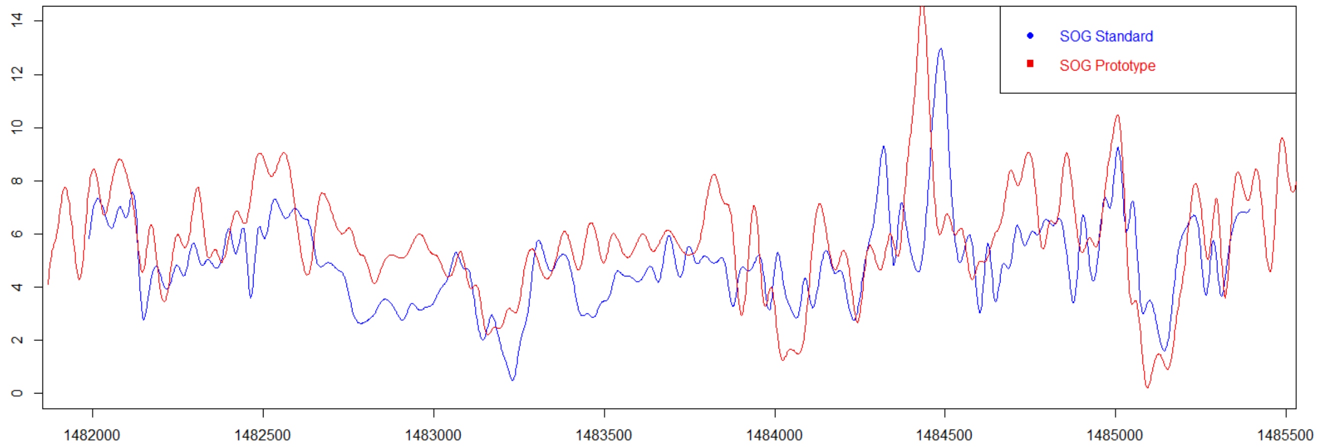

Fig. 27 raw plot of the SOG (no filter or algorithm) over a period. (x-axis … timecode; y-axis SOG [knots]

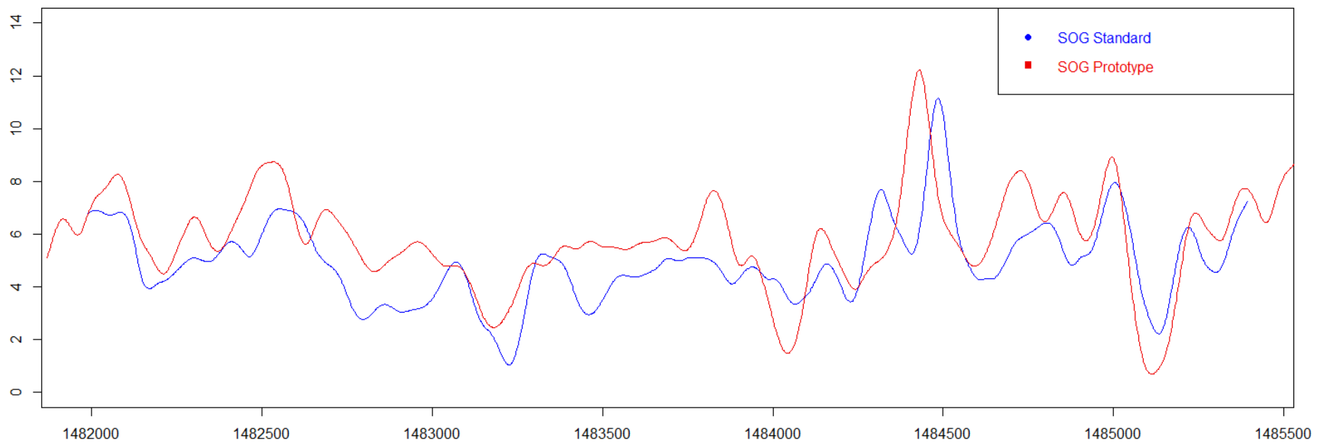

Fig. 28 same plot as Fig. 24 only with a smoothing filter to eliminate the noise of the speed peak.

The first part was to investigate the difference in speed.

In the overview of the sailed sessions there are two main issues that can be seen when looking at the graphs (Fig 27 and 28) One of them is the consistency of speed and second is the absolute speed over ground (SOG). Considering the graph of the standard rig it is to be seen that there are a great amount of “jumps” - although they are small – and even more important the speed losses are greater in the line of the standard (Fig 27). This is mainly a result of the way this boat is to sail. Having a great weight at the top of the mast the actual center of gravity is quite high. Considering that, the torque and the rolling of the boat has a significant effect on the consistency of the speed. What is meant, is that every time the boat heels to either side the boat is slowed down abruptly due to the increased drag and also of the decreased attack angle of the wind on the sail. Especially when sailing in regattas this costs speed and therefore won’t lead to victory. Taking this into account it is important to sail a 29er upright and flat – with as little heeling moment as possible - on the water. Especially for intermediate crews this is quite a challenge and makes the 29er so difficult to sail because the hull itself is quite small with a relatively large rig which makes the whole system quite unstable. (Annotation of the author: This is even more difficult when sailing the bigger 49er as the leverages are much bigger. As already stated in the chapter above the 29er is a youth trainer and therefore it is important to learn to sail the boat upright and flat).

Looking at the prototype the main difference is the smoothness of the plot. Taking into account that the standard rig is a mixture of alloy with a carbon top (10.4 kg) and the prototype is a complete carbon rig (7.8 kg), the carbon rig is lighter in weight and even more important the centre of gravity is lower. As a result the attack of the force is lower in the sail and therefore easier to control.

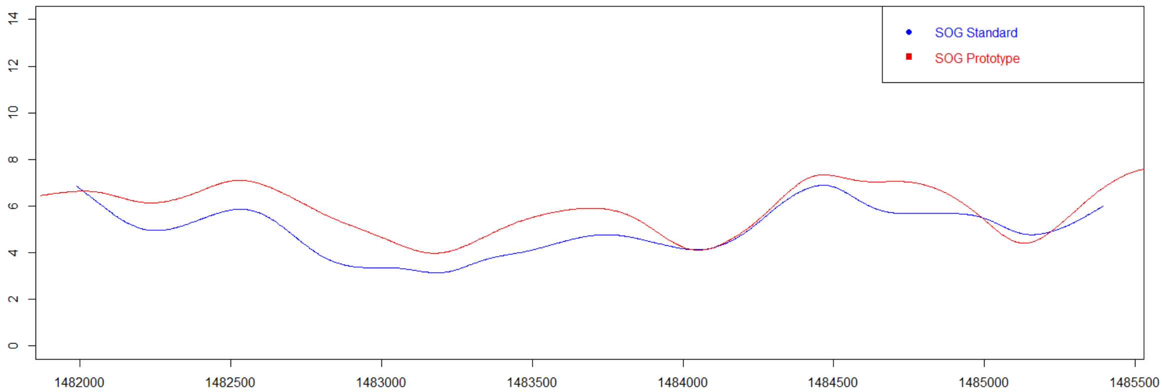

Fig. 29 Same plot as FIg. 24 but with a very strong smoothing filter to eliminate all peaks to see a mean SOG over a certain period of time.

The second objective seen in the results is not that obvious. After applying a strong filter over the results' (compare Fig. 29) tendency of absolute speeds can be seen. Comparing the two graphs one can observe that the prototype has between 15% and 20% more speed overall. This advantage is a matter of two factors: size of the rig (Fig. 30) and less speed losses. Especially the second factor is a result of the lower centre of gravity and therefore less heeling moment, as explained in the paragraph above. When talking to the sailors after testing and also when reading the questionnaires every sailor filled out after sailing the boat, everyone said that especially the square top and the lighter mast made it easier to control as the pressure could escape much easier due to the "automatic rig". (Compare chapter 5)

Fig. 30 The slightly larger prototype rig sail underneath the standard main sail. (Auther) The size of the square top appears larger as there is no curvature of the mast

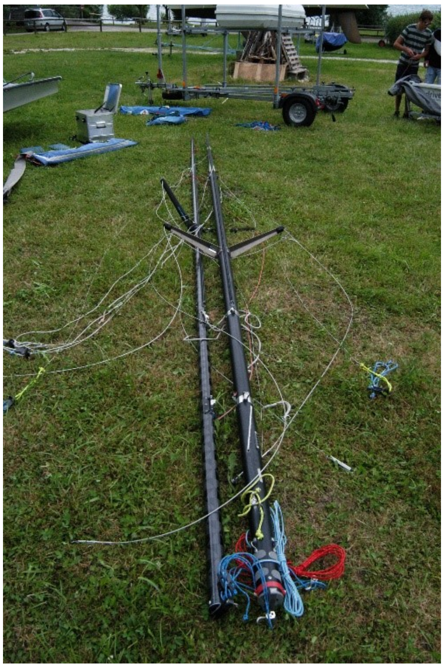

Fig. 31 Different Masts – left the Prototype, right the standard.

6.2. Comparison of sailing angles

6.2.1. True wind angles

The second major criteria when comparing the prototype and the standard 29er is the heading.

Before the comparison can be done it has to be stated that there are loads of outer influences on the heading of the sailing boat:

- Rig tension: when preparing the boat every crew has to set their rig tensions depending on their weight and wind speed.
- Waves and water depth
- Weight and know-how of the crew

- Conditions of the sail

These criteria can be augmented when looking at the angles but will not be taken into account during the investigation.

When comparing the plots of angles one factor hits the eye: The sailing angles of the prototype are different (to the wind) than those from the standard rig. In Fig. 33 and 34 it is obvious to see that the true wind angles of the two boats are different although the two boats are sailing close to each other, in the same wind and not interfering with each other.

Fig. 32 different shape oft he the 29er jibs. On top the standard 29er jib underneath the slightly differently shaped prototype jib (Auther)

This is a factor that occurred right from the first tests and we determined as a matter of different sails. This was also stated in the questionnaires the sailors filled out. The subjective feeling of the sailors was that due to the different shape of the jib and the different behavior the new rig, the prototype has to be sailed on a deeper angle to the wind.

One of the main criteria was that the jib was slightly differently shaped (Fig. 32) with a little more Mylar cloth and therefore a little more camber[25], resulting in the fact that the jib cannot be taken as tight as with the standard rig. As a result the heading of the prototype is more leeward. Comparing it with the overall speed it can be seen that although the angle is larger on the prototype than on the standard, the speed is higher. In terms of sailing this means that the VMG (Chapter 4.4.1.) is still better on the prototype.

[25] Camber expresses the ratio of the bow of the sail to its chord (3)

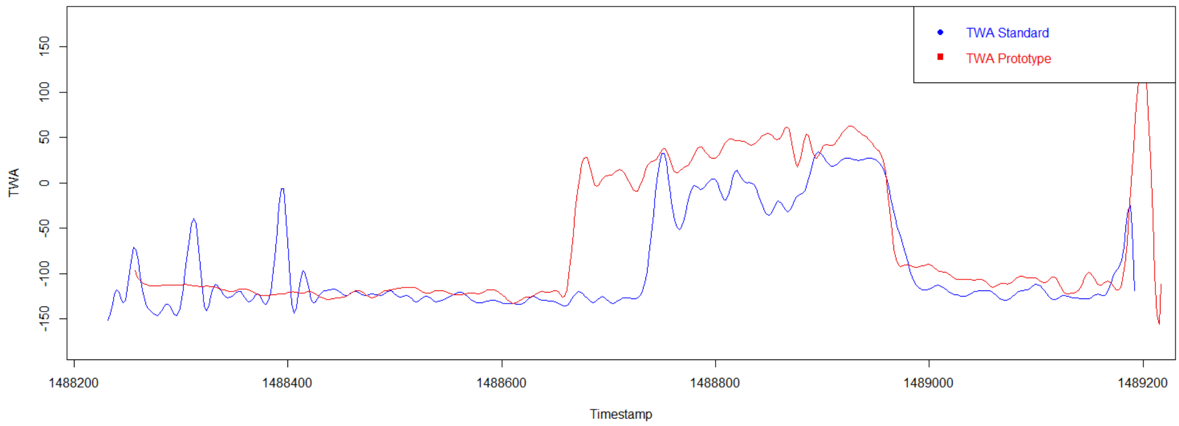

Fig. 33 TWA of the standard rig and the prototype rig showing the different angles of the boats. The analysis showed that the prototype rig has to be sailed on a slightly larger angle to the true wind. Exception here: in the middle part (in this case : during the port tack there was an interference between the prototype and the standard and thus the standard cannot sail as high as it did before the tack).

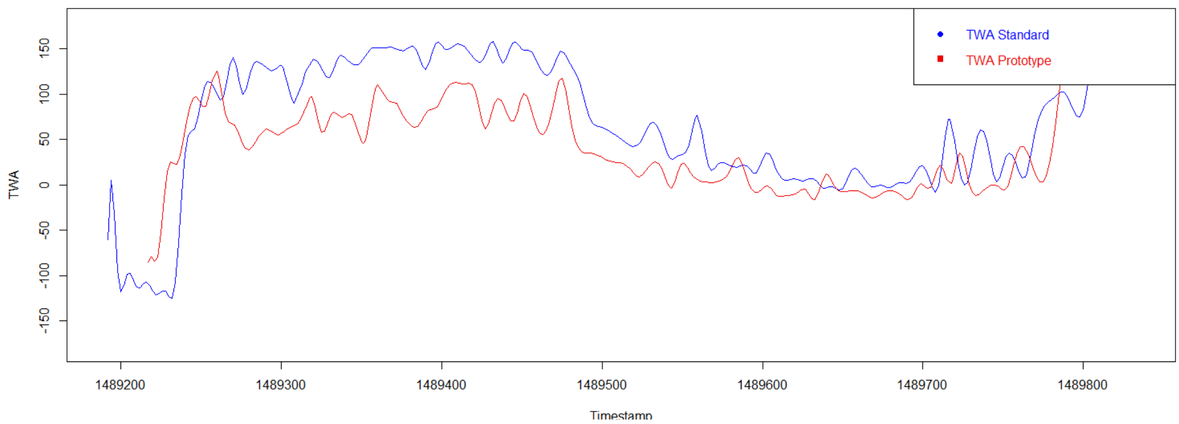

Fig. 34 Downwind tack: The red line is closer to "0" indicating that the angle to the wind is smaller. It shows that the prototype has to sail more distance to get to the mark. .

When testing the prototype with the "old" jib – from the standard 29er, the data was lost due to the strong wind and loss of the wind measuring system. So this cannot be validated in this piece of work.

6.2.2. Apparent wind angles

Analyzing the true wind angles is important to see the general direction and angels a boat can sail. As explained in the previous chapters the 29er is an apparent wind boat sailing with the apparent wind. Meaning especially on downwind tacks the speeds exceed the true wind speed so that the wind does no longer hit the boat from behind but from the front. This is why it is important to look at the apparent wind angles (AWA) as well.

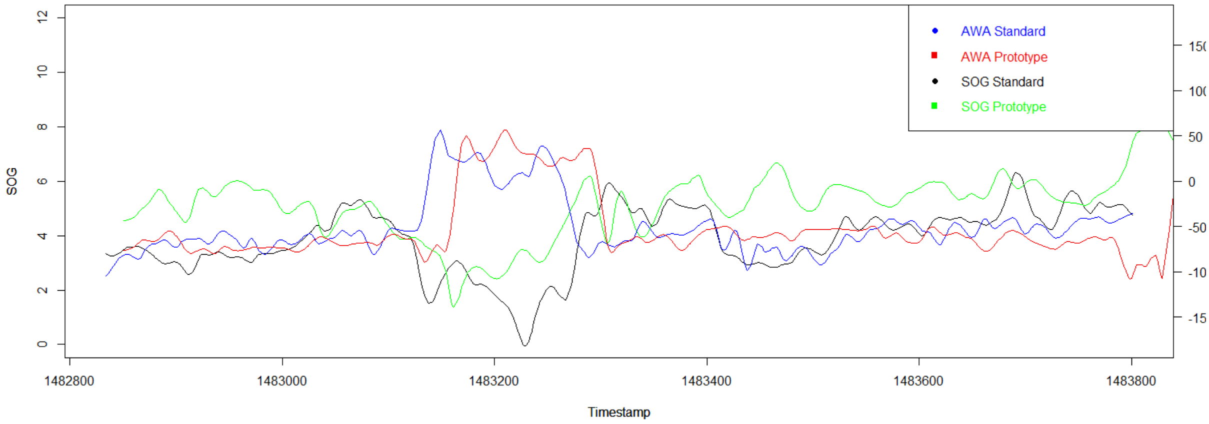

Fig. 35 AWA during an upwind tack indicating that the standard 29er can sail closer to the wind than the prototype. In black and green the SOG is drawn showing that the angle to the apparent wind (of the prototype) is larger the speed is higher.

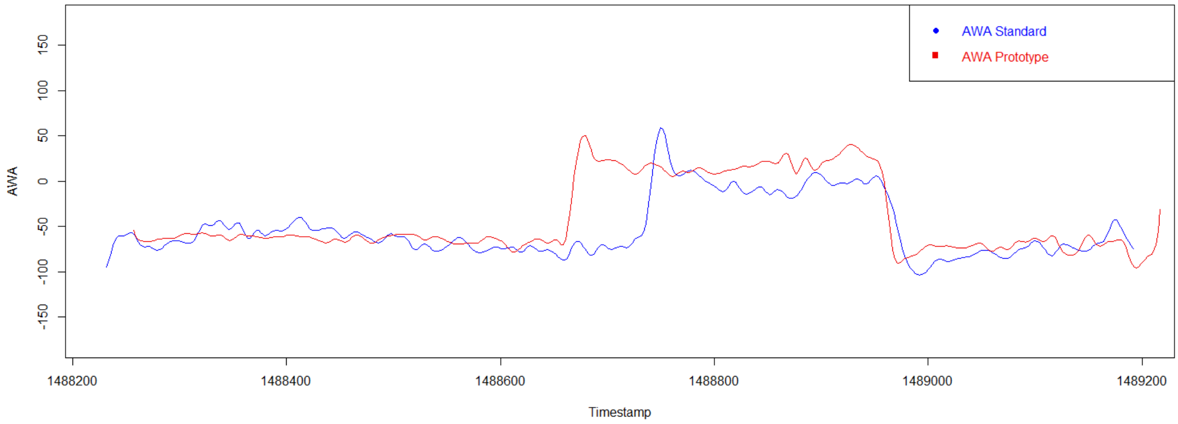

Fig. 36 AWA during an upwind tack. (same time stamp as Fig. 30)

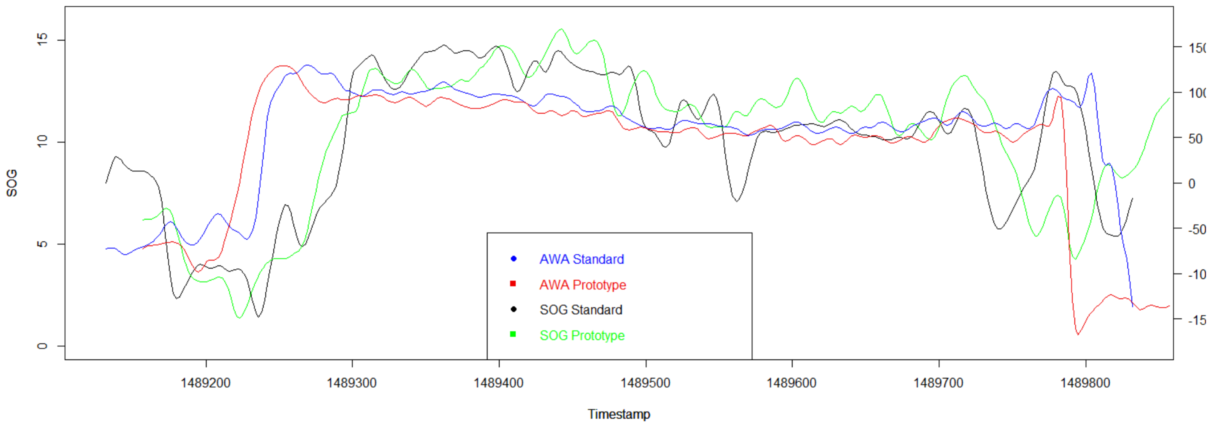

Fig. 37 AWA and SOG on a downwind tack

Looking at Fig. 36 the influence of the apparent wind can be seen. When looking at the true wind angles there is no indication on how the SOG influences the boat. Comparing the TWA and the AWA it (Fig. 38 and Fig. 39) you can see that with speed it is possible to sail more in the direction the wind comes from as the more forward. So basically the reason why the standard rig is slower in means of VMG is that it can actually point higher to the wind. As a matter effect the slower speed is not pulling the AWA around as much. As an example you can say that if the SOG of a 470 dinghy is 5 knots in a 10 knot breeze you will pull the apparent wind approximately 1/3 of the TWA towards you. If sailing a 49er and doing 10 knots in 10 knots of wind, then you will pull the apparent wind ½ of the TWA towards you. Comparing the standard and the prototype you can see that after a maneuver the standard can sail a higher course (AWA) faster than the prototype which needs more speed to reach the same apparent wind angle. After a certain amount of time the apparent wind angles are almost equal, in contrast to the true wind angles.

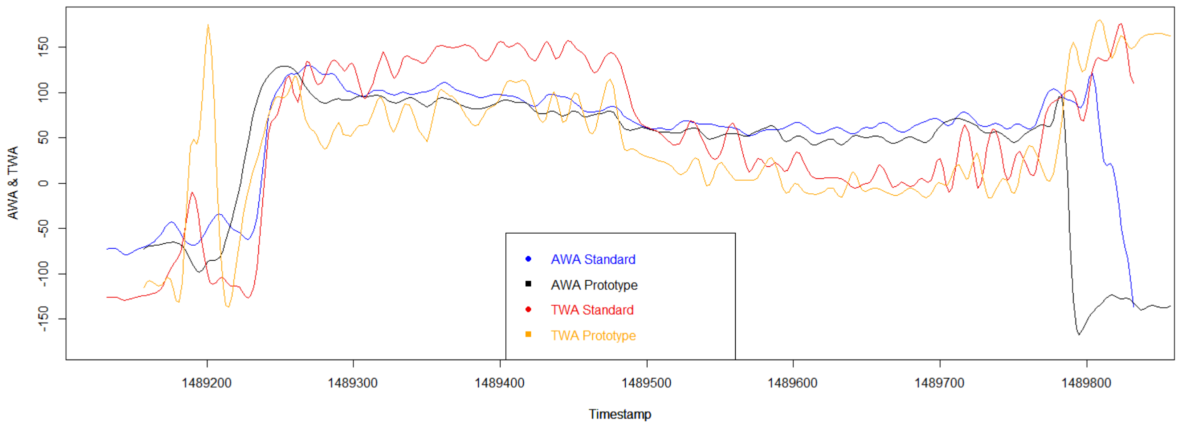

Fig. 38 Comparison between the AWA and TWA (downwind):

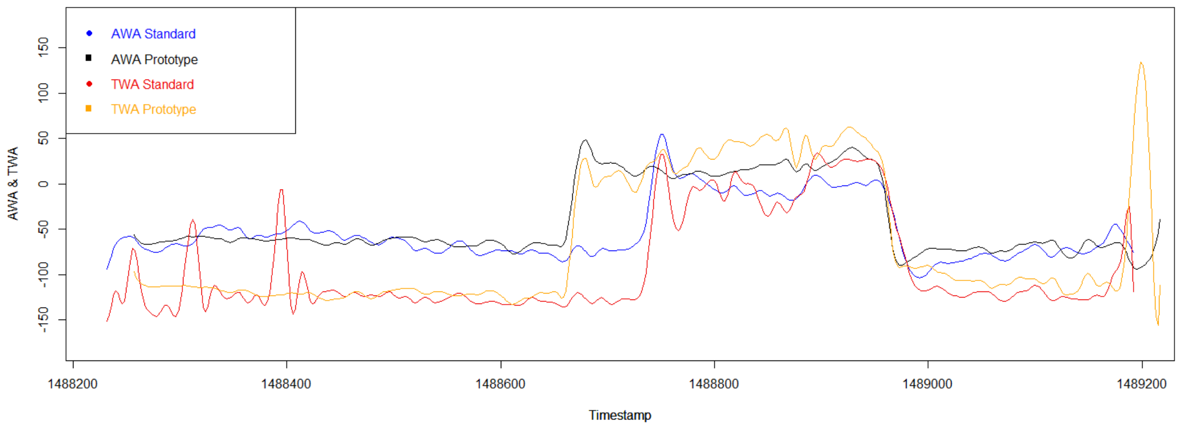

Fig. 39 Comparison between the AWA and TWA (upwind)

6.3. Polar diagrams

The following Polar diagrams are made with the collected data and represent the two 29er on different courses. The diagrams show the course to the true wind with respect to speed. For easier understanding the wind is given as an average throughout the test run and will be given under the picture.

What can be seen is, that all five polars have one common outcome: The purple dots (representing the standard 29er) have a much larger scatter considering the speeds. Although they are not as much spread, in means of angle, the blue dots (representing the prototype 29er) have less speed losses. So basically what can be said is that the prototype has more spread of angle but less speed loss in lulls.

In Fig. 40 and 42 the polar diagram with an average of 8-10 knots and 6-8 knots of true wind from a direction of 230 degrees (SW to WSW) you can see that the speed peaks do not differ much between the two boats. The major difference can be seen in the distribution of the dots. The prototype has a larger spread in angle, meaning that the speed gains/losses are a letter and are converted much easier in a better angle to the wind (compare Fig. 41 and 43). This effect is visible in Fig. 38 and 39. Considering the VMG, which is higher on the prototype, as already discussed in the chapter 5.4.1., you can now see that with more speed it is faster to get to the bottom mark (on a race course). The speed dispersion is larger when sailing the standard 29er meaning that as soon as a gust/lull hits the boat the loss of speed is much higher. The results will be discussed in the chapter 7.

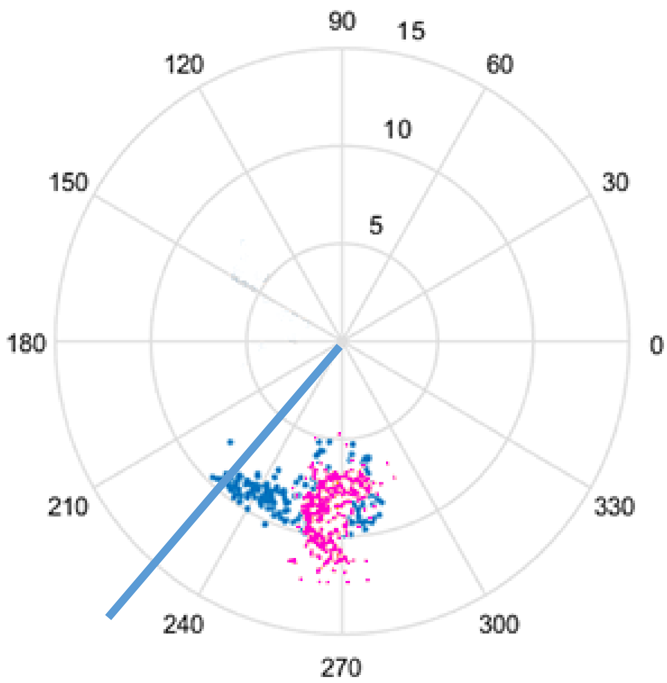

Fig. 40 Polar diagram of an upwind tack in ~8-10 knots of wind with a true wind direction of 230° (blue line). The blue dots represent the prototype 29er, the purple the standard 29er.

The distribution of the purple dots is wider spread than the distribution of the blue dots (speed wise) indicating the letter speed losses in gust and lulls and the better overall speed.

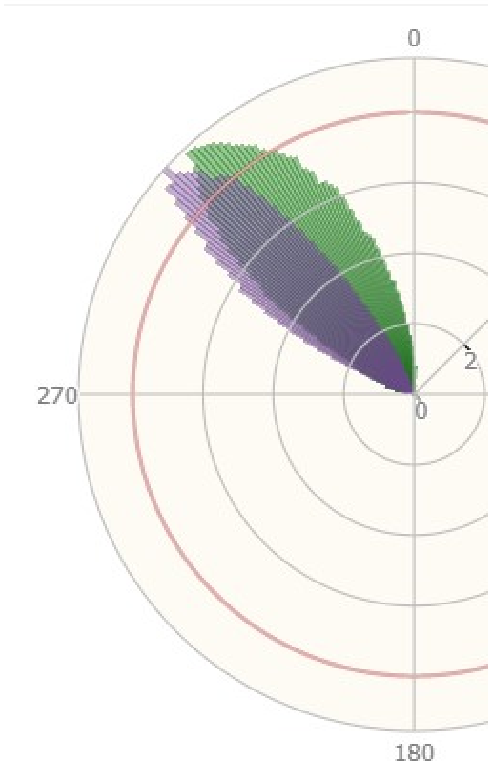

Fig. 41 Polar diagram of an upwind tack (same time frame as Fig. 40) showing the angles of the two boats (violet – prototype, green – standard) here the wind comes from 0° with 8-10 knots

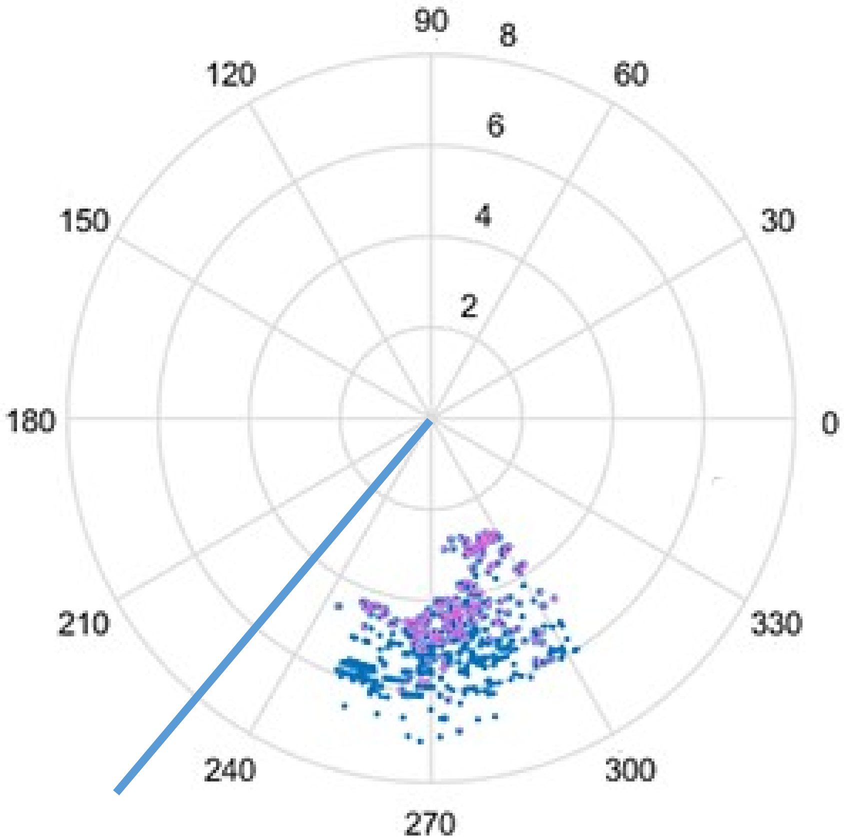

Fig. 42 Polar diagram of an upwind tack in ~6-8 knots of wind with a true wind direction of 230°

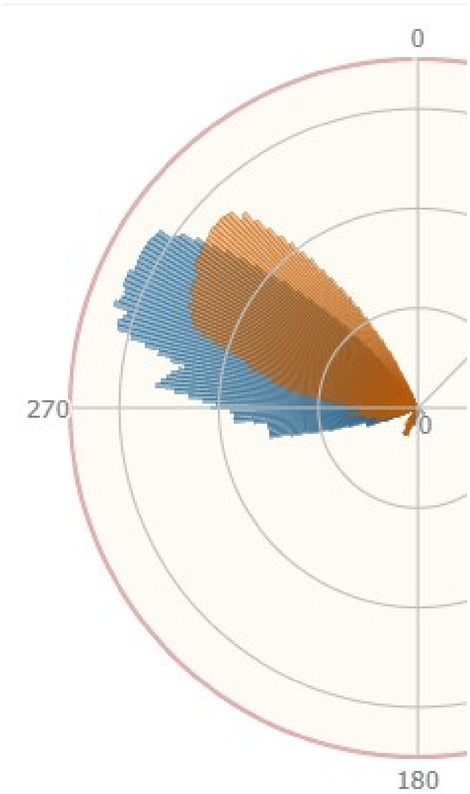

Fig. 43 Polar diagram of an upwind tack (same time frame as Fig. 42) showing the angles of the two boats (blue – prototype, brown – standard) here the wind comes from 0° with 6-8 knots

During a downwind tack (Fig.44) the effects are letter but they can still be seen in the spread of the dots (speed wise). The reason why it is not seen as clearly as in an upwind tack is that the large gennaker is much more effective than the main sail. So basically the gennaker reduces the effect of the square top. Comparing these findings with the results of Watin 2007 it can be seen that the effect is similar to the 49er. When sailed on a downwind tack the carbon mast with the square top simplifies the adjustment of the rig and therefore makes it easier to control and due to the lighter rig it is easier to control the heeling. As a result there is hardly any speed difference in absolute means only the overall speed due to speed losses and gains are less (compare chapter 6.1. and 6.2.)

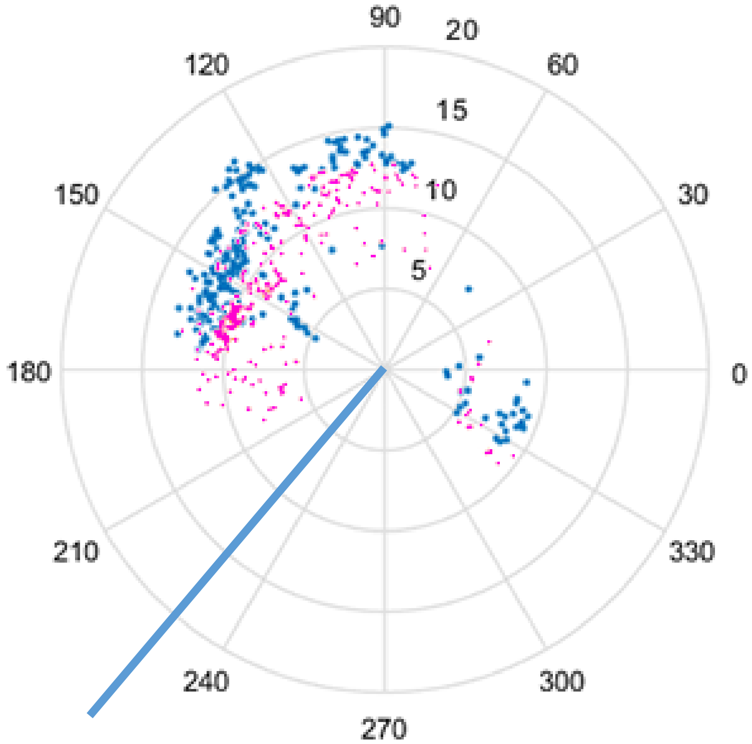

Fig. 44 Polar diagram of a downwind tack in ~10 to 12 knots of wind with a true wind direction of 230° (blue line)

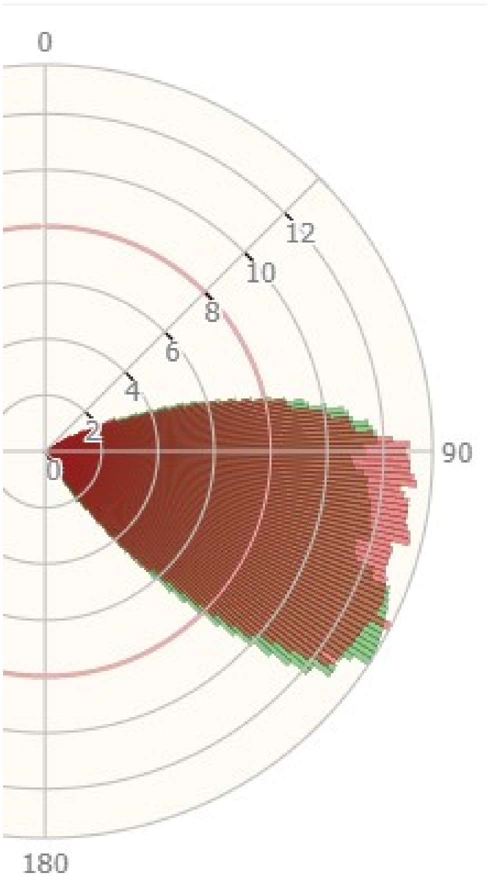

Fig. 45 Polar diagram of a downwind tack (same time frame as Fig. 44 showing the exact angles of the two boats (red – prototype, green – standard) here the wind comes from 0° with 10 – 12 knots

7. Discussion / Conclusion

In competitive sailing it is always a matter of being faster than the other boat and so technology tries to improve whenever possible and tries to make faster boats. Developing a new rig to an existing boat is very difficult as a certain state of the art already exists and therefore a game of trial and error. Both were created and designed by Julian Bethwaite (4) in order to help young sailors improve their abilities on apparent wind boats. As already stated in chapter 4 there are a couple of techniques that changed to the classical 420/470 boat class and the requirements on the sailors are different as well as speeds are a lot higher and decisions have to be made a lot faster.

Experiments and tests with different boat and sail designs showed that square tops are to be preferred in new sailing concepts (eg. Volvo Ocean Race, Americas Cup,…) especially when sailing in high performance boats. As already found by Julian Bethwaite and Simon Watin in 2007 on the 49er and previous studies have also shown that the advantage of the square top is the increased control of speed in gusts and lulls and the control of the boat itself. Considering the chapters before and especially chapter 6 you can see that even on smaller boats like the 29er the square top has its advantages. The speed losses in gusts, due to heeling, are less as the square top depowers the sail "automatically" when the gust hits the sail. Though it seems obvious the key factor to make this work is the carbon mast. One reason is that carbon is a lot lighter than the alloy, lowering the center of gravity to an extent that the leverage forces are less significant on the heeling moment.

The second characteristic of the carbon mast is having just the right stiffness / flexibility that makes the system work. Comparing the differences of the bend (in %) of chapter 4.1., it was obvious that the characteristics of static and dynamic loads are different. In this case the main difference is that the alloy mast bends more in the top section of the mast (due to the carbon top) and the full carbon rig bends along the whole mast resulting in a better control of the twist and camber and general shape of the sail. To control the bend of lower mast section the D1 shrouds are needed. When the gust hits the sail the pressure increases and bends the mast. Whilst doing so the sail can open up to lee in the top section but stays tight in the lower section of the sail. Therefore the righting moment stays pretty much the same and results in a speed gain and hardly any heeling moment. Talking about the mast itself it is important to adjust the sail shape according to the properties of the mast as the mast-sail-combination is of great importance.

Due to the materialistic facts the performance results are to be discussed. The mast that bends more throughout the whole length and the better adjustable automatic rig as well as the slightly larger square headed main sail, all have an effect on the sailing performance. Looking at chapter 6 it is to be seen that the speed differences and angle differences are there. The analysis showed that the speed gain is around 15-20 % which seems to be a lot but this only shows the SOG over all. There is no consideration of angels and external influences. Considering the VMG (compare chapter 4.4.1.) the speed difference of the prototype to the standard is a lot less. Reason for that are the different sailing angles that were discussed in chapter 5.2. and more detailed in Fig. 36 to 39.

When looking at the speed polar diagrams (chapter 5.3.) it can be seen that the standard rig has a larger distribution of angles and speeds at a given true wind speed, than the carbon rig. This is the result of the higher center of gravity on the standard 29er due to the fact of the larger weight of the mast. What it means is that the standard rig is harder to control than the carbon rig, especially for amateur or younger teams. The second factor that can be seen in the speed polar diagrams is the reduction of speed losses in lulls. Comparing the standard rig and the full carbon rig it is obvious to see that due to the carbon mast-sail-combination the speed losses (indicated by the dots (polar) (Fig. 40-45) during reduced wind speed (lull) is smaller than with the standard rig.

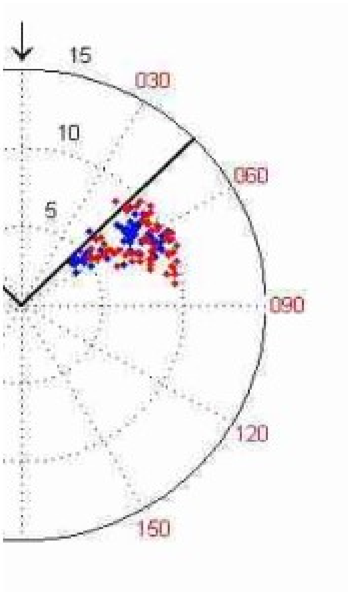

Fig. 46 Polar diagram of a 49er test (13) (red dots representing the old alloy/carbon rig, blue dots representing the full carbon rig). Although the speed peaks are the same the distribution of the blue dots is lesser indicating that it loses less speed in lulls..

One factor that hasn't been taken into account yet is the price. Although there are many advantages for the new rig this factor is very limiting. The boat was created for youth teams to train for the Olympic class the 49er/49erFX and therefore their main objective is that it should be affordable. The alloy mast is relatively cheap and what is even more important it withstands a lot of punishment without any breakages. In contrary the carbon mast is expensive and although the durability of carbon has improved, breakages during capsizes and other human errors will occur earlier. Although the alloy is cheap the major problem is that alloy fatigues with use and the cost over time is quite high. In contrast a carbon mast, although its initial cost is about 7-10% higher due to the more complex production process, the mast life span – if well looked after –can be considered a lot longer and therefore a lot cheaper.

7.1. Limitations

The test runs have been carried out with a single set of test objects. Because of financial limits within this projects and the limited availability of the new prototype mast and sails, I had to lower my sights and reduce the tests to a minimum. The major problem is that the 29er scene is quite small and it's difficult to find people that can sail a boat like this. The second limiting problem is that the support for this class is not as big as it is with other boat classes as the way of thinking is quite Corinthian, meaning that traditions are not easy to be broken and therefore it is hard for some to accept and adapt to new and innovative boat classes. It's always a matter of a couple of innovative people that help to improve a boat class like the 29er.

Testing boats in real life situations is extremely difficult as situations on water never occur as in standardized laboratory situations. Therefore it has to be said that the human error due to crew behavior and the measuring error are high and to be considered whilst analyzing and interpreting the data. The human error is a factor that can only be minimized with time, training and experience but due to the facts mentioned above it was hardly impossible to give the crews enough time to get the boat to know in a professional way.

To test two rigs in terms of pure performance, the influence of nature has to be considered as waves and wind are not steady. In order to suppress these factors the tests had to be a boat to boat comparison, sailing two boats very close to each other (2-3 boat lengths) so that they experience the same wind. Given the fact that these conditions can be realized - the human factor (even if the crews are equally skilled) is still not to be neglected.

It is to be said that the intention was not to find the absolute maximum high end performance of the boat but as the carbon rig is a prototype to find the overall performance difference to the standard rig. As the boat is quite a challenge to handle the focus is also set on the "accessibility" meaning that not only highly skilled youth sailors can handle the boat but also a broader range of youth sailor can access and sail the boat more easily than the standard rig. As we know from the 49er (16) the weight difference is one key factor in that means.

The 29er is regarded as a youth training boat to teach kids and young sailors how to sail skiffs and to train with a skiff for a skiff. So speed is a factor you cannot deny when looking at differences but the goal was not to analyze speed peaks, meaning to see which boat is faster in an absolute means, but to see the overall performance and consistent speed in all kinds of wind situations (gusts and lulls, strong and light wind).

8. Bibliography

1. Vince Lombardi Quotes [Internet]. BrainyQuote. [cited 2018 Apr 16]. Available from: https://www.brainyquote.com/authors/vince_lombardi

2. Klose B, Klose H. Meteorologie: eine interdisziplinäre Einführung in die Physik der Atmosphäre. 3. Auflage. Berlin Heidelberg: Springer Spektrum; 2016. 524 p. (Springer-Lehrbuch).

3. Marchaj CA. Sail performance: techniques to maximize sail power. Rev. ed. Camden, Me: International Marine/McGraw-Hill; 2003. 401 p.

4. Bethwaite F. Higher performance sailing [Internet]. London: Adlard Coles Nautical; 2008 [cited 2018 Jan 15]. Available from: http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=613742

5. alphabetic-ittc-symbols-list-2017.pdf [Internet]. [cited 2018 Mar 17]. Available from: https://ittc.info/media/8214/alphabetic-ittc-symbols-list-2017.pdf

6. Bethwaite F. High performance sailing: faster racing techniques. London: Bloomsbury; 2013.

7. Kimball J. Physics of sailing. Boca Raton, Fla. : London: CRC ; Taylor & Francis [distributor]; 2010. 277 p.

8. Hydrofoil [Internet]. Encyclopedia Britannica. [cited 2018 Mar 17]. Available from: https://www.britannica.com/technology/hydrofoil

9. Püschl W. Physik des Segelns: wie Segeln wirklich funktioniert. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA; 2012. 265 p. (Sachbuch).

10. ORC VPP Documentation 2011.pdf [Internet]. [cited 2018 Apr 23]. Available from: http://www.orc.org/rules/ORC%20VPP%20Documentation%202011.pdf

11. Holger Babinsky. How do wings work? Phys Educ. 2003;38(6):497.

12. Garrett R. The symmetry of sailing: the physics of sailing for yachtsmen. Dobbs Ferry, NY: Sheridan House; 1996. 268 p.

13. Bernoulli's theorem | physics [Internet]. Encyclopedia Britannica. [cited 2018 Mar 13]. Available from: https://www.britannica.com/science/Bernoullis-theorem

14. Larsson L, Eliasson RE, Adam and Charles Black, Bloomsbury Publishing. Principles of yacht design. London [etc.: Adlard Coles Nautical : Bloomsbury; 2014.

15. Wagner P, Reischl GP, Steiner G. Einführung in die Physik. 3., erweiterte Auflage. Wien: facultas.wuv; 2014. 528 p.

16. Watin S. INTERNSHIP REPORT 49er performance enhancement [Internet]. 2004 [cited 2016 Aug 16]. Available from: http://9eronline.com/library/49er%20Performance%20Enhancement%20Report%20by%20Simon%20Watin.pdf

17. Lesson5-Hull_Speed_and_Buoyancy.pdf [Internet]. [cited 2018 May 14]. Available from: https://www.nshof.org/educ/lessons/scienceofsailing/sci5/Lesson5-Hull_Speed_and_Buoyancy.pdf

18. Viola IM, Enlander J, Adamson H. Trim effect on the resistance of sailing planing hulls. Ocean Eng. 2014 Sep;88:187–93.

19. How is Carbon Fiber Made? [Internet]. ZOLTEK. 2017 [cited 2017 Nov 21]. Available from: http://zoltek.com/carbon-fiber/how-is-carbon-fiber-made/

20. Rennie R, editor. A dictionary of physics. Seventh edition. Oxford: Oxford University Press; 2015. 666 p. (Oxford quick reference).

21. carbonfiber and sailboat [Internet]. [cited 2018 Mar 17]. Available from: http://www.finot.com/ecrits/ecritgroupe/confer_jec/carbone_voilier_ang.htm

22. LORIMA - Why a Carbon Mast ? [Internet]. [cited 2018 Mar 17]. Available from: http://www.lorima-carbon-mast.com/en/why-carbon-mast/

23. CST Marine | Company – CST Composites – Since 1995 [Internet]. CST Marine. [cited 2018 Mar 17]. Available from: https://www.cst-marine.com/company/

24. CST Marine | Technology – Innovative and Competitive [Internet]. [cited 2018 Mar 17]. Available from: https://www.cst-marine.com/technology/

25. Bethwaite J. 29er. 2018.

26. International Laser 2 Class Association [Internet]. [cited 2016 Aug 16]. Available from: http://www.laser2sailing.org/boat/

27. 29er Spezifikationen [Internet]. [cited 2016 Aug 18]. Available from: http://www.29er.org/images/stories/pdf/29er%20boat%20specs.pdf

28. 29er working sail dynamics.jpg (JPEG-Grafik, 1100 × 830 Pixel) - Skaliert (94%) [Internet]. [cited 2018 May 14]. Available from: http://www.9eronline.com/library/29er%20working%20sail%20dynamics.jpg

29. America’s Cup [Internet]. [cited 2018 Apr 2]. Available from: https://www.americascup.com/

30. Professional Models [Internet]. [cited 2018 May 17]. Available from: https://loosnaples.com/tension-gauges/professional-models

31. iPhone SE - Technical Specifications [Internet]. Apple. [cited 2018 Jan 2]. Available from: https://www.apple.com/iphone-se/specs/

32. Dhow | Arab sailing vessel [Internet]. Encyclopedia Britannica. [cited 2018 Mar 17]. Available from: https://www.britannica.com/technology/dhow

33. Woodman R. The history of the ship: the story of seafaring from the earliest times to the present day [Internet]. 2012 [cited 2018 Mar 17]. Available from: http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1265094

34. Optimist [Internet]. Optimist. [cited 2018 Mar 17]. Available from: http://www.optiworld.org/

35. Curry M. Yacht Racing - The Aerodynamics of Sails and Racing Tactics. [Internet]. Read Books Ltd.; 2013 [cited 2018 Mar 17]. Available from: http://www.myilibrary.com?id=891561

36. Gusts and other Changes in Wind - Franks-Weather - The Weather Window [Internet]. [cited 2018 Mar 17]. Available from: http://weather.mailasail.com/Franks-Weather/Gusts-And-Other-Wind-Changes

37. Volvo Ocean Race 2017-18 [Internet]. [cited 2018 Mar 17]. Available from: https://www.volvooceanrace.com/en/home.html

38. Home - Vendée Globe [Internet]. [cited 2018 Mar 17]. Available from: https://www.vendeeglobe.org/en/

39. ANNIE: Sandbagger [Internet]. Mystic Seaport. 2013 [cited 2018 Mar 17]. Available from: https://www.mysticseaport.org/locations/annie/

40. The formation of the Corinthian Yacht Club [Internet]. [cited 2018 Mar 17]. Available from: https://royalcorinthian.co.uk/article/4000001/the-formation-of-the-club

41. Taylor DJ. On the Corinthian spirit: the decline of amateurism in sport [Internet]. 2010 [cited 2018 Mar 17]. Available from: https://nls.ldls.org.uk/welcome.html?ark:/81055/vdc_100048692649.0x000001

42. Stannard B. Bluewater bushmen. Bowral, N.S.W.: Heritage Press; 2004.

43. Royal Sydney Yacht Squadron - Home [Internet]. [cited 2018 Mar 17]. Available from: https://www.rsys.com.au/

44. Walsh GP. Foy, Mark (1865–1950). In: Australian Dictionary of Biography [Internet]. Canberra: National Centre of Biography, Australian National University; Available from: http://adb.anu.edu.au/biography/foy-mark-6367

45. Home Page [Internet]. [cited 2016 Aug 23]. Available from: https://www.ovingtonboats.com/

46. International Laser Class Association | www.laserinternational.org [Internet]. [cited 2016 Aug 23]. Available from: http://www.laserinternational.org/

47. globeandmail.com: Ian Bruce [Internet]. [cited 2016 Aug 23]. Available from: http://v1.theglobeandmail.com/servlet/story/LAC.20160425.OBIREMEMBER/BDAStory/BDA/deaths

48. Champions [Internet]. [cited 2016 Aug 23]. Available from: http://49er.org/event/champions/

49. The Boat [Internet]. [cited 2017 Nov 13]. Available from: http://49er.org/class-info/the-boat/

50. 29er_vs_29erXX.PNG (PNG-Grafik, 503 × 258 Pixel) [Internet]. [cited 2016 Aug 23]. Available from: http://www.euroszeilen.utwente.nl/wiki/images/8/8a/29er_vs_29erXX.PNG

51. Xtreme Sailing Products 29erxx Class Home Page [Internet]. [cited 2018 Apr 25]. Available from: http://www.xtremesailing.com/design.php?boat=29erxx

52. Nautivela - 29erXX [Internet]. [cited 2018 Apr 25]. Available from: http://www.nautivela.com/29erxx_intro_en.asp

Appendix

1. Development of the square top

One major change for the new 29er main sail was the change to a modern square top in order to keep more pressure in the sail during gusts and lulls and to maximize the performance of the boat.

1.1. History

Fig. 47 Arabic Dhow (32)

For many years sails have been designed like squares to keep as much pressure in the sail as possible to create the most possible drag. When sailing on the downwind of sail area was directly linked to speed, at least according to general opinion. Especially the Vikings used square sails to propel their longboats to get west even reaching North America around 800AD. Comparing their ships with the "Dhows"[26] (Fig. 47) out of the Arabic region you can see the main difference: The sails. Square Sails were mainly used in downwind conditions, as the main force that was known to that date was drag. Basically these boats were "pushed" forward by the wind. In contrast, Dhows used some sort of "for-and-aft sails" (Fig 48) (9) enabling the people to sail against the wind to some extent. These so called lateen rigs (Fi. 48a) (33) like for example the Optimist[27] rig, are most commonly used in modern sailing. The only thing that changed is that they rotated the "gaff"[28]

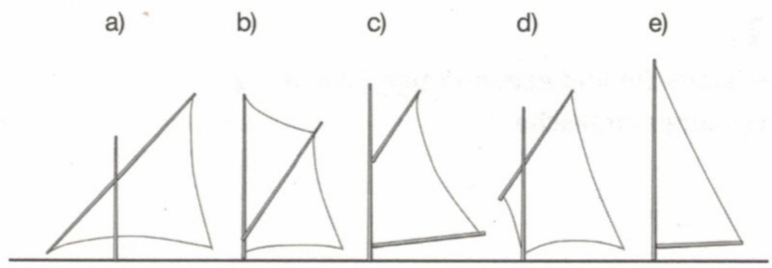

Fig. 48 Different fore-and-aft sails: a) lateen sail; b) spritsail; c) gaff sail; d) lug sail; e) Bermudian rig (9)

---

[26] "Dhow a one- or two-masted Arab sailing vessel, usually with lateen rigging (slanting, triangular sails), common in the Red Sea and the Indian Ocean." (32)
[27] Optimist is a boat class for young sailors further information at the international optimist dinghy association. (34)
[28] The Gaff is an extra part of the mast that supports the sail at the part that is not attached to the mast (Fic) (9)

so it was more vertical, extending the “mast” to give great height. They did not know it at the time but they were increasing the AR [Aspect Ratio] and therefore increasing light air performance significantly Further influence on the development around the world was given and the sails developed into the so called “Bermuda Rigs” (Fig. 48e) and later the “Gaff Rigs” (Fig. 48c) in the 17-18th century.(9)

Fig. 49 Julian Bethwait’s Prime I a two handed 18 Footer) with a “pin head Mainsail” (Author)

When talking about “Pin Head Sails” Fig. 49 the reference is the classical Bermuda rig (Fig. 48e) and later the Marconi rig. Developed in Bermuda the idea was to create a sail that looks like a triangle shaped sail, like the lateen rigs. The only difference is that the main sail is fixed at the aft of the mast, with its head right to the top of it and the luff fixed all along the boom. The tack is furthermore attached to the connection point of mast and boom, whereas the clew is fastened only to the end of the boom in order to control the main sail. In the beginning of the 20th century the Bermuda Rig was improved by the idea of Guglielmo Marconi, who supported his radio masts with wires to stabilize them. The result was basically a Bermudian Rig with shrouds. It was Manfred Curry who compared the sails of a boat with the wings of birds.(35) Studying different wings of different birds he assumed that the curve of the sail should be permanent to enable a permanent flow of the wind along the sail. He and his father’s approach was to “curve” the Sail with battens “*a curvature in the leach of the sail supported by the battens and a level of mast bend*” (25).

Development went on and the sails, materials and technology changed throughout the next 50 years to the time when skiffs became known and the approach of the apparent wind boats.

"*In 1981, I tried and sailed a 2 handed 18teen. Over the next 3 years that developed and what became apparent was with only 2 people, you simply did not have enough hands to do everything, so we need to make the rigs automatic*"(25).

One factor of the automatic rig was to change the workload of the crew changing the way the jib would maneuver through the tack and gybe. The major problem was, when sailing two handed and having the gennaker up and flying, there is simply a hand missing to loosen the jib and take it tight on the other tack. Changing to an automatic rig makes these maneuvers a lot easier and a lot faster as the crew can concentrate on the gennaker and the head on the main sail because the jib just slides on the other side and doesn't need to be loosened and taken tight on the other tack. (4)

The key factor although of the automatic rig is something different. Making maneuvers faster and easier and making the boat faster also means that adjusting the sails and the mast because the rig tension just loosens when a mast bends. Meaning that: *"when they (Julian Bethwaite) bent their lower masts by up to 6% of the mainsail's loff length, the lower masts became shorter and this caused the primary rigging to become unacceptably slack."* (4). While working on that problem Julian and Frank Bethwaite were looking at the way the mast bends. Their findings were that the lower section (on the alloy tube) had to bend far less than the upper section (GRP wound tube). These findings were affirmed by a series of measurements in the backyard of their home and were the base of the way the sails and masts had to be built in future. (4)

Their findings and therefore conclusions can be summed up like this (4)

- The topmast is between two and three times springier in the automatic rig than the typical topmast in a manual-adjust mast.
- There are two sets of spreaders in the automatic rig
    - The stronger lower shrouds from the forestay attachment point (the hounds) to the chainplates on the gunwales. They are tensioned until the forestay is at the tension desired for the expected wind.
    - The springier topmast is supported sideways by lighter independent cap shrouds which run from the masthead through the tips of the upper spreaders to the chainplates on the gunwale.
- There must be a powerful downhaul (Cunningham) to alter the system. The main control function is to increase luff tension, this "bow-strings" the mast and allows the user to alter the mast bend characteristics while sailing. The more tension, the more bending the mast is, less tension the stiffer the mast is. (4)

To understand the way these findings work on the boat, one has to look at the way gusts behave. Normally a gust lasts between 9-12 seconds and increases the wind speed by approximately 25 – 30% (e.g.: 10 knots to 13 knots) and most likely the wind direction differs from the mean direction by 3-5°. This data came from Frank Bethwaite's work at the '76 Olympics in Kingston, Canada, when he got the possibility to see and work with the wind data recorded from the Kingston tower (4,6,36). The main reason for that is, that these stronger winds drop down from higher layers of the air. When dropping down from these upper layers it appears that Coriolis Forces work its way and change the direction by a couple of degrees. Apart from the changing angle which can be altered by the helmsmen quite easily, the major problem is the force of the gust as something like 80-85% of the energy of the gust is found in the first 0.5-1 second.(4,6,36) As forces go up by X^2 the only way of depowering the boat is by easing the sheet. Which results either in losing some angle to the wind or losing power/speed.(4)

With the automatic pin head rig, as the load/gust increases, the mast top bends a lot more than the bottom. As an effect the sail flattens at the head more than on the foot. Simplifying we can say the upper leech opens up. Letting "the air out" and flattening the upper sail moves the center of pressure further down and the righting moment increases. By easing the main sheet a few centimeters, the boom rises and the upper sail twists even more, reducing the angle of attack and the center of pressure moves further down and aft. As the gust drops the automatic rig powers straight back up as the mast top moves back into its original position allowing the main sail to "untwist" and powering up again. All of this takes place within in the shortest amount of time, which can never be achieved by human hands. (4)

As the pin head rig closes approximately at the shape of an ellipse the pressure towards the tip of the sail drops and the vortices around the mast top drop as well. Comparing these "advantages" with the square top one can assume that the square top cannot be any better but as materials and techniques developed it was clear it can be better. (4)

In the late 1980's the masts of boats were a "tree trunk of an alloy" (25) that would not bend. Therefore the sails had to be changed to use the advantages of the findings of the "de-powering" benefits of the pin head automatic rig. (4)

Although there are different materials that are lot more flexible and stronger, the main advantage of carbon is the low weight (compare chapter 6). The manufacturing costs have also come down in the past years. The other material change that has to be considered is Mylar. This enables the main sail, if shaped correctly, to bend the mast in a way that classical sail cloths were not able to. With the combination of the Mylar sail and the carbon mast it was possible to achieve something similar to the "automatic gust response of the pin head rig" (4).

1.2. Square Head on the 29er

Considering all the advantages and ideas of a square head, it is nowadays pretty clear that most of the high performance boats – 49er, 18 Footer, Nacra 17,… and even the bigger boats like the Volvo Ocean Race (37) or Vendée Globe (38) boats - have these sail forms. As the 29er is a youth trainer boat for the skiff class, it is obvious that the future lies in perfect training possibilities and therefore a square head as well. The new rig, developed by Julian Bethwaite and his team, has one of those. Looking at Fig. 50 and 51 the difference in height and form is obvious and performance differences will be explained in the oncoming chapters.

> *"By increasing the width of the mast head, you introduce another element into the mast sail combination. You add a lever right at the top of the sail, and if it is done well the top 2 battens, the one at almost 45° supporting the very top aft corner of the head, and the next one down, which controls the camber, become your "control battens". Because of the laws of "oilier crippling loads" [OCL] and some very smart design which come from trial and error, you can use OCL to trigger the sail to behave in a pre-determined manner at will while sailing. All-sorts of rules apply here, width of the head board, camber, rocking of the stress lines in the Mylars, its complex, but once dialed in, it works."*(25)

Fig. 50 Different 29er sail shapes. On the bottom the prototype squaretop, on top the standard pin head. (Author)

Fig. 51 Different 29er sail shapes fully rigged on the boat. (Author)

2. Historical development of skiff sailing up to modern constructions like the 29er

Around 5000 to 4000 years ago the first vessels with something like a sail are found. When talking of a sailing boat you have to go back around 4000 years (4,9).

Sailing has always been an important means to transport great masses from one place to another or were used to expand the horizons. In order to survive, they had to be adapted to the general surroundings: They were strong and big in order to transport great loads and to serve a long time in a quite unfriendly environment – the sea. The sails they used were small and handy to survive the unpredictable wind gusts out on the sea. For many years, as boats were always built in that manner, speeds and characteristics were quite similar. Materials like wood for the hull and sails made out of linen was normal (4,9).

Talking of these materials the ability to sail was quite limited. The second problem was the lack of most of the modern know how on sailing. Thus the courses to the wind were limited and even with bigger sails the speeds were low and mostly downwind courses were possible. The development on sailing close hauled or beam reach took a long time but were essential for sailing.(33)

When looking at the development nowadays the big cargo sail ships are almost gone and replaced by “motor-driven giants” on sea. Since the 18th century sailing has become a pastime activity in the Netherlands and in the 19th century a highly exquisite sport in England. Only members of the high aristocracy were able to sail as boats and crews were enormously expensive. The term “Yacht” has its origins in the word “jacht” or jachtship (ned. huntingship) which basically means small, fast boat. As a result, sailing has become a sport were only speed matters (9,33).

In the beginning of the 19th century a major change has taken place as basically two groups of boats developed using new techniques in order to sail faster and more efficiently: “the Sandbaggers” from New York and the “Skiffs” of Sydney. Both of them employed the understanding that it is important to shift weights to enable bigger sails (4).

2.1. Sandbaggers from New York

To understand how these faster boats work one has to consider the importance of several inventions.

In the beginning of the 19th century fish was expensive and bringing good and fresh fish to the markets of the growing city of New York was a matter of time. Not only fish but also oysters were a main food staple. To harvest them in the Hudson River fishermen needed boats that were easy to maneuver in the river estuary. In addition they needed to transport big loads and therefore ships had to be built flat but wide bottomed with little draft to be able to skim over river. In order to be as fast as possible the sails that moved these boats were rather big. (4)

The Hudson River estuary was not only for fishing but also a meeting point for the upper society, both sailing and socializing. The area combined a few important features for a good sailing area: a small entrance to the open ocean, which enables flat water because it is protected against the swell from the ocean, water deep enough to sail quite big boats and especially during the summer months the climate is quite enjoyable for spending time in the open as there is always a constant sea breeze. (4)

It was only a matter of time that boats were racing each other to be first to deliver their load to the markets and furthermore people started racing on weekends without load. Therefore longer and lighter spars evolved as well as lighter and bigger sails, but remained rigged with mainsail and jib only. In no time these races attracted more people as *"they mixed working watermen, amateur sailors and crowds of spectators, most of whom bet on the winners of match races."*(39) As sails became bigger and the load less heavy there was a need to compensate the missing ballast and that was done with sandbags – that is the reason why the name "Sandbaggers" was commonly used. In the 1840s a match racing program was initiated and the only rule for each class was the length of the hull. During the time the sails became bigger and more and more sandbags were used to compensate the up righting force. As a result the maneuvers took longer and longer as the amount of weight to be shifted to the other side was enormous. (4)

As they never added an additional sail to their boats (compare Fig. 52) (no spinnaker or gennaker) it was possible to sail with a very small but skilled crew. (a helmsman, a mainsail trimmer and a headsail trimmer) and "hefters" that carry that sandbags from one side to the other. As wind is a variable they needed to adapt to these situations. On light wind days the carried only the minimum amount of sandbags and hefters on the boat and on heavy wind days they added more of both as they needed. Furthermore they reefed the mainsail and headsail prior to the start. (4)

Despite the fact that sailing was a "gentleman sport" and mainly seen in the upper society, it is obvious that these "wide, light, shallow, 'skimming dish' sandbaggers"(4) offended the aristocracy in a couple of ways.

First of all the Sandbaggers were smaller and faster than the ‘gentlemen’s’ yachts and earned money with winning. (4)

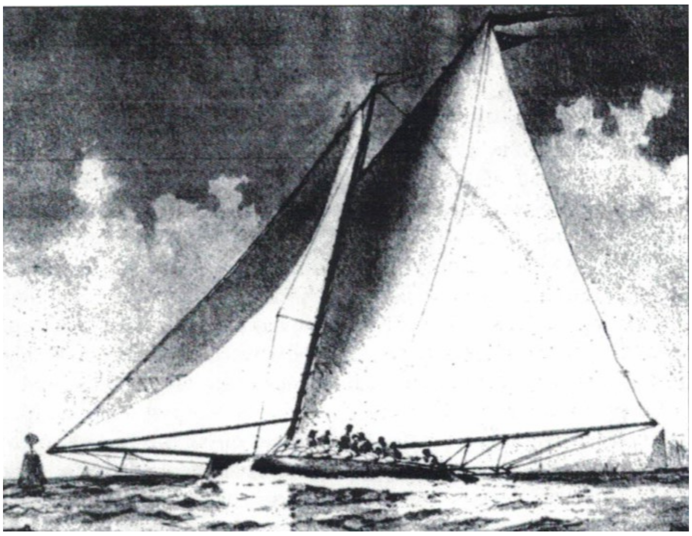

Fig. 52 Pluck and Luck 23ft. Sandbagger dinghy by Jake Schmidt. (4)

Another reason why these boats were a nuisance for aristocratic attitudes was that they were considered as “people’s boats"(4) as the sailors were mostly workers from the area around New York or at least associated to the local waterfront, meaning that the crews of these boats sailed for a living and were paid to do so. Meaning that they were professionals. In contrast the aristocracy and the upper class, were mostly amateurs that sailed for pleasure. When talking of professional sport there has to be prize money and therefore the sponsors – mostly the owners of the ships or the owners of the waterfront bars – wanted to become better and better. To achieve these results crews had to work hard and especially the hefters had to be strong and these had to be paid. Basically the more you win, the more money you earn and you can afford stronger and better crew members. (4)

As a result the small boats earned a lot of respect and recognition from the audience. Because of the small size and the huge sails that resulted in great speed, in spectacular races and even capsizes, the attraction for the spectators was a lot higher than the slow big boats. As the aristocratic amateurs with big and slow boats lost more and more spectators to the sandbaggers, the upper society responded by banning them from the regattas. In the 1890s the yacht clubs not only banned them but also stated the “Corinthian” –amateur regulations[29] and measurement rules to handicap racing yachts.(39) In doing so they lost in two ways: first they lost a lot of spectators because no one wanted to see the slow boats were nothing

[29] Corinthian- Amateur regulations were stated by the Royal Corinthian Yacht Club (established in 1972) with their earliest objective “to encourage amateur yacht sailing”. “[…]A committee composed of yacht owners was appointed to draw up the rules …and the constitution of the Club requires that with the exception of the paid hand, the crews should consist of members of the Club…. the Corinthian Yacht Club will therefore practically consist of a number of yacht owners anxious to encourage amateur yacht sailing and of such of their friends as may be willing to assist […].”(40)

happened and second the support for the sandbaggers grew as the media dubbed them as 'extreme and dangerous' (4,41). Furthermore the Seawanhaka Yacht Club banned all ballast shifting and professionally crewed yachts from entering regattas. (4,40)

Consequently two classes developed or rather were established: those that kept to the roots and were only limited by the length of the hull and those who adapted to the new rules (compare Fig 53). (4)

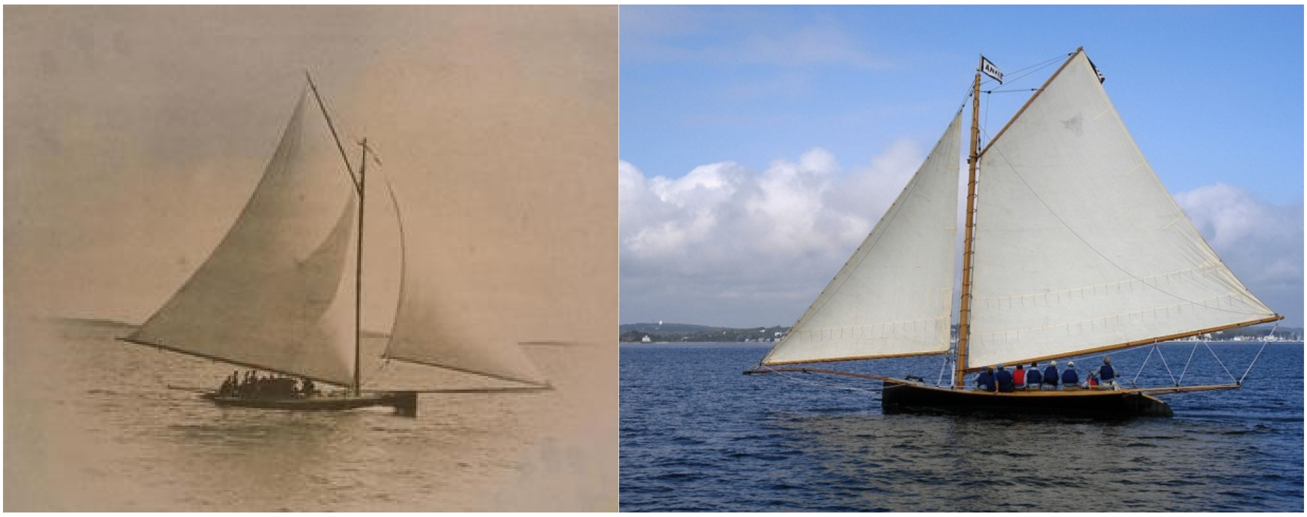

Fig. 53 The 28ft Sandbagger "Annie" (original launched in 1880) was rebuilt in 1968 (39)

2.2 Skiffs of Sydney

At the same time the sandbaggers developed in New York, the workers in the Sydney Harbour also developed a new style of boats: the "Skiffs". The fishing boats that were used during weekdays, were re-rigged for the weekends with bigger, lighter sails for racing against each other. When looking at the topography of the Sydney Harbour you can see that it is perfect for sailing as the Great Dividing Range to the west prevails warm and westerly winds that blow during summer. In addition the high plateau to the northeast and its steep side canalize the sea breeze in the Sydney Harbour to a regular average of 12 knots on summer afternoons. But not only the weather and the wind makes the Harbour enjoyable, also the possibility to watch boats from higher ground and see tactics and racing from an elevated point of view that is not possible were shores are flat.(4)

> *"In the mythology of Australian sport, there are few legends more colourful or enduring than those which surround the great sail-carrying open boats. Throughout most of the nineteenth century, long before cricket and the turf became obsessions in the infant colony, vast crowds jammed every vantage point around Sydney harbor to gape at and to gamble on the incredible antics of the men who dared to race the big boats"* (42).

Sailing and especially sailing sport has always been part of the culture of the Sydney Harbour. Up to now you can see the importance of this sport when wandering through Sydney.

> *"In the 1850s Sydney is said to have had more amateur and professional sailors than any other city in the world. The twenty-four footers often carried up to twenty men – great chunks of 'live ballast' squashed triple banked on the gunwales. The boats were huge, powerful, beamy and very, very wet. They set colossal clouds of sails upwind and more before the breeze. Long before spinnaker were invented they set their extra square-rigged on heavy spars like the great clipper ships. Judged by today's standards they were alarmingly, magnificently over-canvassed. Sometimes the boats simply buried their bows and drove themselves under"* (42).

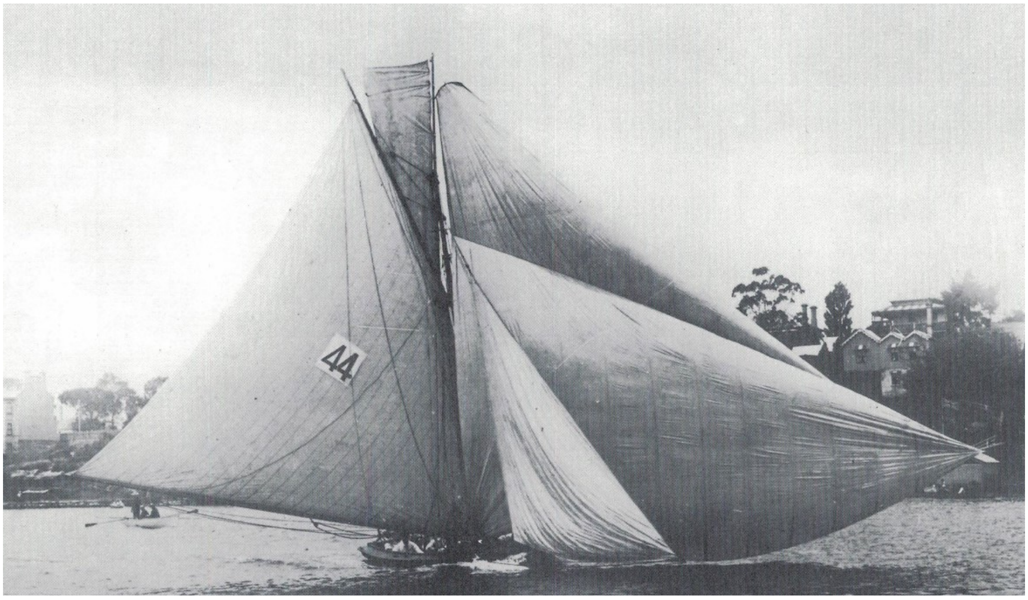

Fig. 54 A 22-Footer of the year 1890 looking like a "giant moth" close to 3000 square feet (≙278.7m^2) of sailcloth. (42)

The differences between the sandbaggers of New York and the Skiffs of Sydney can easily be identified. Whilst the sandbaggers used sandbags to shift weights, the skiffs used the weight of the crew members to reach the same aim (Fig.). (4)

Furthermore extra sails (compare Fig. 54 and 55) were utilized to sail with enormous sail areas. To compensate the sail area in terms of stabilization of the boat, skiffs used huge crews (up to 20 people in 24ft boats) that were used as ballast, which enabled them to move quickly from one side to the other. As the boats were quite small (24ft.≙ 8m) the single individuals had to be "stacked" – the first one sat on the gunwale the second on top of him. (compare Fig. 55) (42)

The second main difference between the sandbaggers and skiffs was the hull. Whilst the sandbaggers had a half-closed deck – the sailors were moving on deck quite easily, the hefters underneath moved the sandbags from on to the other side – the skiffs had a completely open boat so that the crews could easily “run from one side to the other. In order not to fall out of the boat when heeling, ‘lee-cloths’[30] were attached to the gunwales. While sailing the leeward lee-cloth, was swung in to act as a leeward deck to keep the water out, the windward lee-cloth was swung out to be used as a sitting area. (Compare Fig. 55) (4,42)

Fig. 55 Sailing in 18-24ft skiffs with more the 15 people on board, stacked two or three deep on the gunwales. (42)

As a result to the rapid development and popularity of these boats an enormous amount of skiffs were sailed in the Sydney Harbour. Different styles and different sails were to be seen around 1890. From 6ft up to 24ft virtually every variety was present and everyone wanted to race. The smaller boats (6-12 foot) were extremely numerous and needed flat and sheltered waters. As these boats often were family boats there was a tendency to race close to their homes. The bigger boats 18 to 24 footers could be sailed in the Harbour and were an enormous magnet for spectators. In the Sydney Harbour six Yacht Clubs were founded but all of them failed within a few years because they were unable to control their fleets. Except one: The Sydney Yacht Squadron (later Royal Sydney Yacht Squadron[31]) (4,43)

By focusing on one class Mark Foy established a concept that resulted in a Club that exists up to now: The Sydney Flying Squadron. By listening to the needs of the sailors and adding two promotion techniques, he gathered a big crowd of supporters behind him and was able to found the Squadron in 1891 establishing it as an important milestone in the history of sailing in Australia. (4,44)

[30] Lee-cloth: is some sort of timber that was attached to the gunwale of the boat to sit on and when on the leeward side to prevent water from swapping in.

[31] Established in 1862 the Royal Sydney Yacht Squadron (RSYS) is one of the oldest yacht clubs in Sydney. (43)

Two promotional techniques were disposed:

- The big insignia of the Flying Squadron in the Mainsail, to make skiffs recognizable from the distance.
- Introducing the ‘Marc Foy start’ which basically is a handicap start, meaning that the slowest boat starts first, contributed tremendously to the popularity of the races.. The simplification for the spectators is that the first to cross the finish line is the winner.

The development of these two classes – Sandbaggers and Skiffs - indicate the starting point of the 20th century of sailing “sail faster, move ballast and set more sail”. Around the world boat classes like these two emerged. Classes like the “Z” or “M” class of New Zealand (Fig. 56 and 57) reached enormous speeds in the open ocean.

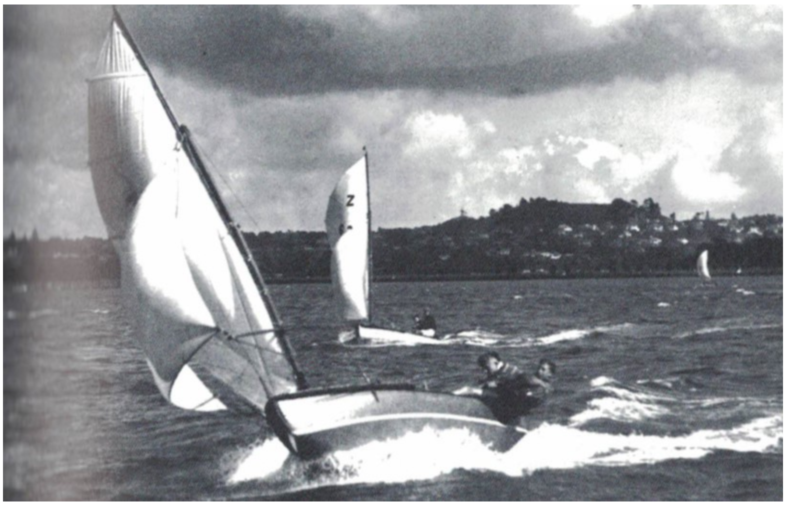

Fig. 56 Z Class Dinghies from New Zealand (1921) (4)

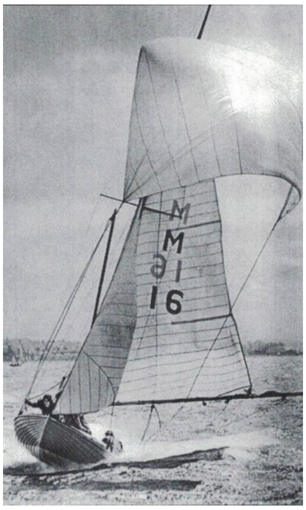

Fig. 57 M Class Dinghies planing at speed (4)

In order to push the speed limits even further, boats developers on the on hand wanted large sail areas but, despite the fact that not the sail is a limiting factor the hulls had to be changed in order to become faster. Meaning that boats had to be built with flatter bottoms to reduce drag so that boats could plane already at relatively small speeds. A major difference between the 14ft Dinghies from New Zealand and those from Sydney was that they were extremely light weight and it was possible to sail these boats with a maximum of 3 people. Two of the main developers for the fourteen footers were Harry Highet from Wellington and Billy Rogers of Auckland. (4)

> *“Putorino (from Harry Highet) was not an extreme design, but in each of the following boats the bow was made sharper at the waterline and broader at the gunwale until the extreme ‘aircraft carrier’ shape of Innocence was reached. These boats could handle*

Wellington worst winds and waves and still plane very fast when reaching or broad reaching (4)*."*

For the Australians it took a long time to accept the dominance of these boats in terms of speed and it took one of the prestigious Royal Hobart regattas in Hobart, Tasmania in 1938 to prove it.

"The performance advantage of the two light New Zealand seagoing planers over the non-planing heavy big-crew Australian fourteens was overwhelming." (4)

2.3. The apparent wind revolution

Worldwide planing boats were developed and some of them won against bigger boats some did not. During the 1950s to 1970s not much changed in the concept. Flat hulls, broad gunwales, big sails like the Flying Dutchman (FD) or the 5o5s were state of the art but no major difference in handling these boats was observed. In the beginning of the 80s the Iceboats set their records on frozen lakes with speeds on the downwind leg at around 150 to 160 km/h in around 17 to 20 knots of wind. The main reason why these speeds were possible was tacking downwind. When looking at the Flying Dutchman you can see that these boats use a symmetrical spinnaker to run square. Running square always limits the boat to sail with a maximum of the wind speed. In contrast to the Flying Dutchman or the 18 Footer, the Tornado (a catamaran) had the approach to use a smaller and flatter spinnaker to tack downwind. Resulting in the fact that when you compare two Tornados sailing the same course the downwind tacking was faster than running square but the 18 Footer with the big spinnaker running square beat them easily. It took a couple of years and a lot of testing to understand what had to be changed to make these boats faster. They had to become smaller, the crews were cut back to only 3 people and changing spinnaker is too slow to win races especially in the Sydney Harbor. With the development of "wings" (Fig. 58) boats could carry bigger sails and sail faster especially on downwind legs when reaching or broad reaching but not when running square. (4)

It took a young talented sailor Julian Bethwaite to revolutionize the 18 Footer. Changing the gybing spinnaker pole to a fixed bowsprit and most importantly changing the symmetrical spinnaker to an asymmetric spinnaker was the first step to create a real apparent wind boat on water. (4)

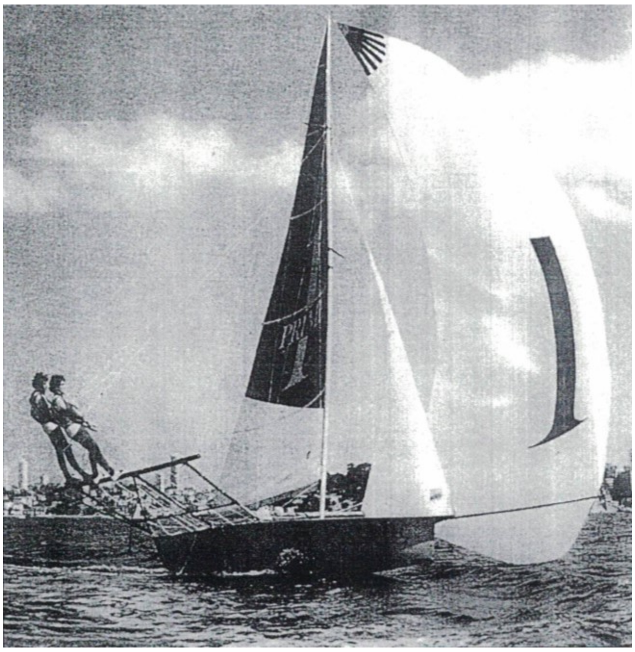

Fig. 58 Julian Bethwaite on his second 2 handed 18 Footer Prime 2 of 1982 (3) standing on wings attached with trapezes to the mast top. Also it was the first "asymmetric spinnaker with full luff and flat leech." (4)

8.1. Development of the 29er

2.3.1. 29er MK I – May 1997

After the design process and the molding of the new 29er hull Frank Bethwaite decided to test the boat for hydrodynamic attributes. Especially the hydrodynamic drag was interesting because this is the key factor for high speeds. The first couple of tests were very interesting as the test was done with a raw hull, meaning it wasn't sanded and polished. As a consequence the drag curve was a lot higher than expected but without any humps, which proved the hull and the test to be quite satisfactory (4). After polishing and finishing off the underwater ship a small B-14 rig (compare Fig. 18) was added. Several tests in the Sydney Harbor made clear that this boat was an apparent wind boat.

> *„In strong winds and big waves, it handled truly and did not bury its bow. When sailed in winter light airs against a benchmark Tasar fleet, it held its place upwind and vanished at speed as it tacked downwind as soon as there was wind enough to inflate*

the spinnaker. It performed well even when crewed far above its design crew weight. In strong winds it handled well and sailed fast in both flat water and waves"(4).

Although it was sailed quite well a couple of changes had to be made. The side decks were too high so that after capsizing the whole boat hat too much floatation and it inverted quite quickly and to get back on board was hard.

2.3.1. 29er MK II

The main changes on the MK II were considered milestones for the 29er. The „foam-sandwich hull laminate" made the boat lighter, the lift stayed the same but the hull was about 50mm thinner. Most importantly the durability increased with this production method. (4)

What was learned from the MK I was that the cockpit had to be changed:

- Because of the new method and as the hull was made without any internal framing, the whole wing was around 50mm thinner and so the crew sat about 2 inch (5.08 cm) lower.
- In order to experiment whether it is better to use a self-draining cockpit or a non-self-draining the cockpit floor was set at the lowest possible position.
- For better stability the center case was set a little forward for better balance when sailing under spinnaker(4)

In September 1997 the MK II was finished and with a youth trainer rig made for this boat, it was launched for the first time.

> „We were delighted with all the changes. The lower side decks now ‚felt' right. When on its side, being righted after capsize, the hull floated lower with the centerboard only a few inches above the water, which was ideal. With the new rig and the new centerboard position the boat now balanced perfectly. Performance, both upwind and downwind, and in all wind strengths, exceeded expectation. This boat did truly 'sail like a skiff to train for a skiff'" (4).

Fig. 59 Julian Bethwaite and his son on the MK II. (Author)

The concept of different rigs for youth and adult was taken from the 18 Footer proved to be an advantage especially in the beginning of the development process. The small rig was built for youth, with one spreader and a larger-rig 'sport' with two to carry a masthead spinnaker and two trapezes (4).

The reason why Frank and Julian Bethwaite were so successful was, that they tried to test and validate every single detail and left nothing to chance. Testing the boats made clear that the smaller rig was a lot faster in a strong breeze but the low cockpit floor made problems after capsizing because the water simply couldn't be cleared from the deck. So fitting a transom was the only way to proceed in the process. As their goal was to create a youth trainer, it was important to hear what young sailors would say about that boat. So they went to local clubs in Wollongong on the Lake Illawarra, Hunters Hill, Northbridge and the Sydney Yacht Squadron, to test with them. During these tests a lot of knowledge and ideas was gained for the future development. (4)

Quickly the word about this boat spread around the world and was asked to be shipped to Europe to display at the Paris and Dusseldorf Boat Shows. Clear instruction were given when shipping and displaying these boats: „*Do not under any circumstances sail this boat publicly unless you first refit the transom, else it will swamp with a hefty crew in drift conditions*“(4).

The fact that the transom was removed and the cockpit floor was about 30mm lower than it is today, the boat can swamp very easily and is very hard to upright after capsizing. After Dave Ovington brought the boat to the UK a heavy crew sailed the boat in light wind. As a matter of fact the boat swamped and resulted in a loss of interest by partners from the UK and America

(Later they admitted it was a big mistake (25). Dave Ovington remained involved in the Project and Ian Bruce (CAN) took the place of the partners that left the Project. (4)

2.3.2. 29er MK III

After the backing down from the American and British partners, critics recommended to drop the idea of an apparent wind youth trainer, building something bigger just with an asymmetric spinnaker on it. But the intention was still to build a boat ‚that sails like skiff to train for a skiff'. Therefore a couple of changes had to be made that were learned from the tests with the youth teams around Sydney. (4)

Lifting the floor around 3 cm and adding the lift by 15kg and shifting the rig just a bit to the front were the main changes that were made to finish the MK III. As the boat was a little bigger, due to increasing average bodyweight, also the sail area had to be increased. One last change seemed necessary: as the boat is righted, after capsizing, due to the low and open deck, it takes off easily and makes it hard to get back on board. Therefore a transom with big scuppers was installed to keep enough water to not take off immediately after righting but draining the cockpit soon after. (4)

The MK III was made available for as many young sailors as possible to generate a significant amount of ideas and meanings on the boat. Generally seen the boat was an immediate breakthrough and it was so well received by the sailing community that several well-known Sailors wanted to sail the 29er. One of them was David Ovington – founder and owner of the company Ovington Boats in Newcastle in Great Britain, who is still building the 29er today (45) – Ian Bruce from Canada – designer and developer of the Laser (46,47)– and Tako Otani from Japan who helped Frank Bethwaite already in earlier designs (25).

2.3.3. 29er MK IV

In February 1998 Frank and Julian Bethwaite decided to change a couple of more things on the hull. The draining vent was changed and the shape was slightly modified to improve the overall performance. The stern and the side deck were also changed in matter of design elements. Due to the fact that the boat shell be sailed by young adults the two-rig-idea was put aside and the bigger rig is being produced. As can be seen on the Fig. 59 the sails in the prototype are transparent and can hardly be seen when sailing, Julian had the idea to make them fluorescent orange to make them easier so see. Furthermore the fabric of the sail changed to Mylar (both Mylar and fluorescent orange are still used in the boat). (4)

End of April 1998 the MK IV was ready and it was again Julian's idea to name the boat 29er. The boat was then air-freight to the 49er Worlds in Bandol in France to be presented and firstly introduced to the people (48).

2.3.4. Neue 29er Designs

In November 1996 the 49er was introduced and ratified as the new Olympic class for men and therefore the first skiff (49). The problem that arose was that the boat was great for male sailors but in matter of physical appearance the boat was close to not sailable for female sailors. As a result the IOC wanted to have a skiff for women in the 2010 Rio Olympic Games. So testing and developing started immediately after this wish was pronounced.

2.3.4.1. 29erXX

The design ideas of the XX came from Julian Bethwaite and Jen Glass to take the 29er with a little more sail area and helmed from the trapeze. To realize this the mast was made 0,45m longer and parts of it were made of carbon instead of alloy. Because of the slightly longer mast an additional pair of shrouds was implemented and to gain more speed. For reaching or broad reaching conditions the gennaker was sailed from the mast top (compare Fig. 60). (50–52)

When sailing this boat one major problem arose as the boat is quite small with such a big sail area, the boat was extremely unstable and even at higher speeds it wouldn't gain a similar stability as the 49er. The challenge for the crew was to minimize movement on board and at the same time not losing balance. As crew and helm are on the trapeze it is a lot harder to sail the XX than the standard rig. (50–52)

- In 2006 the first international regatta was sailed in Weymouth (England)
- In 2007 it was excessively tested in Hyères (France) and was considered fit for use and introduced as the women skiff for the Olympic competitions
- In 2011 the class obtained the status of an ISAF class
- 2014 this status was deprived again.

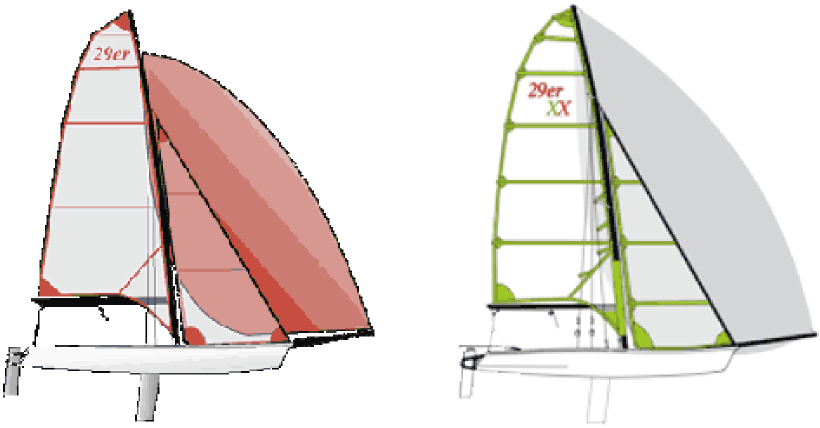

Fig. 60 Difference between a standard 29er and a 29er XX (50)

	29er (Standard rig)	29erXX
Length	4.45 m	4.45 m
Width	1.77 m	1.77 m
Weight (with mast and sail)	70 kg	70 kg
Mast height	6.25 m	6.70 m
Sail area (Mainsail and jib)	12.50 m^2	15 m^2
Gennaker	15m^2	19m^2