Failure of Carbon Fiber Yacht Mast in Heavy Weather

by

Nicolas Meilhan

Submitted to the Department of Civil and Environmental Engineering
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Abstract

For many years Round the World racers and leading yacht owners have appreciated the benefit of carbon. Carbon fiber spars are around 50% lighter and considerably stronger than traditional aluminum masts. The result is increased speed, and the lighter mast also gives the boat a lower centre of gravity and so heeling and pitching is reduced.

The recent spate of carbon mast failures has left concerns amongst the general yachting public about the reliability of the concept and ultimately the material itself. The lack of knowledge about loads acting on the mast prevents designers from coming with an optimum design. But a new program, the "Smart Mast" program, developed by two of Britain's leading marine companies, has been able to monitor loads acting on a mast in real-time with an optical fiber system. This improvement could possibly be a revolution in the design of racing yachts carbon masts and fill the design data shortage.

Some other evolutions in the rigging design also appeared to be of interest, like for example the free-standing mast or a video system helping the helmsman to use its sails at their maximum.

Thesis supervisor: Jerome J. Connor

Title: Professor of Civil and Environmental Engineering

Acknowledgments

I spent an incredible year here at MIT and there are a few people I would like to thank. First I would like to thank my parents for allowing me such an opportunity, all my family for always supporting me. I would like to thank Eric Adams for the wonderful director he is and the good time we had with the Meng class. Also I would like to thank Paul Kassabian and Lisa Grebner for their availability all year long during the project and the thesis. I am very grateful towards MIT libraries which are really an incredible tool and that could get any book from any part of this world in less than a week.

I would like to thank especially Professor Connor who was my advisor and who always supported me in my ideas, was always available to talk and would always have an answer to my questions. Thank you again also for the wonderful birthday I spent in Shanghai in this very nice restaurant.

My last acknowledgment will go for Professor Jerome Milgram who gave me some very interesting insight about different issues that are discussed this thesis.

Prologue

It was important for me to explain why I choose this subject to write about and a prologue granted me this opportunity. Being here at MIT, one of the biggest research center in the world, allowed me to meet great people, to contact famous engineers and also to have access to all the MIT resources.

I love sailing but never really got interested in the physics of it. Therefore, my background in composite materials and structure gave me this unique opportunity of investigating the recent mast structural failure. Since literature about this topic was very scarce and designers did not share their data, I tried to survey all the literature available about racing sailing boats available in the United States and to write about the most relevant evolutions and information I could find. This thesis was meant to be an introduction to the world of sailing yacht by gathering the knowledge published up to now in naval architecture. The references and bibliography gather the results of this literature survey that I could realized thanks to MIT libraries.

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Chapter 1

Introduction

The high specific strength of glass reinforced plastics together with the superior specific stiffness offered by carbon and other high-modulus fiber have led to a dramatic growth in the use of these materials in ultra-high performance sailing craft. Racing boats of this kind, usually sponsored by large industrial or commercial organizations, are an economic aberration: very high material and fabrication costs, which would be intolerable in any other marine vehicle, are accepted, risks are taken and durability is sacrificed in order to achieve minimum-weight hulls and spars which are capable of winning or at least scoring publicity points in prestige events such as the Whitbread Round-the-World Race. This type of construction aims to stretch technology to its limits and provides, potentially, through evaluation of the failures as well as the successes, a valuable spin-off in design methodology and understanding of materials limitations applicable in the design of lower performance craft [1].

Nevertheless, composite materials, due to their relative high cost, are not today used at their maximum potential. Many carbon masts of multihulls broke because the fiber used in the construction was not appropriate to the kind of loads the boat would have to expect. Therefore a lack of knowledge in the way how the material behaves, but also in the loads applied to the structure lead to these failures.

This thesis is a critical review of the literature written up to today about the state of the art technologies employed in the design of racing yachts. After an introduction of the basic considerations that dictate the design of sailboats, the evolution of masts over the last century will be considered. Carbon spars will then be more precisely discussed with a focus on the recent failures encountered by the skippers and the way to tackle these problems. Finally improvements and likely trends in marine technology that will be used to achieve only one goal-going faster-will be discussed.

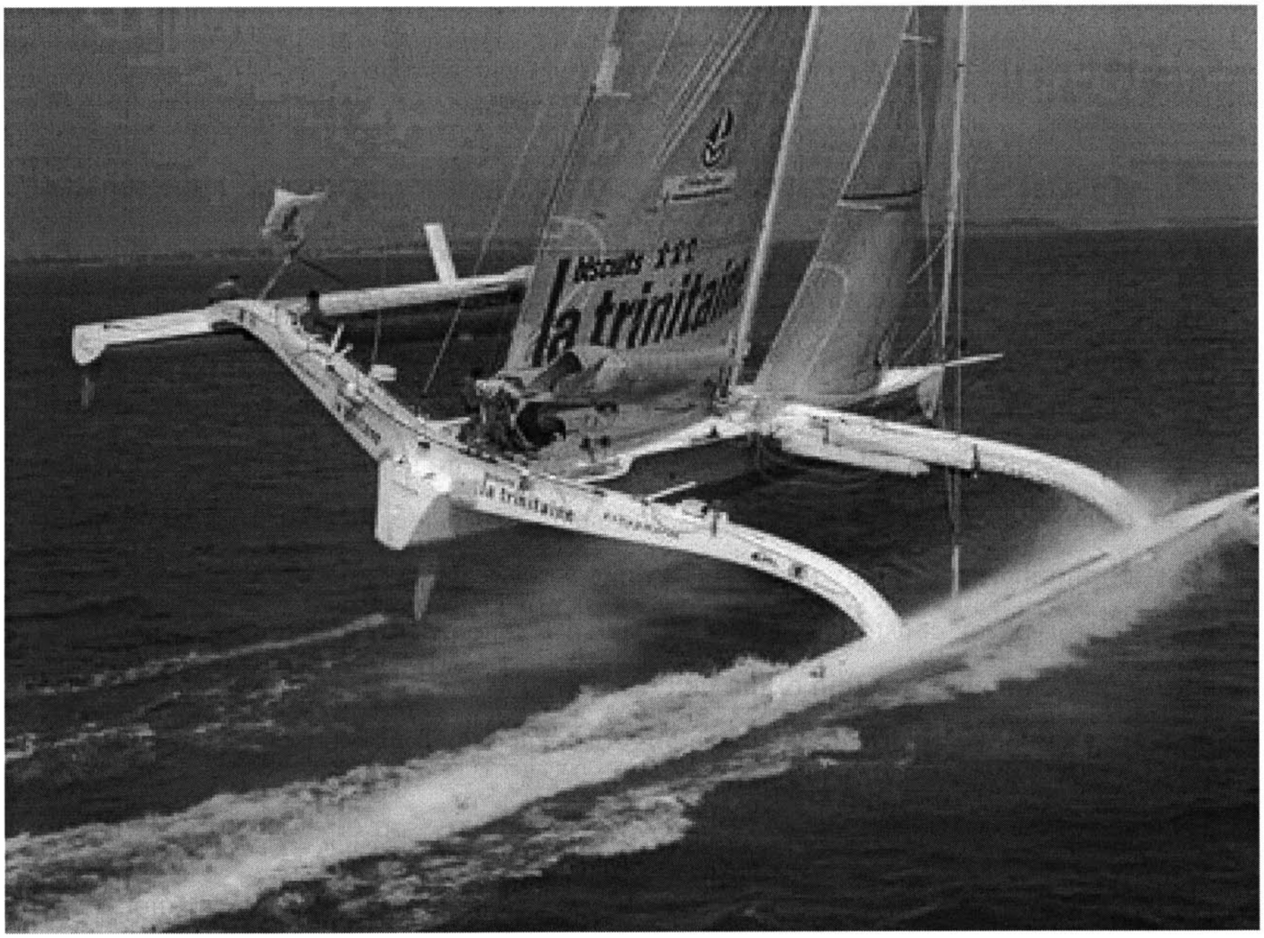


Figure 1.1 Trimaran "La Trinitaine" [28]

Chapter 2

Basic consideration of the forces acting on a sailing yacht

1. Equilibrium of Aerodynamic and Hydrodynamic Forces

When running before the wind the resultant force developed by the action of the wind on the sails of a sailing yacht is approximately in the direction of the heading of the yacht. In that situation a sailing yacht does not distinguish itself from other craft with respect to the attitude of the hull in the water and the hydrodynamic forces caused by the flow of water along the hull (usually called the canoe body) and the appendages. When beating to windward or when a reaching course however, the resultant force of the wind on the sails has a component at right angles to the yacht's heading. This transverse force can be up to about five times greater than the forward thrust component of the sail force. Since in any steady sailing condition equilibrium must exist with the aerodynamic and hydrodynamic forces on the yacht, it follows that the transverse component of the wind force must be in equilibrium with the transverse component of the hydrodynamic force on the canoe body, keel and rudder. [2][3][4][5][6][7][8].

Figure 2.1 Trimaran "La Trinitaine" [52]

The only way for a yacht to develop the required hydrodynamic transverse force, normally referred to as the side force, is to adopt an angle of yaw β (called leeway angle in sailing yacht terminology) relative to the track of the yacht with respect to the water. The keel and rudder of a yacht do not normally have camber, requiring that the total side force be generated by angle-of-attack only. Camber in the lifting appendages cannot be adopted because a sailing yacht must perform equally well on port and starboard tack (an aircraft does not have to perform equally well when flying upside down). Rotatable keels and forward rudders as fitted to the latest generation of America's cup yachts, and leeboards as fitted on traditional Dutch sailing craft, allow for the development of side force without the necessity of leeway angle. The side force generated in moderate to high wind speeds is such that additional side force usually needs to be generated by leeway angle in these cases as well.

To design a sailing yacht with good ability to sail to windward, it is necessary that the required side force be generated at a small leeway angle. A large leeway angle seriously impairs the windward ability of a yacht. In part this is due to the increasing in hydrodynamic resistance of the hull with increasing leeway angle. Mainly, however, a large leeway angle results in a lower value for the component of the boat speed in the direction opposite to the true wind speed V_{TW} than in the case of a small leeway angle. This component of the boat speed, called the speed-made-good to windward V_{MG}, is equal to $V_{MG} = V_B \cdot \cos(\beta_T)$ with β_T the true wind angle.

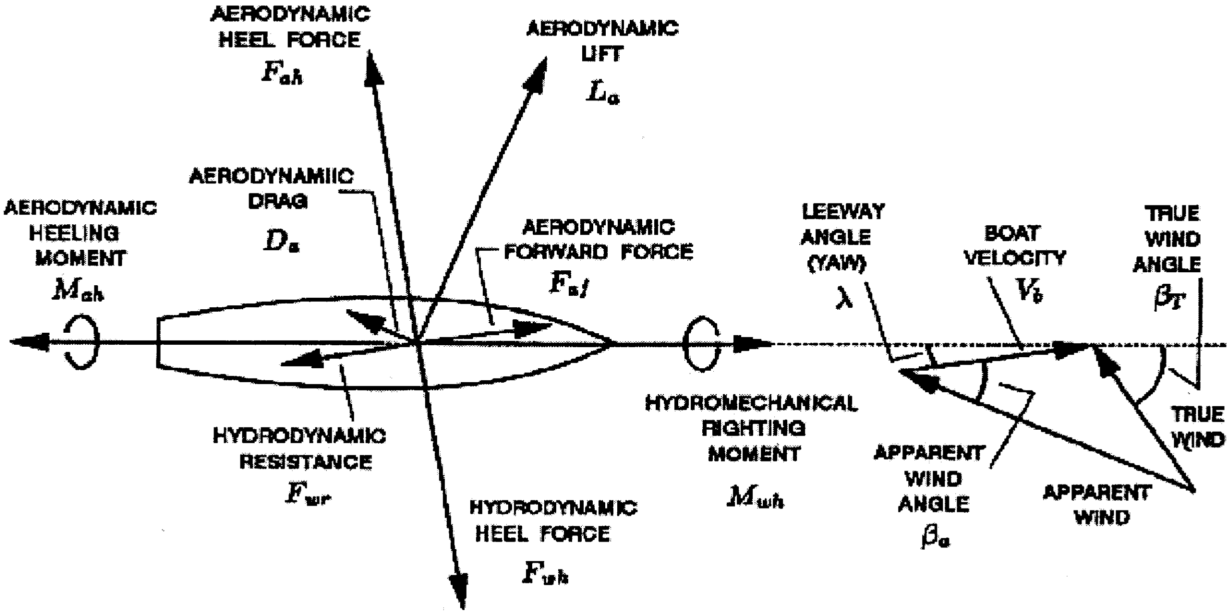


Figure 2.2 Forces and Moments in the deck plane [6]

The most important single problem in the design of a yacht, when windward performance is pre-eminent, can be formulated as how to design an underwater configuration that generates the required side force for a minimum of resistance at a small leeway angle or, how to maximize the side-force resistance, or lift drag ratio, for a given value of the side force, at a small leeway angle.

2. Hydrodynamic side forces

As the hull of a sailing yacht adopts a leeway angle to counteract the aerodynamic side force, it also adapts a heel angle. After equilibrium between all forces acting on the yacht is attained and a steady state value of the leeway angle λ and heel angle ϕ is reached, the angle of incidence of the flow to the keel, which is normally the main part of the yacht with the production to side force, is $\lambda\cos(\phi)$, where ϕ is the angle of heel. If the canoe is considered as a lifting body then its angle-of-attack to the flow is also $\lambda\cos(\phi)$. In the case of the rudder however, when in the normal position behind the keel, the angle-of-attack is usually reduced because of the downwash of the flow behind the keel. A first estimate of this downwash effect is that it reduces the effective value of $\lambda\cos(\phi)$ by half (Scott, 1974).

The horizontal side force component of the lift produced by the keel can be expressed as:

$$SF_K = \frac{1}{2}\rho V_B^2.\lambda\cos(\phi).A_{LK}.\cos(\phi)$$

where ρ is the fluid density, V_B is the boat speed, A_{LK} is the lateral area of keel (equal to span times average cord length).

3. Hydrodynamic resistance

The hydrodynamic resistance experienced by a sailing yacht, for the purpose of speed prediction, can be divided into five main components. Three of these are common to all types of vessels: viscous resistance, wave resistance and added resistance in waves. Because of the significant hydrodynamic side force on the underwater body of a sailing yacht however, two additional components are incurred. The first of these is a consequence of the significant angle of heel adopted by the hull, which results in variations to the viscous resistance, the wave resistance, and the added-resistance-in-waves component, as found for the zero-heel condition. This component is referred to as resistance due to heel. The second component, called induced resistance, is associated with induced flow (the upwash in front of a lifting surface and the downwash behind it) in that it causes the lift to possess a vector component acting opposite to the direction of motion.

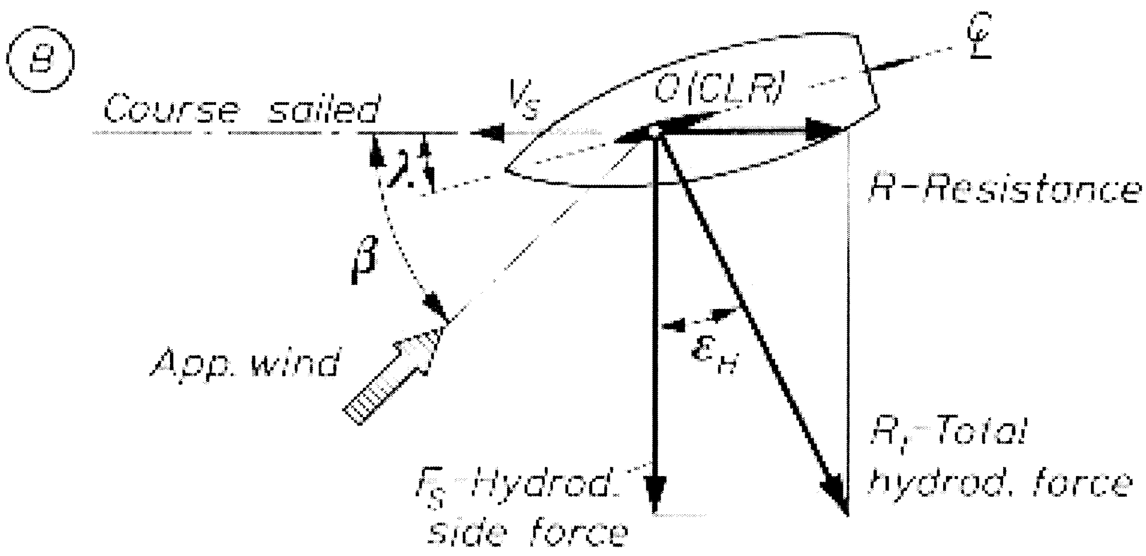


Figure 2.3 Hydrodynamic forces developed on a hull moving through water with angle of yaw [2]

3.1. Viscous resistance

The viscous resistance is considered to be equivalent to the sum of the frictional resistance and a pressure resistance component of viscous origin. The frictional resistance is associated with the force required to overcome the tangential stresses developed between the canoe body, the keel and the rudder and the viscous fluid. The viscous pressure resistance is due to the pressure difference between the forebody and the aftbody as a consequence of the growth of the viscous boundary layer. This causes the pressure on the aft-body to be lower than the pressure on the fore-body, leading to a resultant pressure force on the hull. Since the pressure force has a viscous origin, as distinct from the forces associated with the pressure distribution over a body in potential flow, it is accordingly termed the viscous pressure resistance.

Since the pressure resistance component is usually small, the viscous resistance is often expressed as:

$$R_V = \frac{1}{2}\rho V^2 \cdot C_V \cdot S$$

where $C_V = C_F(1+k)$ and $k = 0.0097(\theta_{entry} + \theta_{exit})$

in which C_F is the specific frictional resistance coefficient of the body. Here, θ_{entry} and θ_{exit} exit are the half-angles (in degrees) of the bow and stern, respectively, at the water plane and S the wetted surface of the body.

3.2. Wave resistance

At normal sailing speed, the flow along the canoe body leads to an increase in pressure in the region of the bow, a decrease in pressure in amidships and an increase in pressure at the stern. The energy expended by the hull in causing waves is significant and greatly dependent on the length-displacement ratio $L_{CB} / \nabla_{CB}^{1/3}$. For displacement ships, which do not experience any dynamic lift causing the hull to come out of the water such as in the case of planing crafts, the so-called wave resistance often increases as much as with the 6th power of boat speed. It is this component of resistance which, in a practical sense, limits the attainable speed of mono-hull to the so-called hull speed, a speed that usually varies between $2.35\sqrt{L_{WL}}$ and $2.72\sqrt{L_{WL}}$, where L_{WL} is the length of the design waterline in meters and where the speed is expressed in knots.

3.3. Added resistance in waves

The combined heave, pitch and roll motions experienced in head and bow-quartering seas and the roll motion experienced in beam seas, sometimes in combination with smaller amplitude surge, yaw and sway motions, are considered to be the main causes of the so-called added resistance in waves, sometimes simply called the added resistance.

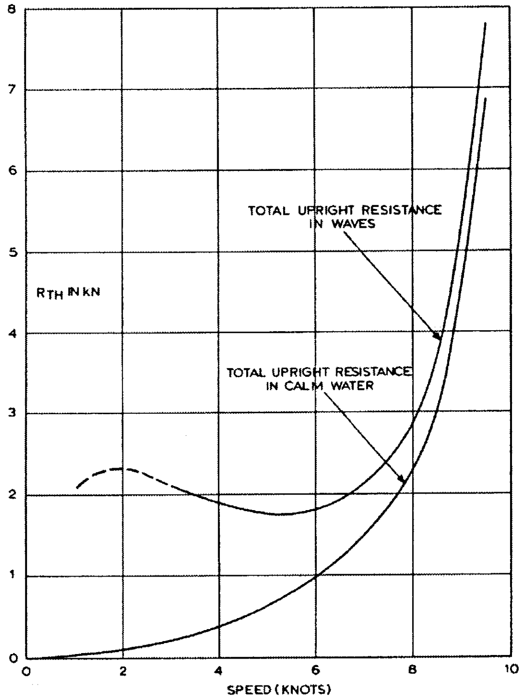


Figure 2.4 Comparison of the resistance in calm water and in waves [5]

The severity of pitching is found to particularly influence the level of added resistance component in waves. By reducing pitch motions, the level of the added resistance is reduced. Another important feature of this resistance is that it is independent of the still water resistance and that the added resistance in waves is proportional to the square of the wave height.

In following seas the overall effect of the waves often results in a speed increase of the yacht. Particularly when the length of the waves is more than 5 times the length of the yacht, the length-displacement ratio is more than about 6, and the following waves have a low encounter frequency, the yacht will surf down the face of the overtaking wave, momentarily reaching very high speeds. At high encounter frequencies, and in less regular seas the effect of the following waves is generally still found to increase the resistance.

3.4. Resistance due to heel

An increase in resistance is usually encountered when the yacht heels. In that case the effective shape of the hull through the water is no longer symmetrical, causing both an increase in viscous and wave resistance.

It is normally only determined for the still water condition and the effect of the change in added resistance with heel is in most studies assumed to be negligible.

The resistance due to heel is sometimes less than zero for heel angles less than about 20 degrees. This is usually due to a reduction in wetted surface area as the yachts heels, particularly when the canoe body has very little topsides flare. In that case the decrease in viscous resistance is often greater than the resistance increase associated with the lesser quality of the flow over the canoe body.

3.5. Induced resistance

This resistance is directly associated with the developed side force. Side force needs to be developed when sailing to windward to balance the transverse component of the sail force. To generate side force the flow has to have an angle of incidence with respect to the centerline of the hull. This is the reason a yacht makes leeway and the cause of the so-called induced resistance. The induced resistance is the component of the generated lift force on the hull in the direction opposite to the path or track of the yacht. For a given design the induced resistance is approximately proportional to the square of leeway angle times velocity, and in most successful design is not greater than about 10 to 15 per cent of the total resistance when going to windward.

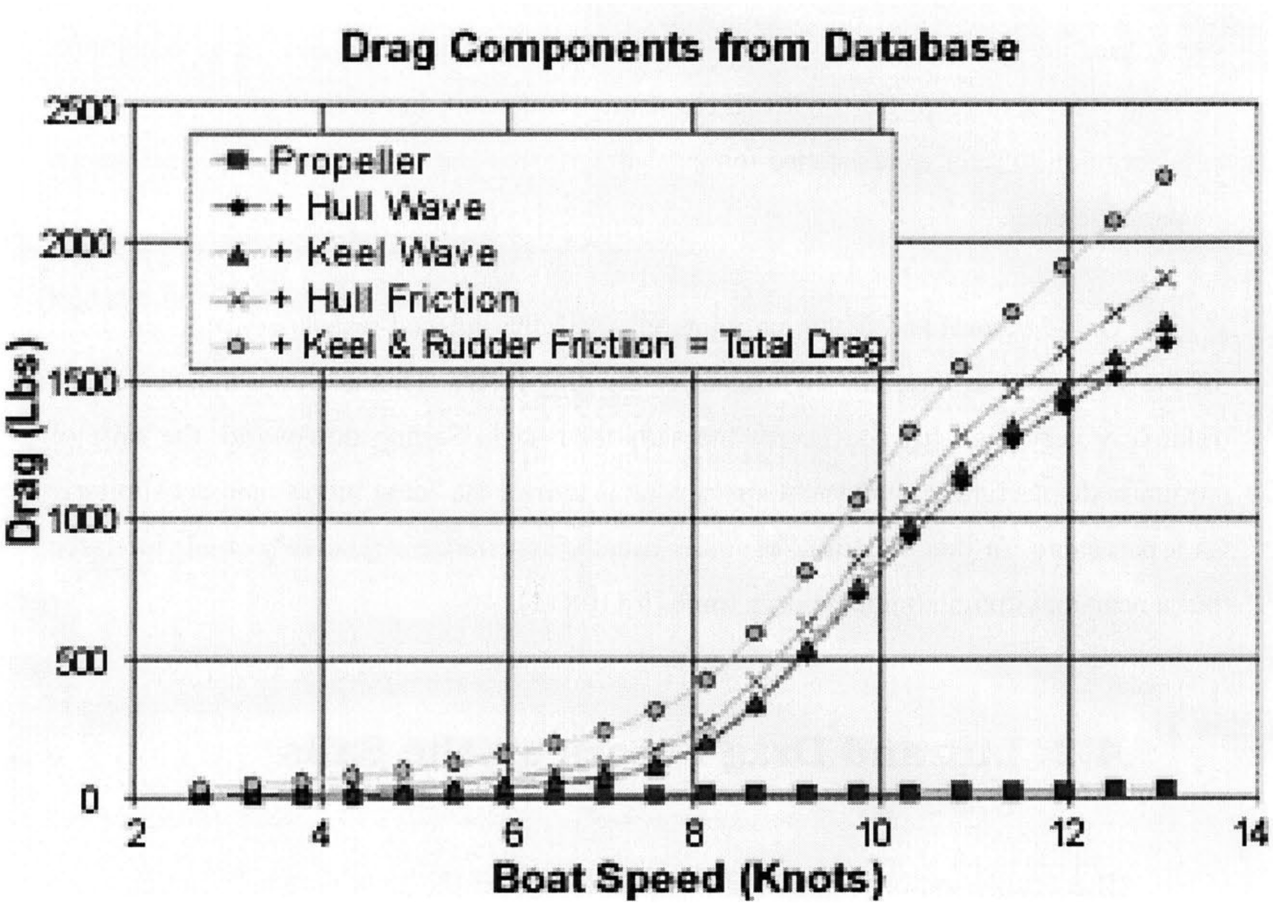


Figure 2.5 Increase in the Drag with the speed of the boat [53]

4. Aerodynamic forces

4.1. Components of the Total Aerodynamic Force

The aerodynamic force experienced by a sailing yacht are those associated with the wind acting on the sails, hull, superstructure, mast, standing and running rigging, crew, etc. In general, these are all friction, viscous pressure and flow separation resistance forces except for the lift forces acting on the sail. In the field of aerodynamics, it is common to refer to resistance forces as drag forces and to refer to viscous resistance as parasitic drag.

On windward and reaching points of a sail, the induced resistance (induced drag) of the sail is by far the most significant of the drag forces. This is a consequence of the relatively very high lift coefficient the sails then have. Sailing downwind, the sails of common displacement-type yacht are in what is termed the “drag mode” and act similarly to a parachute. In this situation, the sails usually experience a relatively small lift force but a near-maximum attainable drag force.[9][10][11].

4.2. Lift and Drag Forces on the Sails

The determination of the aerodynamic forces on the sails is usually much more difficult to achieve then the determination of the hydrodynamic forces on, for example, the keel. This is a consequence of the fact that no accurate experimental technique has yet been devised for the determination of the lift and drag components of the force on the sails other than carrying out very expensive large scale tests on the actual yacht or on special test rigs. There are three prime reasons for this. The first of these is associated with the fact it is extremely difficult to model the stretch and other properties of the sail material on small scale.

The second is associated with the fact that when the sails are set to their optimum trim, yielding the highest boat speed, the sails are often found to operate close to their maximum lift coefficient on reaching points of sail and at their maximum drag coefficient on downwind point of the sail. Such sail settings invariably invoke a significant amount of flow from the sails. When, as is normally the case, the full-scale Reynolds number cannot be adhered to in the test facility (usually a wind tunnel), this fact leads to significant inaccuracies since flow separation phenomena are prone to large scale effects when the Reynolds number is not adhered to.

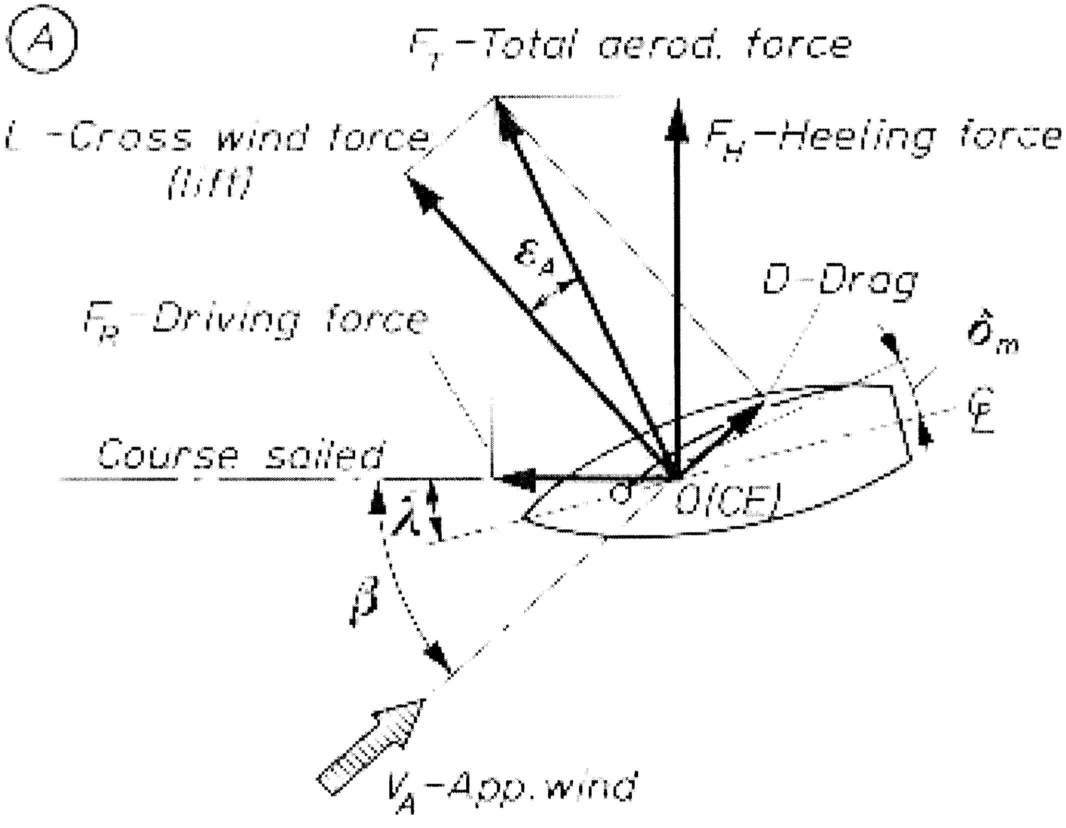


Figure 2.6 Aerodynamic forces on a yacht rig sailed upwind [2]

Thirdly, the significant interaction between the various sails is dependent on many variables, such as the amount of sail overlap (between genoa and mainsail and between mainsail and spinnaker), sheeting angles, sail shape (as associated with aspect ratio and the amount of roach or leech hollow), sail trim, etc, which makes it almost impossible to accurately predict the sail forces at full scale from previously-attained model or full-scale test results, irrespective of any other problem.

Up to now, the problem of accurately predicting sailing lift and drag forces has still not been dealt with accurately. Many noteworthy experimental studies have been carried out which have helped to provide insight into this difficult subject and which have yield important quantitative information. Also, many numerical studies have been carried out to derive design data for sail lift and induced drag None of these studies have been conclusive, however, with respect to the lift and drag data obtained.

Notwithstanding this, a situation has presently been reached in which reasonably accurate sail lift and drag data have been defined for the purpose of determining maximum boat speed potential. This data represents the upper bound of attainable sail performance, assuming optimum sail trim and sheeting angles, and, hence, cannot be used to determine the actual performance on the water at any one time, at non-optimum sail settings. This data assume that the boat is at all times sailing to its full potential.

4.3. Aerodynamic Parasitic Drag forces

In most speed prediction methods, whether these be based on model tests or on numerical procedures, the calculation of the aerodynamic resistance of the hull, superstructure, mast, rigging and crew is usually not carried out in a very refined way. At best, a constant drag coefficient is adopted and the representative frontal area is calculated. The reason for this is that the forces involved are normally relatively small compared to the forces exerted by the wind on the sails. When sailing high on-the-wind, however, close to the maximum attainable V_{MG} , this drag force is an appreciable effect on performance.

5. Hydrodynamic an Aerodynamic force Inter-dependence

It is important to note that the resultant hydrodynamic and aerodynamic forces acting on a sailing yacht are inter-dependent. When the force of the wind on the sails is increased and a straight course is maintained, (normally requiring a helm angle adjustment), the yacht will adopt a greater leeway angle thereby producing the necessary increase in the hydrodynamic lift force to maintain equilibrium. In actual fact this process is much more complex because the heel angle will increase at the same time when the sail force increases, causing initial loss in side force form the keel, in itself requiring a helm angle correction and a greater leeway angle to maintain equilibrium.

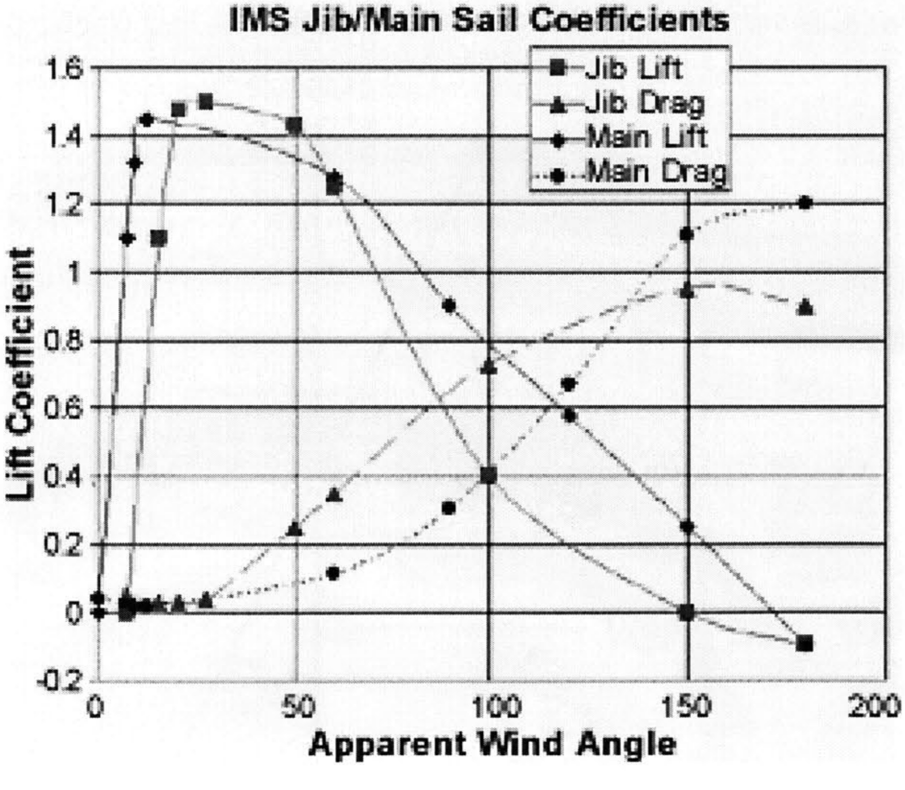


Figure 2.7 Variation of Aerodynamic lift and drag coefficients with respect to apparent wind angle [53]

For equilibrium it is necessary that the following equation is satisfied:

$$\beta = \varepsilon_H + \varepsilon_A$$

where β is the angle between the course sailed and the apparent wind direction, ε_H is the aerodynamic drag angle in horizontal plane and ε_A the aerodynamic drag angle in horizontal plane.

The hydrodynamic and aerodynamic drag angles are defined as follows:

$$\varepsilon_H = \arctan(\frac{R}{F_S}) \quad \text{and} \quad \varepsilon_A = \arctan(\frac{D}{L})$$

where R is the total hydrodynamic resistance, F_S is the total hydrodynamic side force, D is the component of total aerodynamic resistance in horizontal plane and L is the component of total aerodynamic side force in horizontal plane.

This equation is attributed to F.W Lanchester [2].

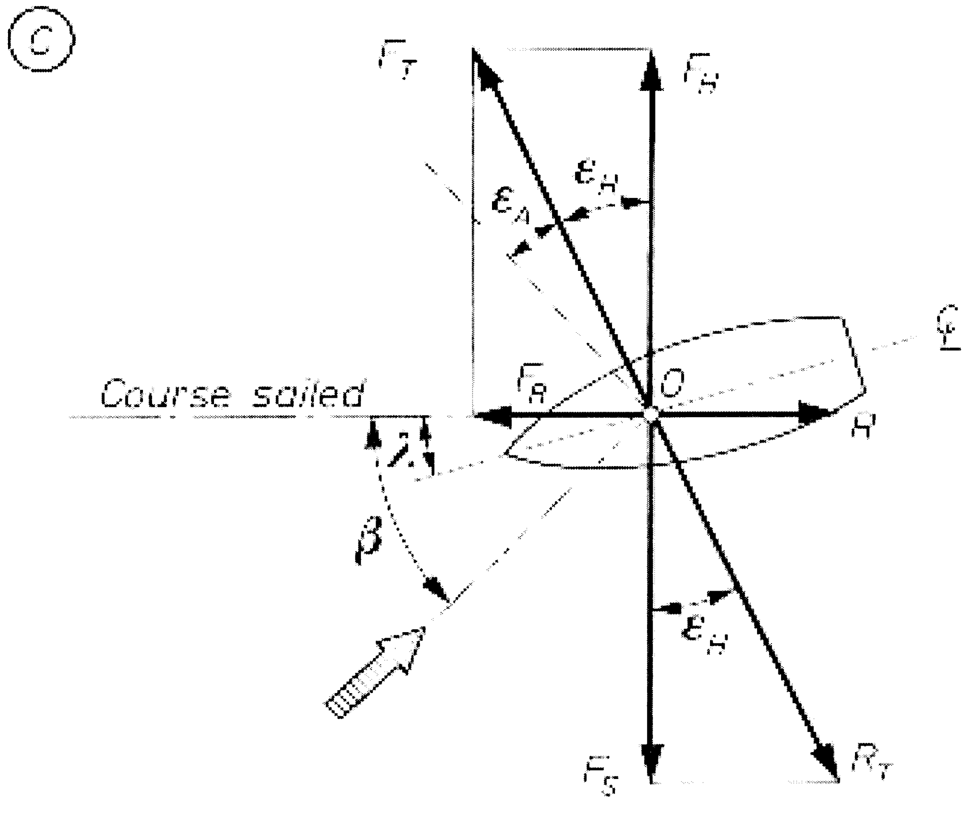
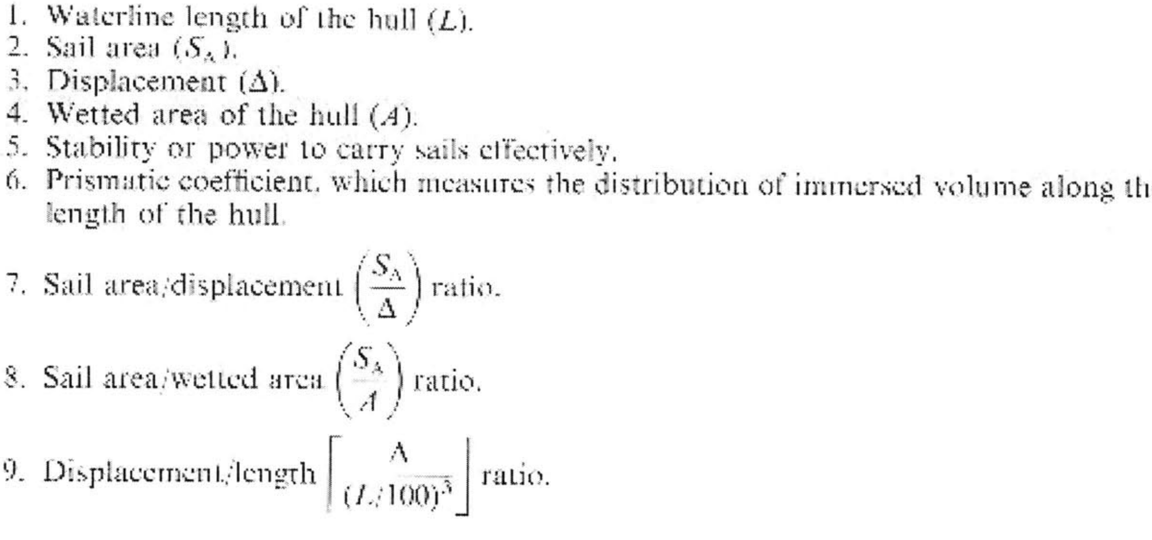


Figure 2.8 Equilibrium of aerodynamic and hydrodynamic forces [2]

6. Design for high-speed sailing

What limits the speed of a boat is first of all its sail area. One would easily understand that the more sail area one boat has, the bigger the driving force is, but also the larger is the heel angle. This is the main trade-off that drives the design of monohull crafts, whose stability is inherently restricted to a low angle of heel and hence relatively limited power to support large sails effectively.

The multihull concept allowed boats to reach much higher speed. These craft comprised of slender, light and easily driven hulls abreast of each other, provide large lateral stability, not requiring heavy ballast as for a monohull.



1. Waterline length of the hull (L).
2. Sail area (S_A).
3. Displacement (Δ).
4. Wetted area of the hull (A).
5. Stability or power to carry sails effectively.
6. Prismatic coefficient, which measures the distribution of immersed volume along the length of the hull.
7. Sail area/displacement $\left(\frac{S_A}{\Delta}\right)$ ratio.
8. Sail area/wetted area $\left(\frac{S_A}{A}\right)$ ratio.
9. Displacement/length $\left[\frac{\Delta}{(L/100)^3}\right]$ ratio.

Figure 2.9 Basic speed affecting factors [2]

The other factor that limits the speed is the rapidly growing wave making resistance as the speed of the yacht increases. To tackle what is considered today to be the reason why a boat cannot sail faster than 50 knots, the displacement of the hull has to be reduced to its minimum, which means that any feature on the boat as to be redesigned in order to reach the lightest weight possible. Slender and long hulls are found to minimize this resistance, and this dictated the shape of the hulls of trimarans and catamarans. By reducing their displacement while increasing their sail area, those yachts offer a much more interesting trade-off than monohulls except when sailed in heavy weather. One advantage of monohulls is their renowned sea worthiness in heavy weather, whereas, as will be discussed later, multihulls's behavior is much more difficult to handle in storms.

Reducing the weight of the rigging therefore became of primary importance if one wanted to reach higher speed. [12][13][14][15][16].

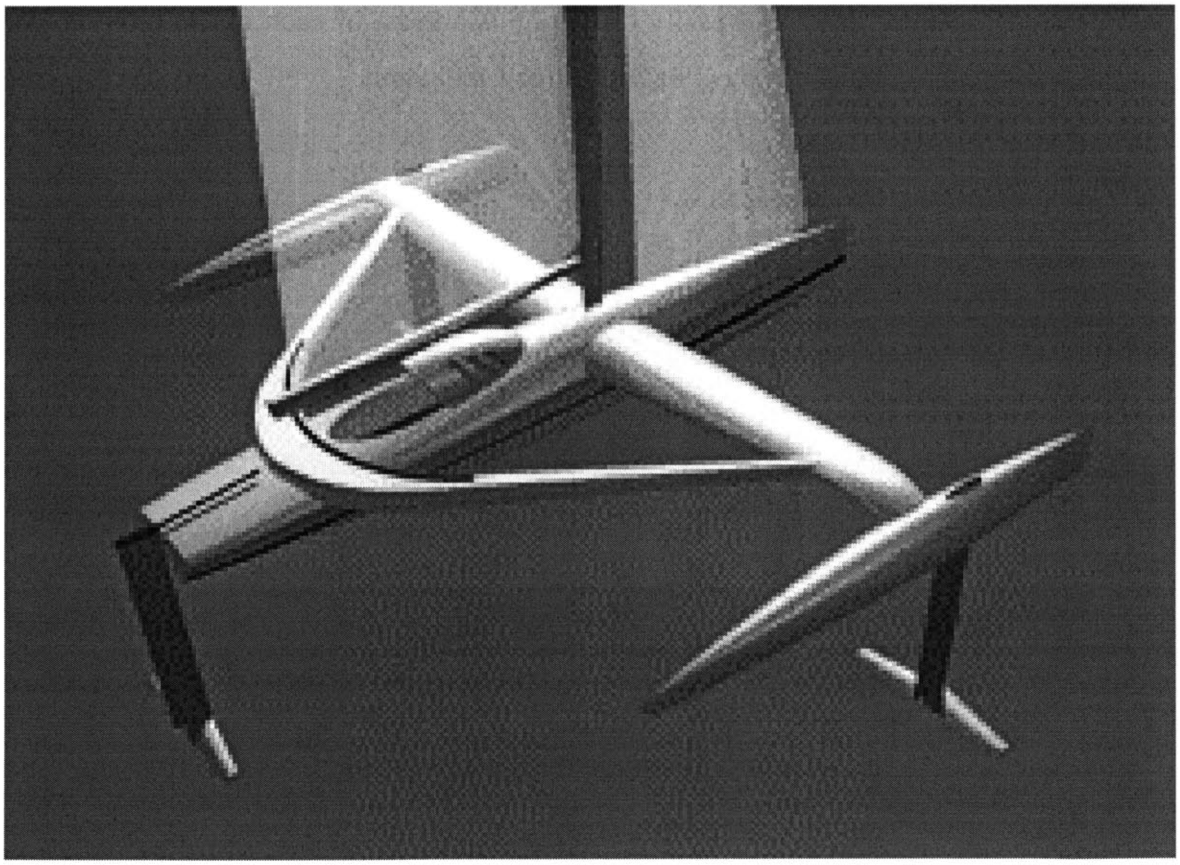


Figure 2.10 Trifoiler "SCAT" a 37 foot flying foiler [54]

Chapter 3

Evolution of Sailing Yacht Masts

1. Introduction:

The rig is the powerhouse of a sailing boat. Through the development of new rig materials and technology efficiency and reliability of the rig can be increased. This enables yachts to become faster. In the second half of the 19th century yacht racing was borne as a sport. Initially, as events such as the America's cup were started, this type of racing led to the development of measurement and handicap rules

Significant improvements in performance could be found by the development of better rigs. Since the beginning of this century there have been a number of developments in materials and manufacturing, from the use of wooden spars at the turn of the century to the Carbon rigs found aboard the new breed of yachts.

Figure 3.1 America's Cup race

With racing yachts new developments are usually first developed and tested for yachts competing in the top of the sport. The most expensive and radical developments are found in America's cup yachts. This has been the source of most new technological developments sine the cup first started in 1851.[17][18][19][20].

2. Mast Materials and Manufacturing.

2.1. Mast developments

The sailing yacht mast has been through three major evolutions over the last century; the main developments happened in the following order: wooden, aluminum, and composite mast materials. Although at present all these materials are still used in yachts and dinghies, only carbon fiber is used in high performance racing machines.

Wooden masts

Wood was the most common material used in masts in the beginning of the 20th century. Nevertheless, it does have three major drawbacks:

- It is not a light material, especially in comparison to modern composite masts.
- Greatest strength is achieved by using a single length of wood.
- Prone to rot if it is not treated correctly.

Wooden masts have been in use for many thousands of years and proved themselves to be a reliable means of carrying sail. But as boats began to be built solely for speed and racing other more competitive solutions had to be found. The cost of labor and cost of materials compared to the final wooden mast was no longer economic.

Aluminum masts

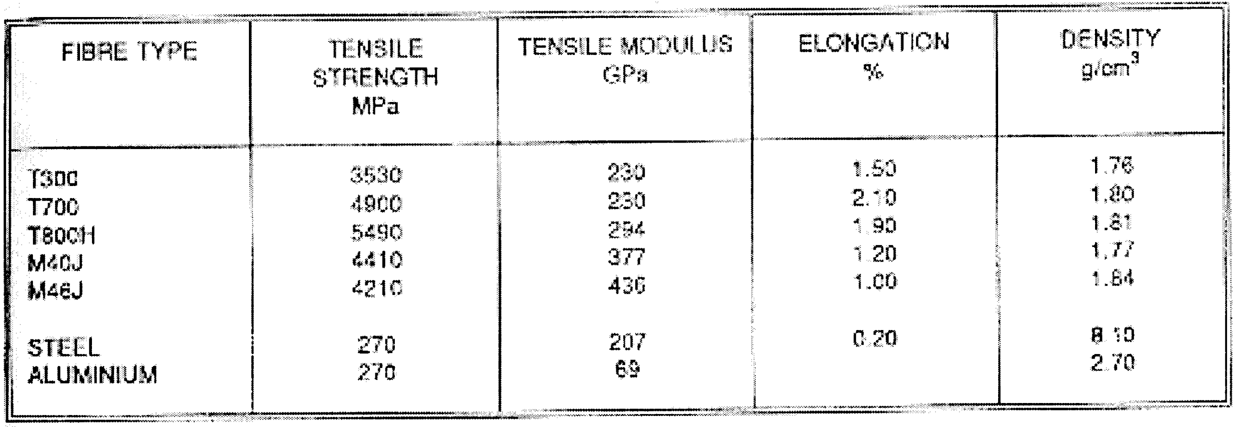
Aluminum masts in dinghies were 1st seen after the Second World War. They were tried in the development class dinghies such as the international moth and the international 14. There was a relatively cheap supply of aluminum standard foil sections from the aerospace industry, which were tried out in these development classes.

At present aluminum masts are the most common for most cruisers and a large number of racing classes.

The latest development in aluminum masts is the use of “Alustartm”. This is an aluminum alloy developed for the marine industry. With a 20% increase in the strength of the alloy over other marine grades the plate thickness used can be reduced, therefore reducing the weight of the mast. It keeps its corrosion resistance, bendability and weldability of other aluminum alloys in its group. This alloy is available in plate form with which aluminum plate masts are constructed. These masts are said to be stronger and lighter than extruded aluminum masts, although as yet no comparisons of strength have been found.

Carbon fiber masts

Carbon masts began to be used in the early 90's, initially in the America's Cup and Admirals Cup yachts. In the decade since their first use carbon fiber is still not as widely used as one might think.



FIBRE TYPE	TENSILE STRENGTH MPa	TENSILE MODULUS GPa	ELONGATION %	DENSITY g/cm^3
T300	3530	230	1.50	1.76
T700	4900	230	2.10	1.80
T800H	5490	294	1.90	1.81
M40J	4410	377	1.20	1.77
M46J	4210	436	1.00	1.84
STEEL	270	207	0.20	8.10
ALUMINIUM	270	69		2.70

Figure 3.2 Fiber properties (unidirectional fiber in epoxy nature [17]

Through the use of carbon fiber a mast can be manufactured lighter and stiffer than an aluminum mast. This can significantly improve the performance of the rig but it has a price. A typical carbon mast will be approximately 7 times the cost of an aluminum mast, due to the additional cost of the materials and the increased labor involved.

Through the use of modern computer technology, such as CFD (computational fluid dynamics) and FEA (finite element analysis) the load distribution of the sail on the mast can be calculated. Therefore a carbon mast can be built with increased strength in the direction of the principle loads. For optimum sail shape the bend of the mast is very important, it flattens the sail, since a carbon mast can be manufactured with precisely controlled orientation of fibers it is possible to create a mast which has the correct bending characteristics. This is an important advance in technology; complement this with new sail technology and they form a superior aerodynamic shape that could ever be achieved with an aluminum mast and polyester sails. The use of CFD can also determine the flow around the mast and on the more powerful programs the interaction of the sails and the standing rigging can also be taken into account.

Carbon fiber is an extremely well suited material for the manufacture of masts. It offers high strength with low weight, complex shapes can be produced and they have also proven to be reliable. However, there have been problems with carbon masts recently. The development of carbon masts for IACC yachts have shown that when a carbon mast fails (usually due to under engineering the mast or failure of another rig component leading to the failure of the mast) splinters of carbon fiber are produced and can cause harm to the crew or the boat.

Future mast technology

Since the introduction of Carbon masts there has been little further work done on alternative materials. There is however continuous development in the design of the masts to get the most out of the material.

Figure 3.3 Trimaran "Rexona" pulling a water-skier [52]

Chapter 4

Design of a carbon fiber reinforced mast

1. Mast structural behavior

The rig of a sailing yacht is, in a certain sense, a simple structure composed of wires and beams; however, when the boat is sailing, it is very impressive to observe very large deformations owing to the mast's slenderness and attitude. The mast is subjected to stresses typical of beam-columns, being loaded by axial and transverse forces acting concurrently in the longitudinal and transverse planes. This bending is balanced by stays in the fore-and-aft direction and by shrouds athwart ship. Stays and shrouds also help the mast to withstand higher compression loads by shortening the unsupported length.

For the calculation of mast and rigging, the literature presents a number of empirical design criteria. For little and medium sailboats, the compressive load on the mast is often assumed equal to the boat's displacement. A widely utilized method consists of computing the mast compression and the tensile loads on rigging as a function of the righting moment. Another approach considers the mast and rigging as a truss, applying to the mainsail a uniform pressure of about 5 kg/m2.

However, when dealing with heavily loaded rigs, like racing yachts, empirical criteria must be regarded with caution because they do not distinguish between pleasure and extreme yachts, or between large and small sailboats. In fact, the rigs of racing yachts and pleasure sailboats have different characteristics. In the first category, the main design objective is the optimization of yacht performance, increasing the sail efficiency, and minimizing the weight. A well-designed mast must have a thin transverse section to avoid, as much as possible, parasitic wind resistance and interference with the sail, and good flexibility to allow the crew to rapidly give the desired shape to the main sail. In the second case, the main constraint is the security of crew and passengers. The mast becomes a very stiff beam with very low deformations.

Masts can be distinguished as flexible or stiff structures, the former having large displacements and the latter negligible ones. As a general rule, a rigorous stress analysis of masts has to be performed by finite elements programs operating in the non-linear domain able to analyze large displacements structures. However, for very stiff masts, it is possible to achieve satisfactory results with the utilization of linear programs and assuming simplifying hypotheses. This finite element technique very closely simulates the behavior of a stiff structure. As a consequence, the accuracy of the results heavily depends on the knowledge of the loads distribution. Thus, it appears very important to perform an accurate study of the load model to be employed in the numerical analysis studying first the mechanism by which the mast is loaded and then a mathematical model to determine the force developed by sails.[21][22][23]

2. Application of composite technology to masts

Carbon fiber, invented in the 1950s, is available as a filament in many different grades. There are now more than 30 different grades of fiber available commercially.

The principal material and mechanical properties of various commercial carbon fibers suitable for spar building are listed below. These properties are the manufacturers' 'as quoted' fiber properties. It can be seen that there is a large range in terms of tensile/compressive strengths and tensile/compressive modulus. This shows fibers manufactured by Tri-Cast but most of the principal manufacturers produce similar materials. Higher strength and/or higher modulus materials generally cost more. Surprisingly selection of a higher price material does not necessary lead to proportional product price increase. Increased material strength and/or stiffness often permit sufficient material quantity and labor saving to offset the higher unit raw material cost.

MATERIAL	TYPE	TENSILE STRENGTH (MPa)	TENSILE MODULUS (GPa)
High Strength	T300	3530	230
	T300 J	4210	230
	T400 H	4410	250
	T700 S	4900	230
Intermediate Modulus	T800 H	5490	294
	M30 S	5490	294
High Modulus	M35 J	4700	343
	M40 J	4410	377
Ultra High Modulus	M46 J	4210	436
	M50 J	3920	475
	M55 J	4020	540
	M60 J	3920	588
	M46	2550	451

Figure 4.1 Manufacturers' 'as quoted' fiber properties [26]

The dry fiber comes from the fiber manufacturer with a coating known as the 'sizing' which is applied to the fiber in order to make it compatible with the laminating resin system to be employed.

A resin system is used to finally bond all the fibers together to create the final laminate; once again a wide variety of resin types are available with different types being suitable for different operations.

Manufacturers will often give laminate properties for their fibers and these are generally derived from laboratory specimens built in optimum conditions and a unidirectional laminate matrix (all the fibers being aligned in one direction). Accepted nomenclature for fiber alignment is to express it as a degrees orientation to the principal structural axis, e.g. 0°, +45°, -45°, 90°.

Every application will require its own laminate structure which should be designed to accommodate the applicable loads. For a tubular mast structure, a suitable laminate will comprise a proportion of material on the 0° axis to take the compression load, the 90° axis to give hoop strength to the structure and off-axis material, normally at +/- 45°, to give torsional strength. The proportion of fibers on the various axis will vary throughout the mast structure to accommodate local load.

For a typical stayed mast, the general tube structure typically comprise 68% material on the 0°, 22% in the 45° and 10% in the 90°.[24][25][26]

3. The recent failure of carbon masts

The break of the carbon masts of the 18 meter multihulls that occurred just before the Road of the Rhum (2002) set a new problem the designers had to solve. What puzzled skippers, architects and calculators is that most of them fell a short time after their first exit in conditions of wind and sea calmness.

Since 1994, carbon masts were based on the same design principle. But geometries (shape, width, length), aerodynamics (profile) and materials (fibers of carbon mainly) evolved. Settings remained the same while platforms evolved being stiffer, faster and more powerful

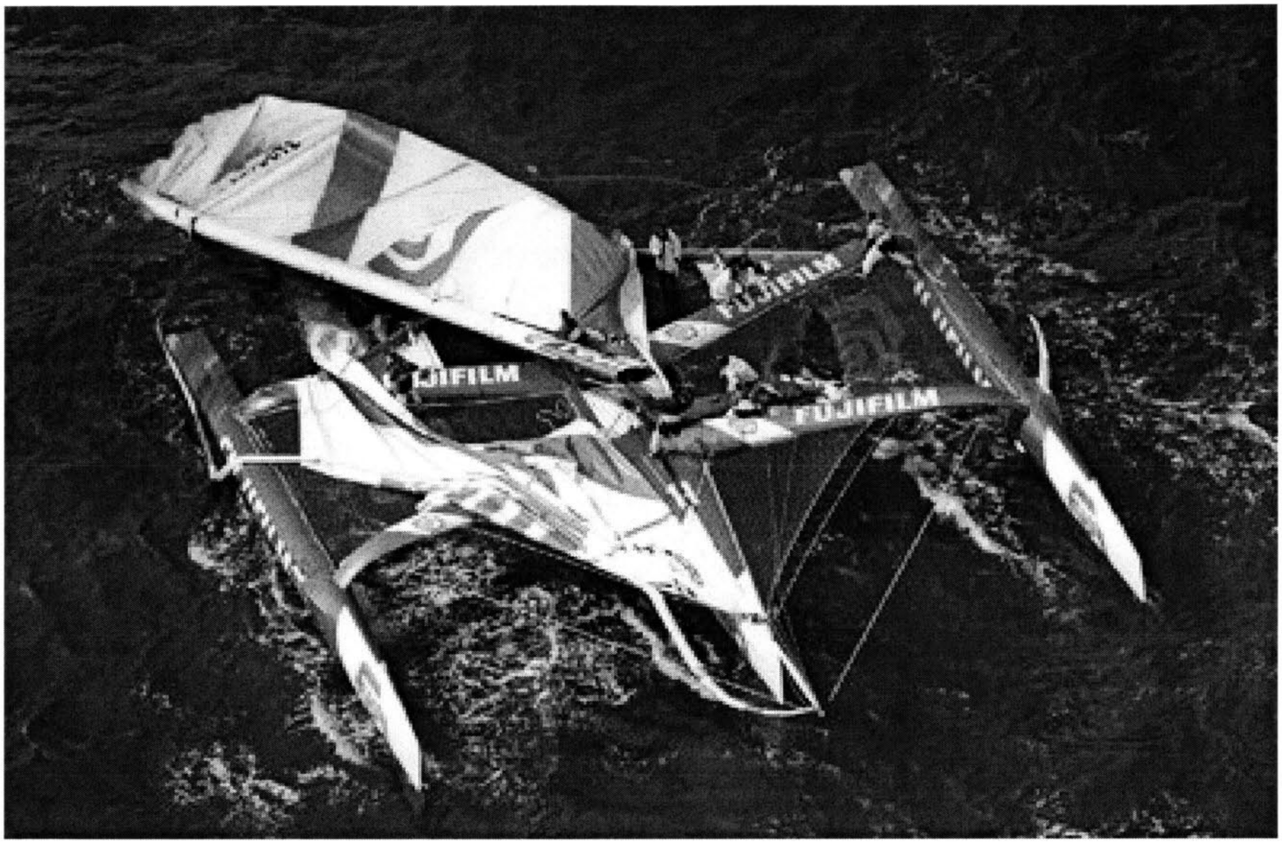


Figure 4.2 Trimaran "Fujicolor" after the break of its mast [28]

The common reason of the failure of these eight 30 meters masts is the use of a carbon very effective, the M55J or pitch, with a very high modulus but very little ductility.

The mast is the transmission between the sail (motor) and the platform (frame). This transmission must be responsive so that the boat is effective. There must not be any waste of energy. Therefore, to be very effective, one necessarily has to use very effective materials. The choice was made to use carbon fibers with very high modulus to the detriment of their ductility (to the shocks, to the propagation of damage and to fatigue).

The problem is that we do not have any insight on their behavior over time.[27][28]

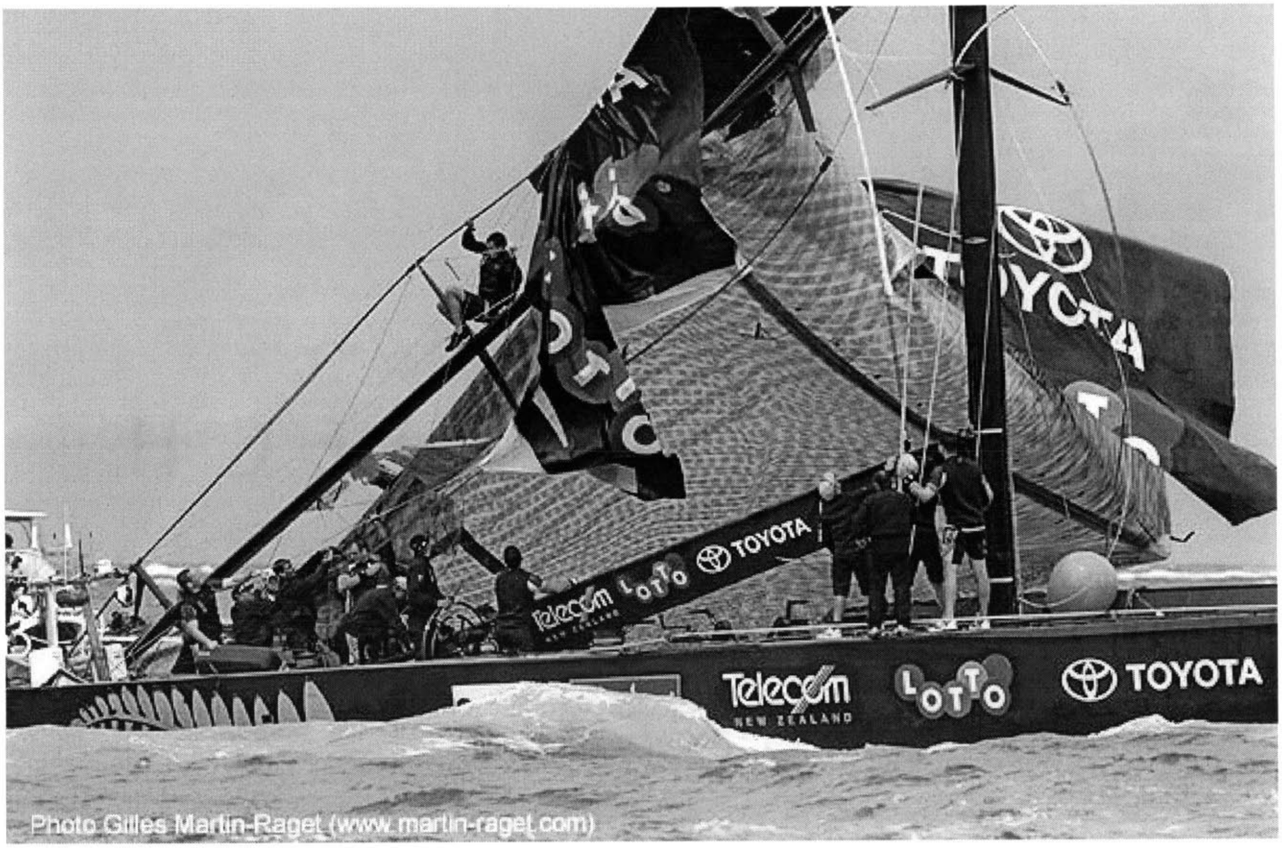


Figure 4.3 America's Cup finalist mast failure in 2003

4. Strain measurement by an optical fiber system

Knowing the loads acting at any place in the mast in real-time would provide the designer with a much better understanding of the loads and also the behavior of the mast, allowing them to refine their design and finally build a lighter rid, their ultimate objective. It seems today that an optical fiber system might be able to achieve this goal and provide very useful information about forces acting on a mast.

Optical fiber, since its development for telecommunications during the 1970s and 1980s, has been a flexible vehicle for new sensing techniques. Measurements of physical parameters such as strain, temperature, translation, gyration, humidity, magnetic and electric field strength are all possible using optical fibers and associated system components. The special qualities and advantages over conventional electrical methods which optical fiber bring to measurement problems have long been recognized. These qualities include complete immunity to electrical interference, vanishingly small mass and size of the fiber (optical fiber is typically 1/8th mm in diameter and weighs as little as 30 micrograms per meter), very high data ranges (GHz and beyond) for measurement information and the ability to cascade many sensor regions along a single fiber allowing distributed measurement.

Over the twenty or so years that optical fiber sensors have been under development a plethora of techniques has emerged for every type of measurement. In particular, for monitoring structural load, an existing new capability has emerged over the last five years, based on a fiber strain sensor called a Bragg grating.[29][30][31][32][17]

4.1. The optical fiber 'Bragg grating'

The optical fiber Bragg grating is a structure typically two or three mm in length, which is formed within an optical fiber. The structure is imprinted by a photo exposure method using coherent laser light at Ultra-Violet wavelength. Standard optical fiber produced by the kilometer for the telecommunications industry, can be sensitized to the effects of the ultra-violet laser light by undergoing 'soaking' at high pressure in a hydrogen atmosphere. The sensitized fiber records this pattern as a periodic ripple or grating of refractive index, invisible to the eye, in the exposed region in the fiber. This region is called a fiber Bragg grating.

The Bragg grating will transmit the light that is now launched down the fiber, but in a highly selective manner. The grating will reject light of a precisely defined wavelength, reflecting it back along the fiber, but will allow all other wavelengths to pass. The reflection wavelength is defined by the periodicity of the refractive index ripple or grating, i.e. the physical spacing between the peaks and troughs of the grating pattern. In a typical device, this period is in the order of 0.5 microns in length. The interdependence of reflection wavelength and grating spacing places an equivalent interdependence on strain.

As the fiber containing the grating is stretched or compressed in response to a load, the grating spacing widens or narrows and the reflection wavelength shifts proportionally. Hence, by precise measurement of the reflection wavelength of an optical fiber Bragg grating, the strain in the grating can be measured. If the grating region of the fiber is bonded to a structure, the device can be used as an optical strain gauge.

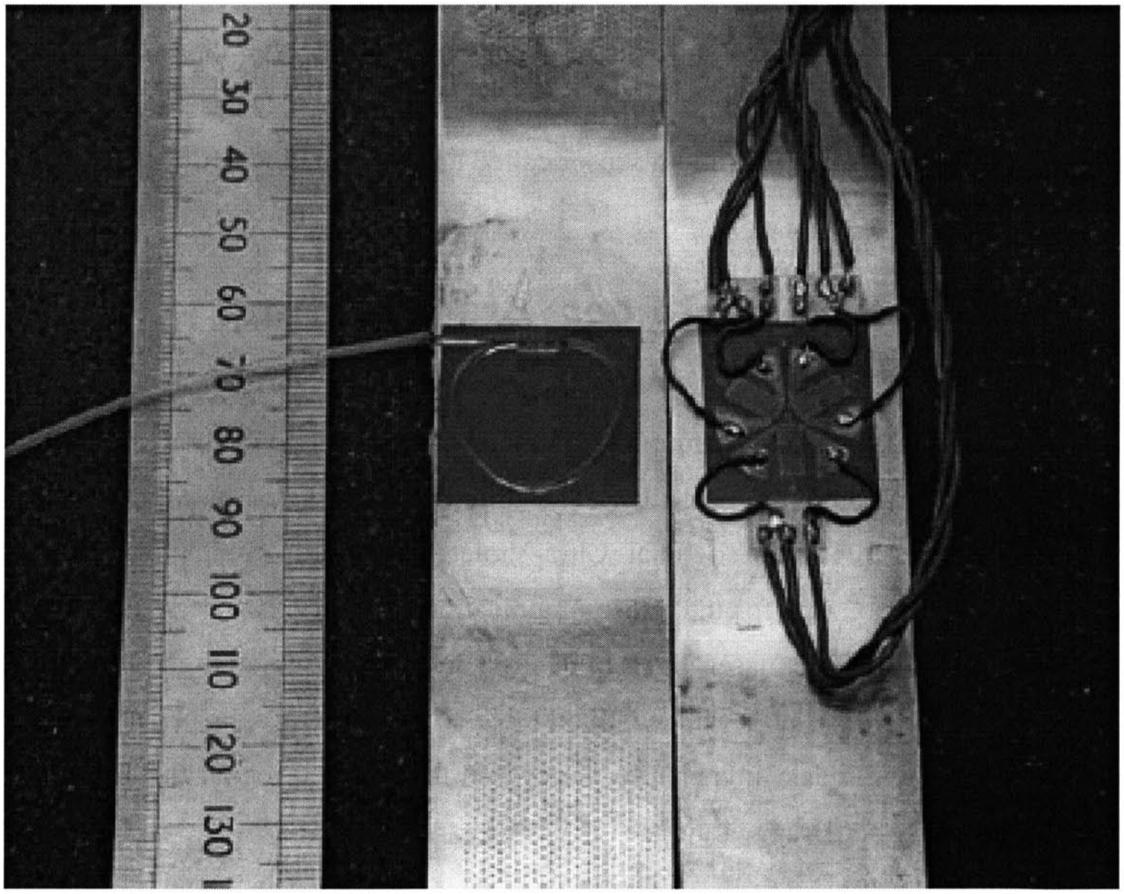


Figure 4.4 Optical and electrical strain gauge rosettes [31]

Unlike electrical strain gauges and their electrical connections, more than one Bragg grating can be placed along a single fiber. The only constraint on the number of gratings which can hold in a given length of fiber is the length occupied by the grating themselves. This can be from 1 mm to several tens of cm.

For a strain measurement based on optical fiber Bragg grating the picture is of a length of fiber containing Bragg gratings at predefined-intervals. The fiber is spread around the structure with the grating regions bonded or embedded to pick up load-induced strain. The fiber and sensors are integral, forming their own link to a remote opto-electronic instrument module that converts the optical wavelength measurements into multichannel strain data.

4.2. The “SMART mast” system

The “SMART mast” strain monitoring system is a collaboration between Carbospars' sister company Smart Fibres Ltd in a $1.8 million joint research program with Pendennis Shipyard, one of the world's leading superyacht builders, Aston University and British Aerospace Military Aircraft Division.

Primarily aimed at the performance and luxury market sector “SMART Mast” utilizes the leading edge of fiber optic technology by incorporating a network of Bragg fiber grating sensors embedded into the composite structure. The aim of introducing such sensors into these structures is to provide a means of structural monitoring using a non intrusive, robust and structurally integrated measurement technique. This “SMART mast” system can provide structural strain data which can be used not only as a design development tool but also as an in-situ structural health monitoring system. Operational loads can be recorded and indicated in real time to skippers and crew giving an on-line picture of the mast status during a voyage. Ultimately, a health and usage record of the mast can be built-up over the lifetime of the structure.

Structural health and usage monitoring is also of interest to aerospace manufacturers and aircraft operators. Such capabilities could drastically reduce the cost of ownership of craft by reducing inspection overheads.

The system comprises three main elements: the fiber sensor arrays, the remote optoelectronic instrument module and the data display or man-machine interface. These elements, which have been developed under this collaborative smart mast project, will now be considered in turn.

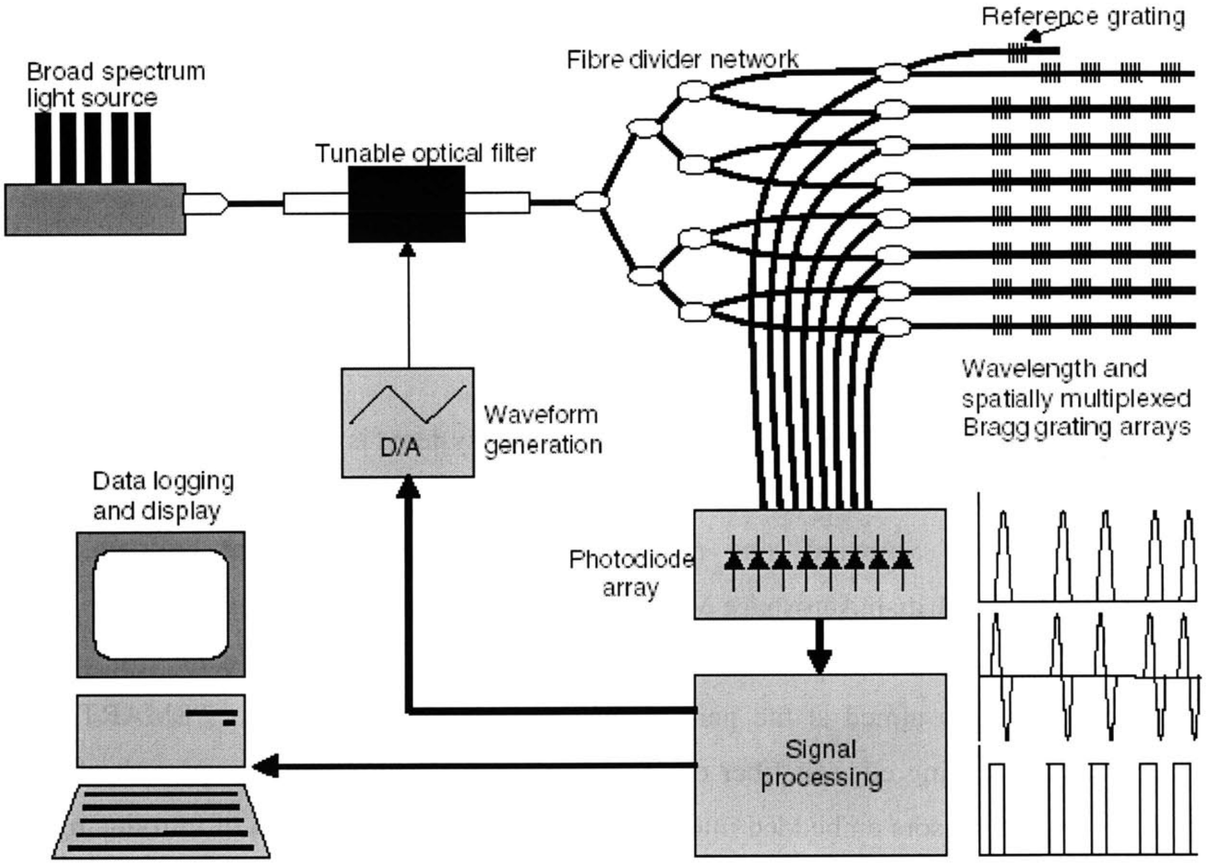


Figure 4.5 "SMART Mast" optical fiber Bragg grating system [17]

Sensor arrays

In designing arrays for the "SMART mast" program, a number of generic constraints exist for sensor configuration and number, regardless of the size or nature of the mast. Firstly, the number of Bragg grating strain sensors in each single length of fiber is dictated by the available wavelength bandwidth of the light source used in the instrument module. A useful analogy is the FM radio spectrum. A limited bandwidth is available across the whole spectrum and all channels have to occupy non-overlapping channels within this bandwidth. The same concept applies to the Bragg grating sensors. Each sensor will occupy a channel within the available optical spectrum. The spectral channel width allocated to each sensor will define the maximum range of strain that each sensor can measure before overlapping a neighboring channel. A trade-off exists, therefore between the number, N, of sensors per fiber, the strain range for each sensor, $\varepsilon_{\max}$ and the available bandwidth $\Delta\lambda_{\max}$ expressed by:

$$N = \Delta\lambda_{\max} / \Delta\lambda_{sensor} = \Delta\lambda_{\max} / \lambda_0 \gamma \varepsilon_{\max}$$

where $\Delta\lambda_{sensor}$ is the spectral width of a sensor channel, λ_0 is the normal peak reflection wavelength of a given sensor grating and γ is an optical gauge factor determined empirically.

For the smart mast systems developed in this project a maximum of five sensors could be allocated for each single fiber. Their nominal (unstrained) wavelengths were separated by 5 nm giving a strain range for each sensor of ± 3500 microstrain. To increase the total sensor count, a system of eight parallel fibers was adopted each containing a maximum capacity of five sensors and all linked to a single remote instrument module. This system had a total capacity of 40 sensors.

The layout of each sensor i.e. the position of each sensor along a particular length of fiber can be tailored to the structure to be monitored. Smart masts up to 60 meters in length have been fitted with these sensors array. Each installation has required different fiber lengths and sensor positions. The sensors themselves are installed at predefined locations and are identified by their unique reflection wavelengths.

The remote optoelectronic instrument module

The second component within the strain monitoring system is the data acquisition unit. In summary, the data acquisition units contains the optical source and detection modules necessary to continually monitor any network of optical sensors. It also contains an embedded PC that does any initial data processing and sends data, via an RS232 port to the display PC.

Man-Machine interface

Strain information is downloaded on request from the sensor instrument PC to the display PC where it can be displayed in one of two possible formats. The strain information is presented as value in the range -100% to +100% of the strain range for each sensor location. Also included is a facility for polling the maximum strain that appears in a quick display. This also drives a remote 'traffic light' indicating onset of critical loads. The current design displays color-coded strain information in display 'bubbles' at each sensor location. The live display is updated at a rate no greater than 5 Hz.

Data recording also takes place within this display PC to the following format:

- All sensor data at 5 Hz for 5 minutes
- Peak strain value in 5 seconds for each sensor location, for up to 1 hour.
- The average strain for each sensor at 5-second intervals for up to 1 hour.
- The peak value and sensor location presented by the quick display value in five-minute intervals for the lifetime of the structure.

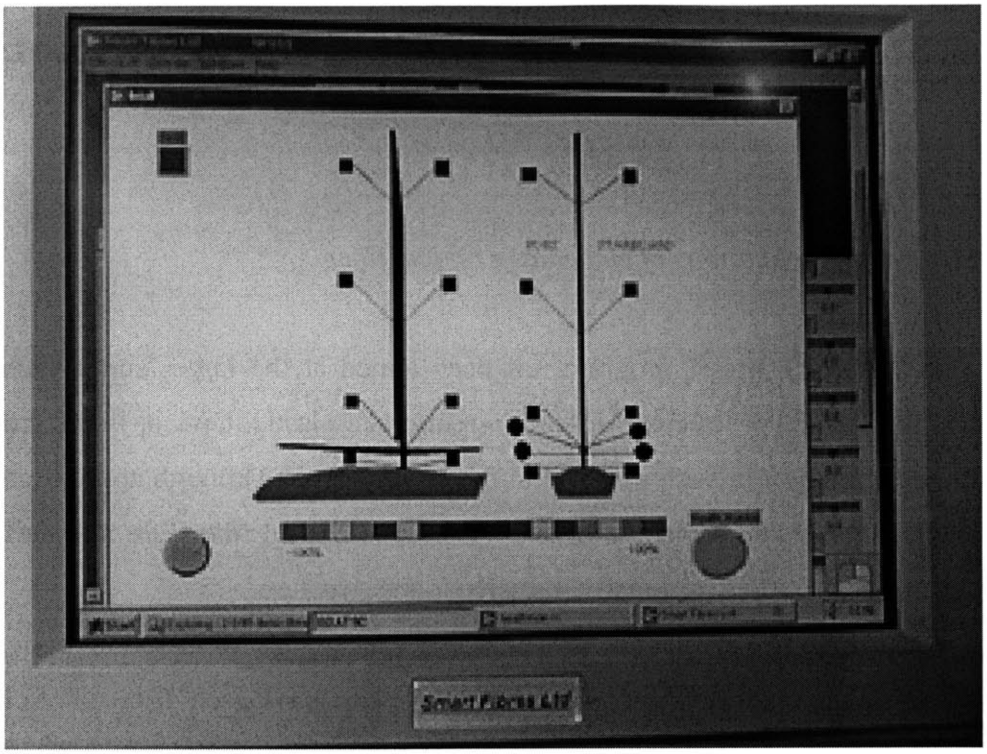


Figure 4.6 On board data display using touch screen PC [32]

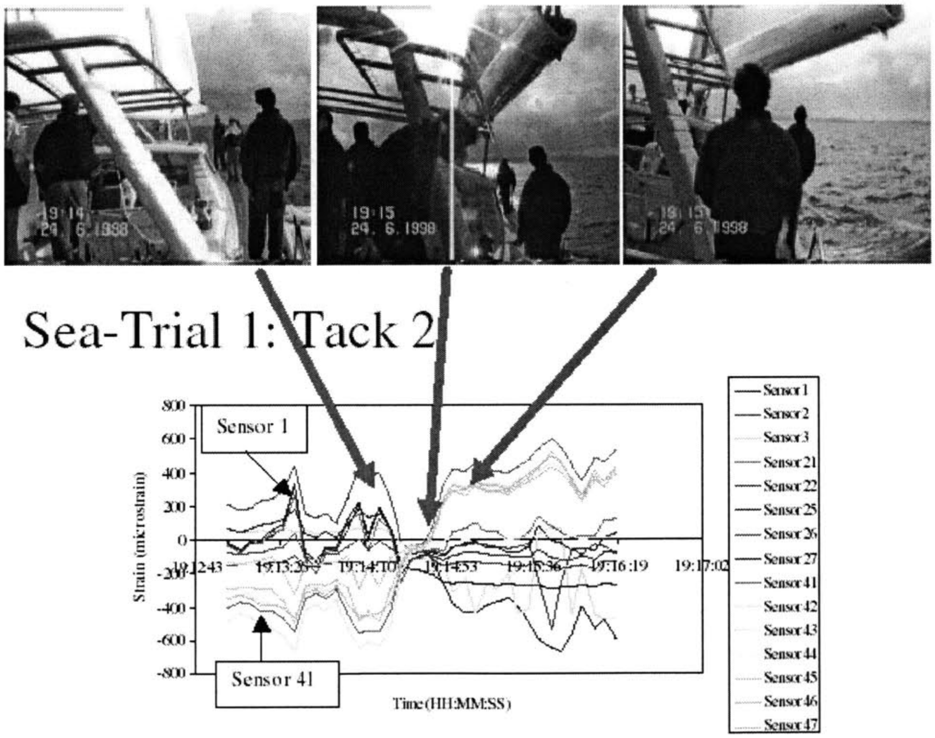


Figure 4.7 Comparison between video footage of load transition event and the optical strain sensor data [23]

4.3. Installation of optical fiber sensors in masts

Structural implications of embedding optical fiber

This "SMART mast" program has been aimed at the large 'super yacht' mast installation with primary structure of carbon-reinforced plastic. Optical fibers are ideally suited for incorporation in such material in the lay-up stage. Although approximately ten times the diameter of the structural carbon fibers, the optical fibers are still sufficiently small in cross section to be minimally intrusive in the structure.

To evaluate and quantify the effect on material strength of including optical fiber, a series of test coupons have been undertaken. The tests have used T300/SP Ampreg 20 material and resin systems and were aimed at uncovering any strength knockdown factors caused by the presence of optical fiber in the material matrix.

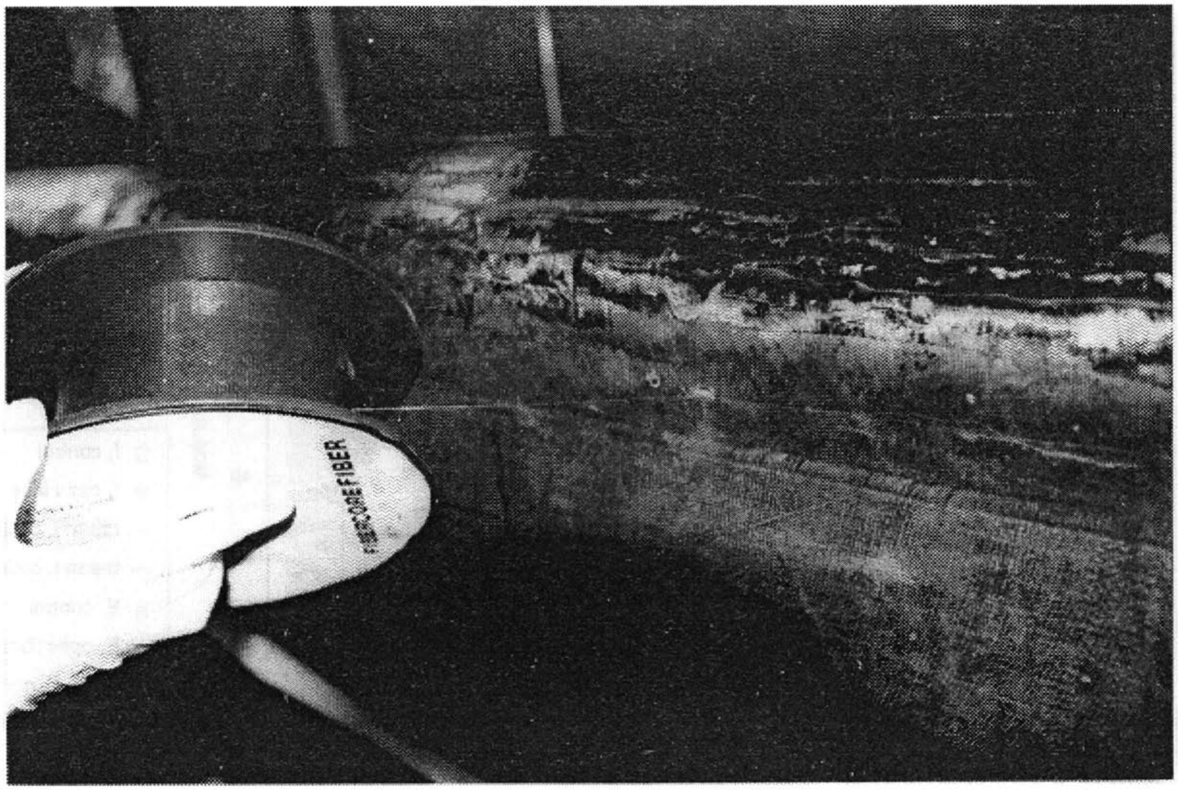


Figure 4.8 Laying optical fiber Bragg grating sensors in a mast [17]

The conclusions from these tests are two-fold: firstly, the inclusion of optical fiber within typical carbon mast does not significantly affect structural integrity and, secondly, the optical fiber strain sensors are sufficiently resilient to withstand composite fabrication, cure and prolonged fatigue conditions while still functioning satisfactorily.

Advantages of optical fiber sensors over electrical technology

Conventional strain gauging has been used for decades for structural testing purposes and well-qualified components and procedure have been evolved. However, on-line operational load monitoring of a super yacht mast poses some problem for these techniques. Electrical gauges generally require three independent connections for each gauge, 40 sensors would therefore require 120 cables with routing and shielding for each. For the distance involved in a super yacht mast (anything up to 60 meters) this would almost certainly entail use of local line driver amplifiers near sensors locations which require electrical power supplies. This would be a complex wiring task and could add significant weight to the mast. Strain gauges are also vulnerable to environment degradation.

The optical system described here achieves wireless sensors coverage using just 8 optical fibers with no local amplifiers or power requirements.

Whether mounted on the inner or the outer surface of a mast, the salt spray environment would pose a significant threat to the long term stability of an electrical strain gauge as well as the quality of bond to the structure. Embedment of the gauges within the carbon composite is not an option due to their size and the need for electrical connections (they would represent a significant inclusion in the material and act as a site for delamination). The small but significant electric conductivity of the carbon fibers, which would also partially shunt the gauge unless extra insulation, was added.

As an indication of the durability of electrical strain gauges, the fatigue tests described in the previous section also included surface bonded electrical gauges for comparative measurements. The electrical strain gauges typically failed after 50,000 cycles and none survived beyond 500,000 reversals.

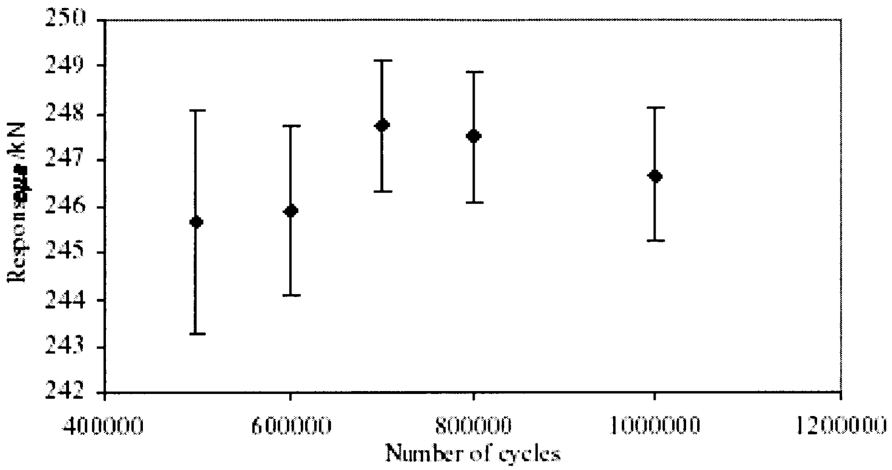


Figure 4.9 Typical strain response of an embedded fiber Bragg grating sensor after fatigue loading [31]

Drawbacks of this new technology

The optical system does have some disadvantage when compared with the existing strain systems. The optoelectronic components in the remote instrumentation module are currently expensive and complex devices. The signal processing necessary to convert optical data to strain data is more complex than a simple strain bridge and requires some computing power. The sensors themselves are not readily available from qualified suppliers and are significantly more expensive than equivalent strain gauges. Also, the method of interconnection between the structure and the instrument module requires single mode optical connectors. These are well developed for relatively static telecommunications environments both terrestrial and submarine, but are a potential weakness in an application involving dynamic strains.

Most of these problems are, however, problems of market scale. Component costs are poised to plummet as the domestic optical fiber network industry gathers pace. Commercial suppliers of generic Bragg grating sensor systems are now beginning to appear. Additionally, the telecommunications and aerospace industries are forcing the pace of single-mode optical connector development.

Practical optical fiber sensor installation in carbon masts, results to date

Over the last years the "SMART mast" program has installed fiber Bragg grating sensors fabricated by Aston University in the following masts:

- A 20 meter Aerorig subsequently installed in a Beneteau 42-s7.
- An 8 meter mast of a Topper International Boss 4.9 meter dinghy.
- The 'Velsheda" 60 meter, stayed mast on J-class yacht
- A 35 meter AeroRig
- A spar for a cruising 32 meter super yacht

4.4. A revolution in the design of masts

As was discussed earlier, such a technology, provided working properly, would be of an inestimable value for the designers of masts. It is possible to estimate the rigging loads when the boat is moving dynamically in waves, and the load distribution of the sail on the mast really requires running a finite element program with the aerodynamic loading (can be estimated) and the sail shape (also can be estimated) as inputs. Nevertheless it has never been done before and nobody can claim to know the impacts of the waves on the structure of the mast. Therefore, when designing a mast, the dynamic loads of the waves are not taken into consideration and the design is not optimum.

Chapter 5

State of the art technology applied to masts

Many different concepts have been imagined by designers in order to increase the speed and the efficiency of the boats. This chapter introduces the more promising technologies that have been conceived up to know and which might lead to important progress in the next twenty years.

1. Rigid winged sails

Figure 5.1 Catamaran with rigid winged sails

The predominant reason why wings developed was to optimize the power of the sail area, when it is limited. With slots and flaps, winged sails can develop much higher lift coefficients than sails. The theoretical maximum lift coefficients for lift are 40-50% higher than that of a conventional sail. Also, wing shape can be more accurately established and controlled than with sails, even if they are fully battened. This reduces drag and improves efficiency.

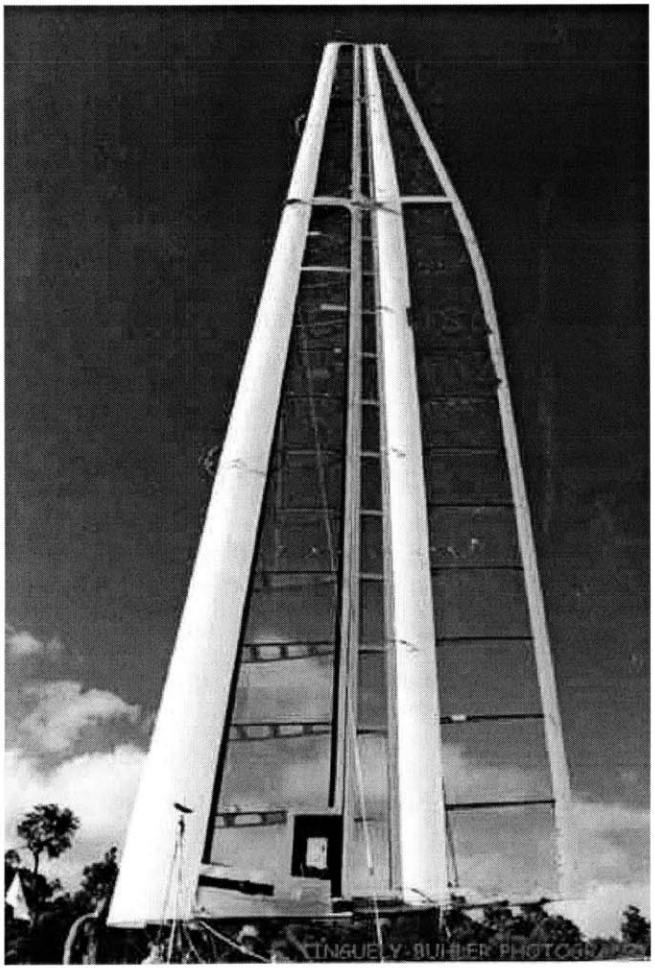


Figure 5.2 Camberable double surface foil

Camberable double-surface foils have been used. As with the wings of airplane, asymmetric sections would be more efficient aerodynamically, but unlike the airplane wing, these have to work equally well on both tacks (fly upside down).

Nevertheless, this kind of multi part, hard surface wing sails used in the C-Class catamarans cannot be practically used on larger vessels. For heavy winds and storms, it is necessary to take down and stow or reef sails and this requires fabric or fabric-like materials.[33][34][35][36].

2. Automatic sheet releases for multihulls

In recent years the attention of researchers has been drawn to the tasks of analyzing the stability of sailboats in waves. Many cases of capsizing racing and cruising sailing yachts at sea in ocean waves are well known. The problem of dynamic stability in waves for sailing multihulls is of great importance. Capsizing of sailing catamarans and trimarans in wave conditions and squalls are very frequent type of damages, the results of which are not only the loss of yachts, but also loss of crews.

Figure 5.3 Trimaran "Fujicolor" sailing in heavy weather [28]

2.1. Multihull dynamics

The trimaran suffers from two fundamental disadvantages when you compare it to the catamaran. Even under normal pressure of wind the trimaran heels more than a catamaran. Also, because the leeward hull is closer to the main hull than the spacing between the two hulls of a catamaran, the lifting of the main hull causes a greater initial roll (angular rotation) rate in the trimaran than in the catamaran.

The larger moment of inertia of the trimaran, which is an advantage when there are no waves, is a disadvantage in waves. The enormous force of the wave gives the trimaran a greater initial angular rate, and therefore much greater angular momentum, which is then more difficult for the reduced righting moment at high heels angle to overcome.

Even without taking waves into account, a craft usually capsizes in 2 seconds and it is obvious that in so short time the crew cannot react to prevent capsizing.

To prevent capsizing, the potential energy (due to the righting moment) must increase. This is equivalent to decreasing the heeling moment of the wind. This can be accomplished automatically in the following ways:

- Decrease the angle of attack of the wind (by heading up, or stretching the sails, or bending the mast with the sails)
- Creation of a constant anti-heeling moment (by easing sails or installing an anti-heeling hydrofoil)
- Releasing of the main sheet with a sudden gust of wind.

2.2. Automatic sheet releases

Clearly there is a need for automatic devices that ease sails and secure safe sailing in wind and waves. There are at least two general approaches to releasing sheets based on the heeling angle of the yacht.

During the last "Route du Rhum" race, many trimarans capsized because the skippers where working in the boat and did not have time to release the sheets. Francis Joyon, one of the multihulls's skippers, describes what happened with those words: "I was manoeuvering at the foot of mast when a sudden squall arrived. The trimaran immediately went up on the leeward hull. I rushed into the cockpit but I didn't have the time to release the sheet".

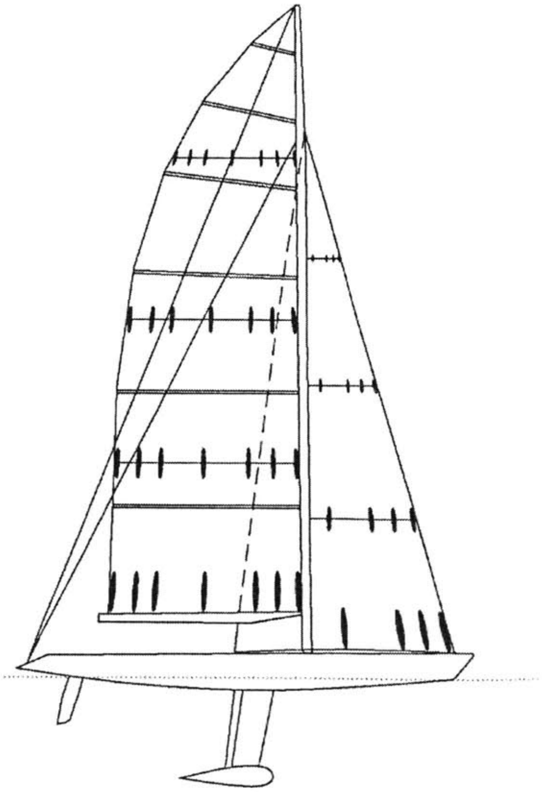
Figure 5.4 Trimaran "Foncia" at high angle of heel [52]

This kind of mechanism would really worthwhile when a single person handles the multihulls. This would also tackle the Achilles' heel multihulls have compared with monohulls: their difficulty to handle huge waves.[37][38][39].

Figure 5.5 Monohull "Sodebo" burning into a wave [51]

3. Sailspy

3.1. The system



SailSpy is a real-time system that has been developed for automatically measuring sail shapes and masthead rotation on racing yachts. Versions have been used by the New Zealand team in two America's Cup challenges in 1988 and 1992.

SailSpy uses four miniature video cameras mounted at the top of the mast to provide views of the headsail and mainsail on either tack. The cameras are connected to the Sail Spy computer below deck using lightweight cables mounted inside the mast. The SailSpy computer automatically analyzes images received from the cameras, and sail shape and mast parameters are calculated. The sail shape parameters are calculated by recognizing sail markers (ellipses) that have been attached to the sails, and the mast rotation parameters by recognizing deck markers painted in the deck.[40].

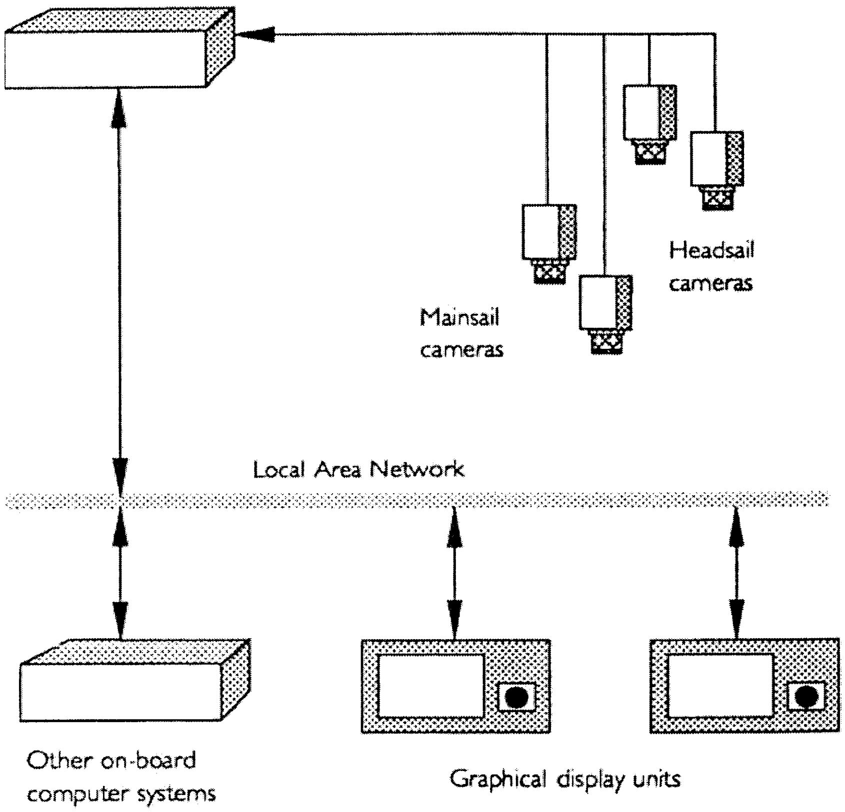


Figure 5.6 SailSpy system [40]

3.2. Value added by a real-time measurement device

Such a system, if it is well operated, provides very useful information for the crew. MIT Professor Jerry Milgram, who has been designing America's Cup boat for more than twenty years, estimated that at least eight syndicates were using such a video system during the last America's cup. Fast boats must have efficient sails, and combine low drag with maximum stability and maneuverability. To achieve the maximum performance for the sails, it is important to maintain optimum sail shapes.

Sail design, testing and modification

Using SailSpy during trials, the sail designer can gather sail-shape information and use this to assist with the design and modification of sails to suit specific conditions more accurately.

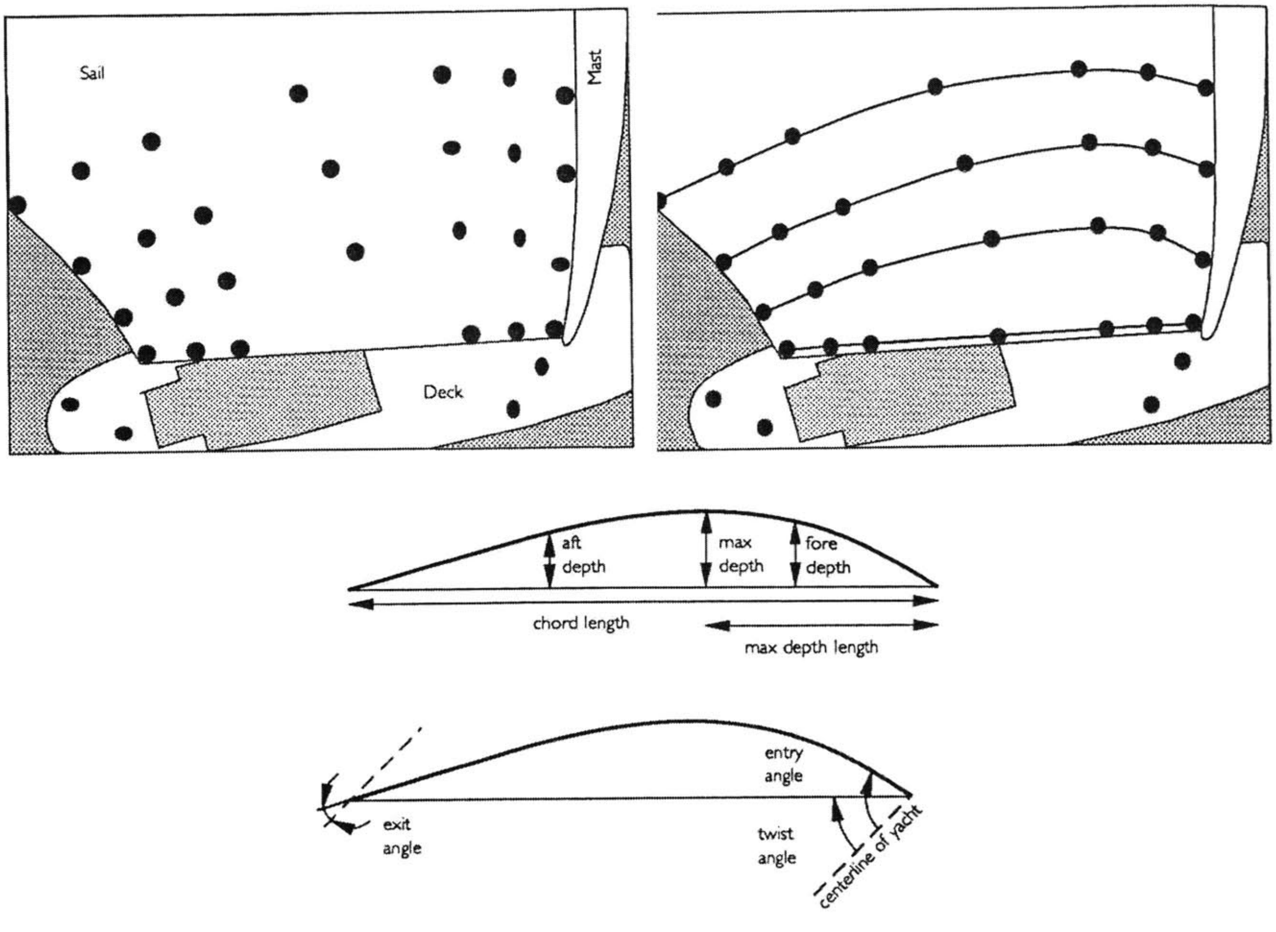


Figure 5.7 Measurement of sail shape [40]

Mast twist measurement

In addition to sail shape measurements, SailSpy provides mast-head rotation information that can be used to provide corrections for the mast-head instrumentation. Modern carbon fiber mast under loading from the sails can twist by as much as 15 degrees. It is therefore essential that the wind direction measurements, which are obtained from a transducer mounted at the top of the mast, are corrected for this twist.

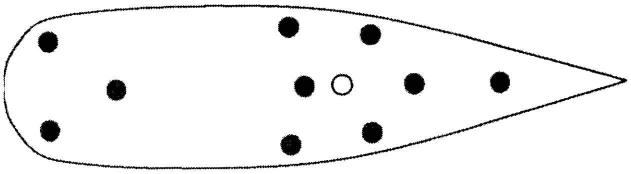


Figure 5.8 Deck with markers shown [40]

Sail trimming during trials and races

SailSpy enables the crew to determine rig and sail settings for optimum performance under varying conditions. Using the information gathered during trials, it helps the crew achieve peak performance during races.

4.3. Future improvements

At present the SailSpy system uses both sail and deck marker that require user intervention. It is hoped that the system can be further developed so that these calibrations are totally automated, which will yield to even more accurate measurements.

4. Rotating wingmasts

In the last decade, a great breakthrough allowed performance of sailing yacht to improve significantly. The first improvement was the change in the shape of the mast. From circular masts designs evolved to wingmasts, which has an elliptical basic aerofoil section. The leading edge of radius of an ellipse is exactly what airflow likes to see to remain smooth and attached to the surface. If the leading edge is too round, as in a circular section mast, airflow near the mast surface has to change direction too abruptly, and it can separate easily from the mast, thereby reducing lift and increasing drag. Also, when sailing upwind, a wingmast works like a foil, allowing an extra lifting force to act on the rig, therefore providing more driving force.

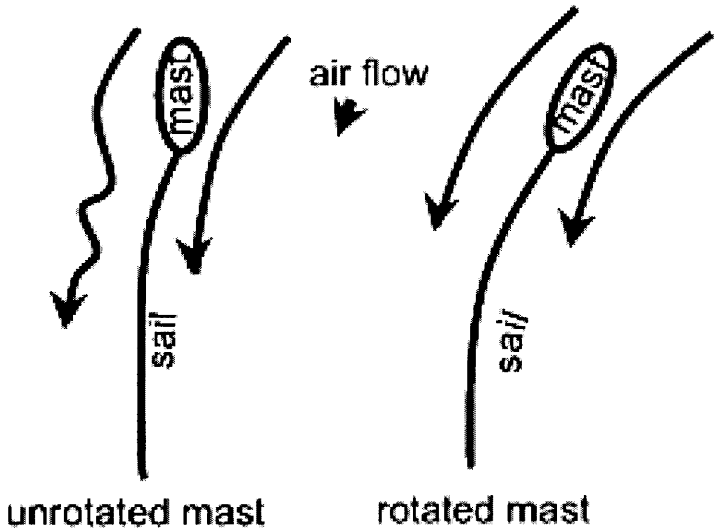


Figure 5.9 Difference in the air flow between rotated and unrotated mast [41]

The other revolution in the design of rigs was to introduce mast that could rotate. Rotating improves performance by reducing turbulence on the mainsail. Wind tunnels experiments have shown that the lift force on a sails was created about 25% of pressure force on the windward side of the sail and 75% of suction force acting on the leeward side. Therefore the leeward region just after the mast is really critical in the generation of the lifting force, since the flow should remain laminar for the best suction force. Masts that do not rotate have an area of disturbed air behind them which causes the mainsail near the mast not to be effective in generating lift.[41][42][43].

A mast that can be rotated is allowed to rotate until the leeward side of the mast continues the smooth curve of the sail eliminating the disturbed air on the leeward side. There is still disturbed air on the windward side of the mainsail but this increase in disturbed air on the windward side is not nearly as much a loss in lift as the gains made by cleaning up the airflow on the leeward side.

But more than allowing the leading edges of the sails to be always at optimum, fair to the wind regardless of the point of sail, this new trend provides other benefits:

- Sails can be raised, reefed, or stowed without changing course. This is particularly important when sailing downwind, because one does not have to turn the boat first broadside to the weather, and then into the wind in order to change sail. One holds course and just lets the rig weathervane while the tasks are carried out

- When sailing downwind, one can set the booms well forward of the beam with the masts pointing aft to get really great lift downwind, which is much more powerful than drag—downwind speed goes way up.

- With the booms so far forward and set wing and wing, the boat is naturally stable and extremely resistant to broaching. Uncontrolled gybes almost never happen because forward-set sails cannot get caught by the lee; one sail or the other will naturally pull the boat back onto course should she ever get pushed off by gust or wave.

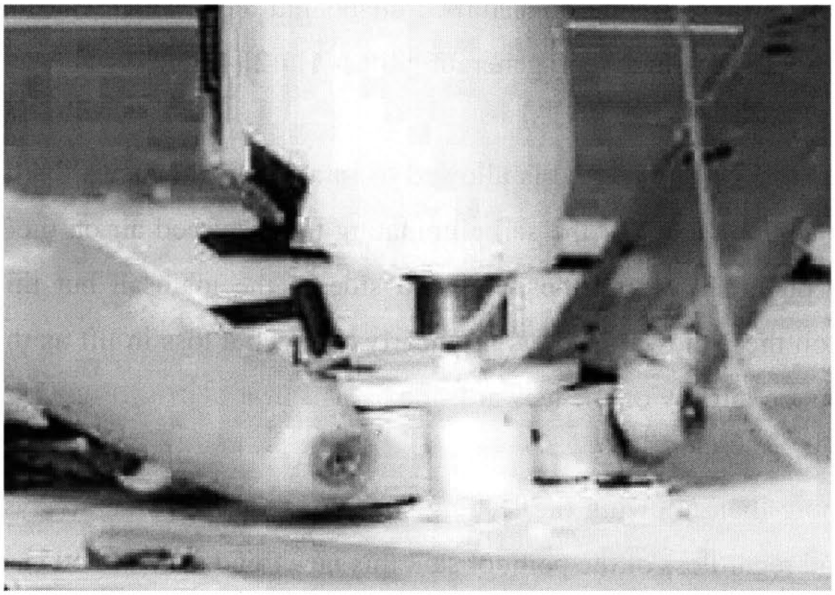


Figure 5.10 Mast foot of a rotating wingmast [42]

5. Free standing masts

5.1. Introduction

Most modern offshore racing sailboats have just one mast which is fixed in place by shrouds and stays. The headstay and backstay define and confine the shape of the sailplan to a triangle. Some curvature in the mainsail roach stretches past the backstay a little, but basically the sails form a triangle.

A triangle is the absolute worst possible shape anyone could ever conceive of for a lifting surface because it has inordinately high induced drag. Induced drag is that drag which is inescapably created along with lift. You can reduce it, but you never can get rid of it. In a triangular rig, the upper half of the sailplan creates almost pure drag with very little lift. This is because of the narrowness of the sailplan up high compared to its width down below, and the resulting airflow around this shape.

Theoretically, you can reduce a triangular rig's induced drag if you could do but one simple thing-twist the head of the sail to windward. Unfortunately, with fabrics sails, this is impossible to do, and even if you could, twisting a sail to windward increases angle of attack preciously close to stall, where lift suddenly drops to zero. It would be a continual knife-edge balance between power and stall, which cannot be done when you are sailing through waves since the rig moves around too much. So if we insist on wires to hold the mast, we must accept a more or less triangular sailplan that is just not very powerful.

However, some people were bold enough to let the laws of physics govern rig design and do away with the wires, rather like airplane designers did back in the 1920's. Without wires, the sails are no longer defined and confined by triangles, but can be shaped elliptically which is much more aerodynamically efficient-least induced drag for more lift. Also, eliminating the rigging totally eliminate parasitic drag. And not only are the sails much more efficient, but larger ones and more of them can be raised.

Figure 5.11 Beneteau 42s7 sailing yacht with free-standing mast [32]

Eliminating the wires in the rig also greatly improves safety. A stayed, triple-spreader rig such as on an Open Class 60 sloop has over 500 separate parts holding up the mast. If any one of those parts fails or falls out, the rig has roughly 95% chance of falling over the side. If that happens, and it does regularly in round-the-world races, the boat will most likely be out of race. On Project Amazon, the two masts are held up by a total of 4 parts. Safety and reliability increase in proportion, 500+ to 4, roughly 12500%.

The rigs of windsurf represent today the state-of-the-art aerodynamically efficient sails with a combination of carbon spars that allow a lot of bending to work better in all types of weather and also sails whose shape efficiency is not to be proven any more. The trick is to manage in a way or another to apply all this knowledge and technology to boats, finding new solutions to hold the mast, since for boats the helmsman is not part of the rig like for windsurf.

Figure 5.12 State-of-the-art sails used in windsurf [28]

5.2. Design of free-standing masts

A freestanding mast is basically a cantilever supported by the deck and the hull structure and therefore the strongest part of the mast has to be at the deck level.

The design of a freestanding mast is fairly simple. Whereas a stayed mast always carries its load in compression, due to the pull of the rigging wires, a freestanding mast always bends. The pressure of the wind on the sails causes a bending moment load on the mast which is zero at the top, maximum at the deck and gooseneck, and zero again at the heel. The maximum possible bending moment the mast can ever carry is equal to the maximum righting moment of the boat itself.

The mast must be as slender as possible consistent with strength, stiffness and weight. Generally, larger cross-sectional shapes make lighter masts because the wall thickness gets thinner with increasing section size. There is a point where section size can be too big and wall-thickness too thin, making the mast too delicate to handle or subject to premature buckling. Every mast has an optimum size for each boat design, and wall thickness should be between 3.2 and 12.7 mm in most instances.[43][44][45][46].

Figure 5.13 Cat-ketch yacht Paratii 2 with two free-standing masts [32]

Chapter 6

Conclusion

The racing yacht technology is a domain where still persist many unknowns. The lack of methods that could very accurately predict the static loads and especially the dynamic loads that wind and waves have on a boat leaves to the designer many niches, that his boldness might help him explore. There are a lot of improvements and progress to be made and many research areas should be investigated in order to achieve the ultimate goal: sailing faster.

The Bragg grating system might be an extraordinary evolution for the designers, since for the first time they would have an access in real-time to the loads applied to the mast, with a very good accuracy. It should then allow them to reconsider their calculations and reach some trade-offs with the materials and the structure much more efficient than was has been done up to now.

This thesis focuses mainly on the rigging of the yacht and the improvements that could be implemented to it. Improving the performance of a boat also encompass the progress made in the hull design, which was not developed. Nevertheless, the introduction of rotating keels, ballasted with a bulb at its very end, allowed designers to considerably increase the performance of monohulls, and a lot of research is on-going in this area. The technology of hydrofoils, which has been implemented on boats for more than thirty years, could also provide very interesting results with our better understanding of composite materials.

Another trend that has to be mentioned is the spectacular improvements done during the last ten years in kite sailing. By eliminating totally the problem of the boat heeling, you can reach much higher speed with a kite then with a conventional rig. People have been able to reach speeds up to 50 knots, which is very close the highest speed ever reached by a sailing engine on the water.[47][48][49].

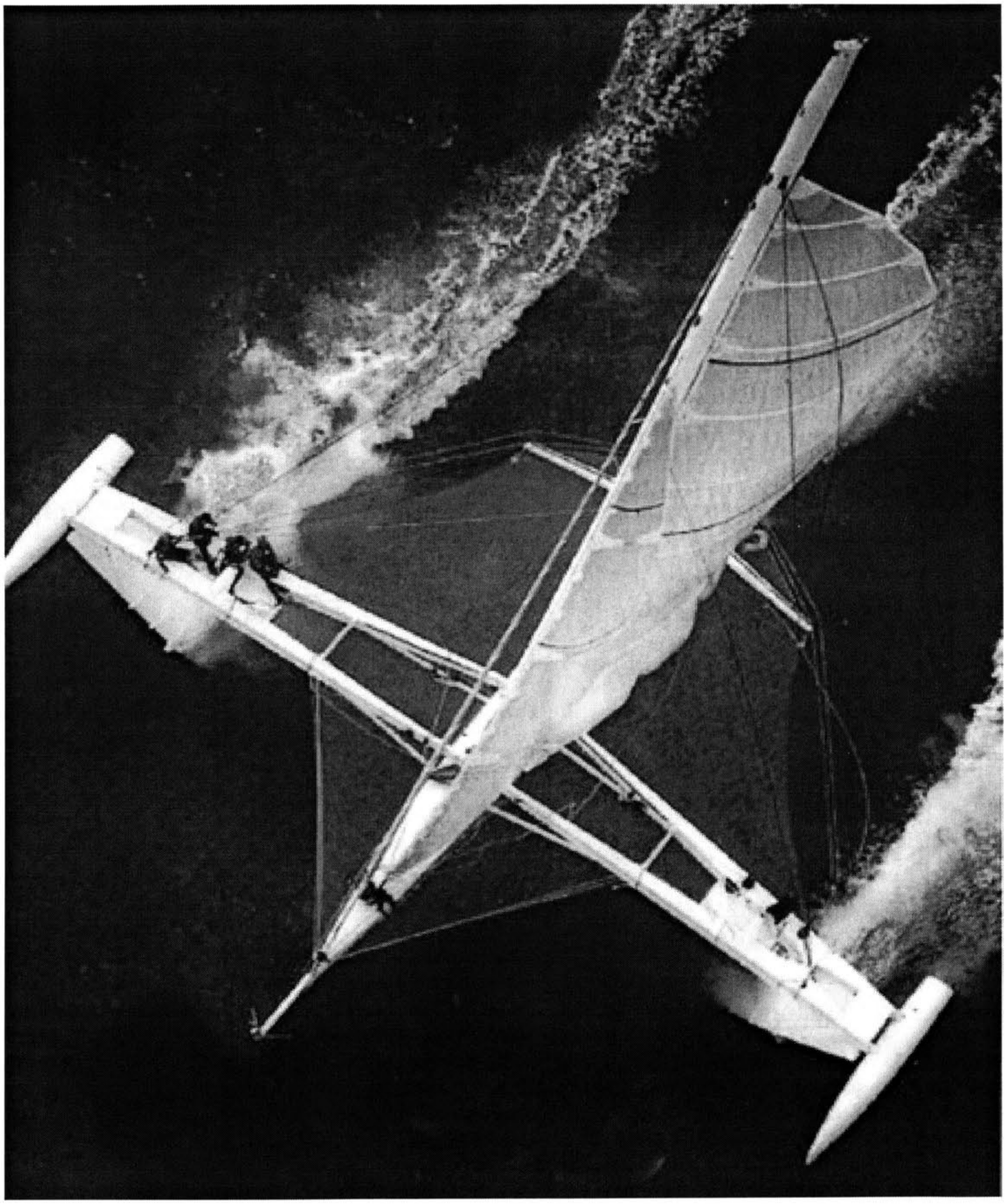


Figure 6.1 Hydrofoil "Hydroptere" flying above the sea [50]

Last but not least, the lack of funds is the main reason of the lack of knowledge about racing sailing yachts. Since the technology is very expensive, everyone works for themselves, and the results of experiments are almost never shared among designers. Therefore it reduces tremendously the possibility of achieving important breakthrough, even if very few colloquiums are scheduled from time to time.

Uncertainties and unknowns are finally what make this sport so amazing: whatever boat you have, however are your sailing skills, the sea will always have the last word. Laurent Bourgnon, a Swiss skipper, thoughts about those multi failures of mast was: “having a state of the art boat is not worth it if it is not reliable. [..]. Anything can be designed, but there are two things that one will never succeed in dominating them: the wind and the sea, last space of liberty. [..] Sailing remains an adventurous sport that has not arrived yet to its maturity. Some things have to be readjusted. And the relevant questions have to be addressed. So that all it acts as lesson."

The next ten years will probably see huge improvements in this domain due to a better understanding of, on one hand, the materials, and on the other hand the loads acting on the different parts of a racing yacht.

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