ISSN 0144 - 1396

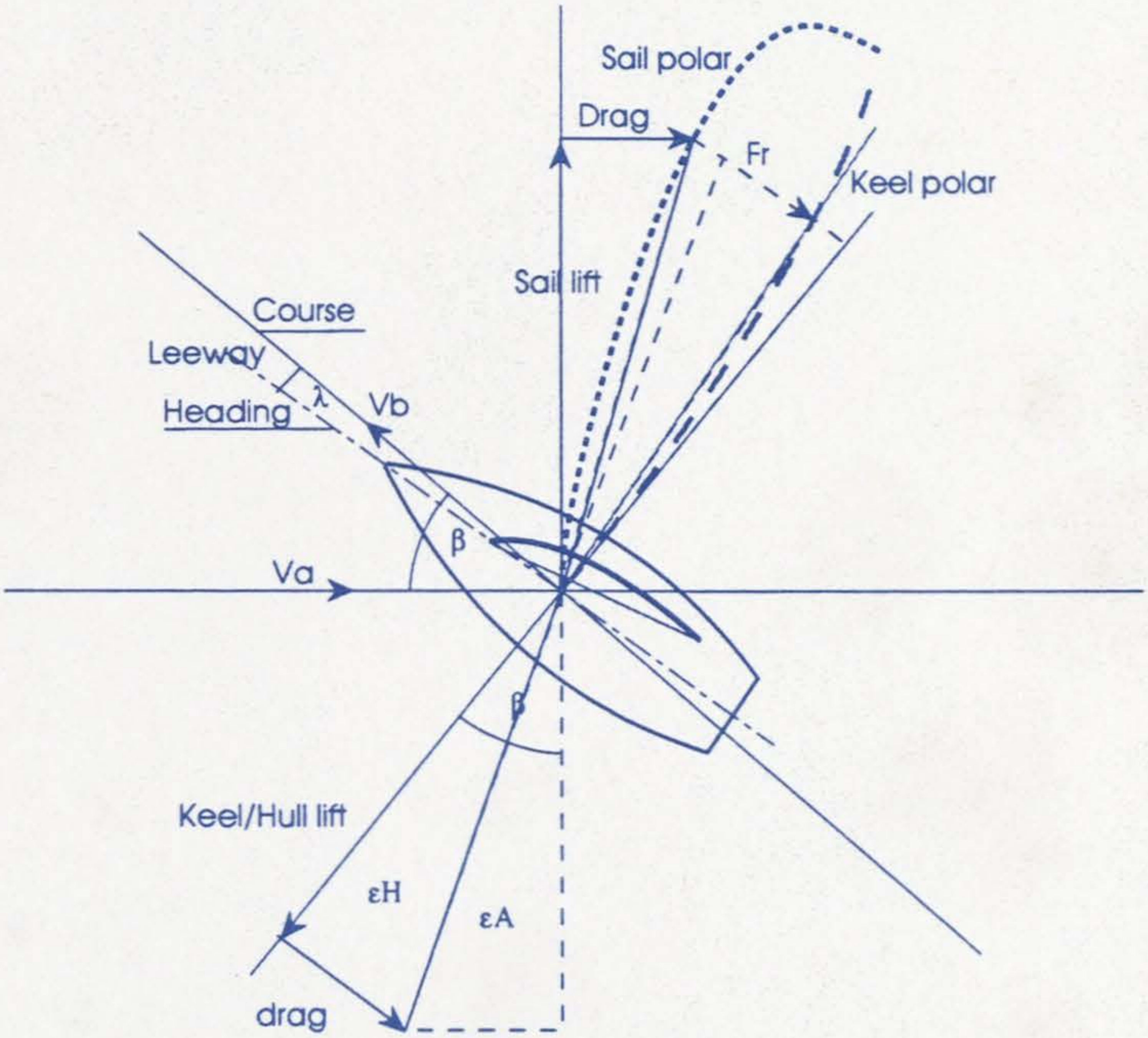
AYRS 113

AMATEUR YACHT RESEARCH SOCIETY

AYRS

Advisers to the Professionals since 1955

RIG THEORY



by Ian Hannay

The Amateur Yacht Research Society

Founded in 1955 to encourage Amateur and Individual Yacht Research

President
HIS ROYAL HIGHNESS
THE PRINCE PHILLIP, DUKE OF EDINBURGH
KG KT OM GBE QSO

Vice Presidents
Austin Farrar FRINA
Beecher Moore
Sir Reginald Bennett
Founder: the late Dr John Morwood

COMMITTEE 1993/1994

Fred Ball	Surrey	Chairman
Ian Hannay	Hampshire	Vice Chairman
Graeme Ward	Surrey	Hon Secretary
Michael Ellison	Plymouth	Hon Treasurer
Theodor Schmidt	Switzerland	European Rep.
Dick Newick	USA	North America
Robert Downhill	Sussex	Speed Week
Tony Kitson	Twickenham	Publications
Simon Fishwick	Hertfordshire	Boat Show
Roger Glencross	Wimbledon	Coordinator
Alistair Stewart	London NW2	
Clive Anderson	Truro	
David Trotter	Somerset	

The Society (open membership) furthers the theory and practice of nautical science and related subjects. Educational Charity (No 234081) and a company (No 785327) without share capital, limited by guarantee.

Subscription £25.- or $50.- USA
Entrance fee £5.- or $10.- USA
Life Membership donations £1,000. or $2,000.

Amateur Yacht Research Society
BCM AYRS, LONDON WC1N 3XX

AYRS Publications inc. p & p. (surface rates)

1	Catamarans	1955	£1.50
2	Hydrofoils	1955	£5.50*
3	Sail Evolution	1955	£5.50*
4	Outriggers	1956	£1.50
5	Sailing Hull Design	1956	£5.50*
6	Outrigger Craft	1956	£1.50
7	Cat. Construction	1956	£5.50*
8	Dinghy Design	1956	£5.50*
9	Sails & Aerofoils	1956	£5.50*
10	American Catamarans	1956	£1.50
11	The Wishbone Rig	1957	£5.50*
12	Amateur Research	1957	£5.50*
13	Self Steering (book)	1957	O. of P.
14	Wingsails	1957	£5.50*
15	Catamaran Design	1957	£5.50*
16	Trimarans & Outriggers	1957	£5.50*
17	Commercial Sail	1958	£5.50*
18	Cat Developments	1958	£5.50*
19	Hydrofoil Craft	1958	£1.50
20	Modern Boatbuilding	1958	£5.50*
21	Ocean Cruising	1958	£5.50*
22	Catamarans 1958	1958	£5.50*
23	Outriggers 1958	1959	£5.50*
24	Yacht Wind Tunnels	1959	£5.50*
25	Fibreglass	1959	£5.50*
26	Sail Rigs	1959	£5.50*
27	Cruising Cats. (book)	1959	£6.00
28	Catamarans 1959	1959	£5.50*
29	Outriggers 1959	1960	£5.50*
30	Tunnel & Tank	1960	£5.50*
31	Sailing Theory	1960	£5.50*
32	Sailboat Testing	1960	£5.50*
33	Sails 1960	1960	£5.50*
34	Ocean Trimarans	1961	£1.50
35	Catamarans 1960	1961	£5.50*
36	Floats, Foils & Flows	1961	£5.50*
37	Aerodynamics I	1961	£5.50*
38	Catamarans 1961	1962	£1.50
39	Trimarans 1961	1962	£5.50*
40	Yacht Research I	1962	£5.50*
41	Yacht Research II	1962	£5.50*
42	Catamarans 1962	1963	£1.50
43	Trimarans 1962	1963	£5.50*
44	A.Y.R.S. Yachts	1963	£1.50
45	Basic Research	1963	£1.50
46	Catamarans 1963	1964	£5.50*
47	Outriggers 1963	1964	£1.50
48	Yacht Electronics	1964	£5.50*
49	Keel Yachts	1964	£1.50
50	Catamarans 1964	1965	£1.50
51	Foils & Floats	1965	£5.50*
52	Trimarans 1964	1965	£5.50*
53	Solo Cruising	1965	£1.50
54	Catamarans 1965	1965	£5.50*
55	Trimarans 1965	1966	£5.50*
56	Sailing Figures	1966	£1.50
57	Round Britain 1966	1966	£1.50
58	Practical Hydro foils	1966	£5.50*
59	Multihull Design/Cats.	1967	£5.50*
60	Multihull Seamanship	1967	£5.50*
61	Sailing Analysis	1967	£5. 50*
62	Hydofoil Victory	1967	£5.50*
63	Multihull Capsizing	1966	£5.50*
64	Catamarans 1967	1968	£5.50*
65	Trimarans 1968	1968	£5.50*
66	Foils/Ice Yachts/Sails	1968	£5.50*
67	Catamarans 1969	1969	£1.50
68	Outriggers 1969	1969	£1.50
69	Multihull Safety Study	1969	£5.50*
70	Retirement Yachts/Polars	1969	£1.50
71	S/H Transatlantic Races	1970	£1.50
72	Catamarans 1970	1970	£5.50*
73	Trimarans 1970	1970	£1.50
74	Sailing Hydrofoils (book)	1970	O.of P.
75	Deepwater Seamanship(book)	1971	£5.50
76	Sail Trim, Test & Theory	1971	£1.50
77	Trimaran Selection	1971	£1.50
78	Cruising Cats. (book)	1971	O. of P.
	AIRS 1 - 11	1971-5	£1.50 each
79	Rudder Design (book)	1974	£7.00
80	Round Britain Race 1974	1974	£1.50
81	Sail Rigs 1976	1976	£5.50*
82	Design/Fast Sailing (book)	1976	£11.00
83.A	Journal 83A	1976	£5.50*
83.B	Journal 83 B	1976	£5.50*
84.	Hydrofoils'76	1976	£5.50*
84.B	Hull Research '76	1976	£5.50*
85.A	Kite sail rigs '76	1976	£1.50
85.B	Boatbuilding & Materials	1976	£1.50
86	Ostar '76 & Safety	1977	£1.50
87	Kites & Sails	1977	£3.50
88	Yacht Tenders & Boats	1977	£3.50
89	Facts & Figures	1977	£3.50
90	Hydrofoil Options	1978	£3.50
91	Power from the Wind	1979	£3.50
92	Deep Seamanship	1979	£3.50
93	Speed Sailing	1979	£3.50
94	Shallow Draft Craft	1980	£3.50
95	Racing Hydrofoils	1982	£3.50
96	Cruiser Development	1983	£3.50
97	Sails, Rigs & Hydrofoils	1983	£3.50
98	Windmills & Kites	1983	£3.50
99	Megalithic Boats	1984	£3.50
100	Efficient performance	1985	£3.50
101	Windmills and Hydrofoils	1985	£3.50
102	Sailboards & Speedweek	1986	£3.50
103	Optimum Yachts	1987	£3.50
104	Multihull Cruisers	1988	£3.50
105	High Speed Sailing	1989	£3.50
106	Seaworthiness/Stability	1989	£3.50
107	Low Drag Craft	1990	£3.50
108	Foils & Hapas	1991	£3.50
109	Propellers & Solar Boats	1991	£3.50
110	Developments in Yacht Design	1992	£3.50
111	Rig Efficiency	1993	£5.50
112	AYRS Projects	1993	£5.50
113	Rig Theory	1993	£5.50

* Photocopies = Out of print. Prices subject to change

Amateur Yacht Research Society

BCM AYRS, London WC1N 3XX)

Rig Theory

A study of the theoretical limits

on sail performance

and

their application

by Ian Hannay

Amateur Yacht Research Society

BCM AYRS, LONDON WC1N 3XX

CONTENTS

Preface

The aim of this publication is to help define and explain Nature's limits behind wind powered sail propulsion. There are distinct physical limits that no designer, sailmaker, or sailor, however clever (or powerful the computers they may use), can overcome. This includes a maximum possible performance under sail for any given hull and stability and is regardless of the style or area of the sails used.

In any discussions on sail efficiency there is often confusion as to where the laws of nature end and traditional bias or prejudice begins, with the direct application of aircraft aerodynamics (designed for different conditions and uses) usually adding further confusion to the discussion.

Over the last sixty years the yacht racing world has lived effectively in a *mono-culture* of Bermudan sails, Genoa jibs and symmetrical spinnakers. These have unfortunately been treated with such religious reverence by the racing fraternity that alternatives have either been banned or at least penalised out of existence. The result is that several generations of sailors have been brought up to believe that the traditional Bermudan rig is the most efficient and that there are no other alternatives worth considering.

Despite the artificially imposed limitations, the modern racing rig has been developed into a very efficient propulsion system. Any alternatives will have to produce similar levels of refinement before they will have a chance to threaten the dominance of the Bermudan rig and its triangular headsails.

There is no one size or type of rig that is superior to all others in all situations. Each rig has its good and bad points and these have to be weighed up to arrive at an optimum rig for a boat and a set of conditions.

To fully understand the concepts presented the reader should be conversant with standard aerodynamic terms such Lift, Drag, Induced Drag etc, as applied to aero and hydrofoils, also a copy (or knowledge) of AYRS 111 – Rig Efficiency – would help, as this information is referred to extensively.

The sections on sail and rigging loads first appeared several years ago and is the basis of the computer programs used by many of the leading yacht design offices and fitting manufacturers. This is another case of the AYRS advising the professionals.

Ian Hannay *Fleet* *November 1993*

Rig development

Ever since the first sail was hoisted on a dugout canoe there has been a continuing effort to improve efficiency on all types of sailing craft both in performance and to ease handling.

The changes of style have almost universally come about through the availability of new materials. For instance in recent years manmade materials have completely changed the level of loadings that can be applied to sails, making them lighter and stronger than anything that existed before. It used to be necessary to heave to in force 6 for fear of blowing out sails or breaking something. Now yachts continue to race with the wind well over 60 knots, this gives something like a five-fold increase in ultimate loadings.

Throughout the ages the better rigs have always been surprisingly close to the optimum for the materials and manpower available. That is not to say that other arrangements may not have been just as good, but any alternative would have had little real advantage over the standard rigs then in use. The regional variation in traditional rigs show how different styles can achieve similar results.

All rig development has been a continuation of the traditional method of trial and error using the materials available, without any form of theoretical or scientific input. Even in recent years the scientific contribution has been minimal and used mainly to present what has already been known in a more scientific form (and that includes this AYRS publication).

Even with today's extensive knowledge and powerful computers it would be very difficult to improve on the first sails of over 2,000 years ago, given the materials and technology available at the time.

Up until the last century there were virtually no artificial restrictions on the development of sails and rigs. Natural developments evolved efficient rigs for crossing oceans with small crews or for speed to and from the fishing grounds. In these cases failure was not only a commercial disaster, but could also be fatal, and there were therefore strong inbuilt pressures to develop reliable and efficient systems for use with limited manpower.

Coastal rigs tended to be fore and aft, in order to ensure that there was some form of windward performance. The classic ocean-going square riggers only became fully developed when they could rely on auxiliary engines being available in the form of steam tugs at each port of call.

The rig is part of an integrated package that makes up a total design.

Racing

To find the performance of boats it is necessary to have some form of speed measurement or race for the comparison of results, and here the trouble starts. We all know that a *"good big 'un"* will always beat a *"good little 'un"* and so some form of correction is required to cope with the different sizes and speed potential. Unfortunately there is no form of correction that can be applied which will be true in all conditions, so any handicap system will always have some sort of built in error. Unfortunately this results in most of the effort in the designing and tuning of racing boats being spent in overcoming an arbitrary set of rules rather than improving real performance – IOR yachts were an example of this limited approach.

Close racing has one very important feature, it is the only practical way of developing any depth of knowledge of how to refine the performance of a sailing craft. No instrumentation will ever show the small changes that become noticeable in top level racing.

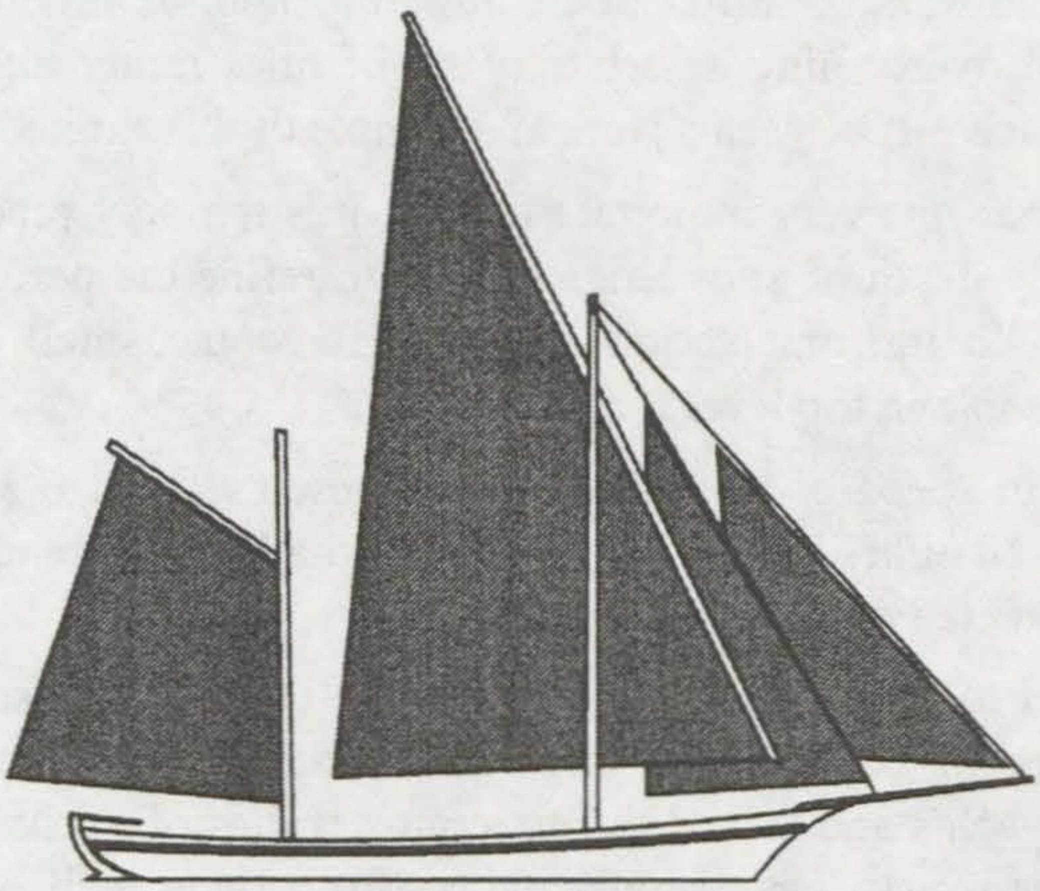
A difference in speed of just 0.01 knots represents about 0.3 m, one foot per minute or 18 m/hr. This is just about the smallest difference that can be reasonably detected during close quarter racing.

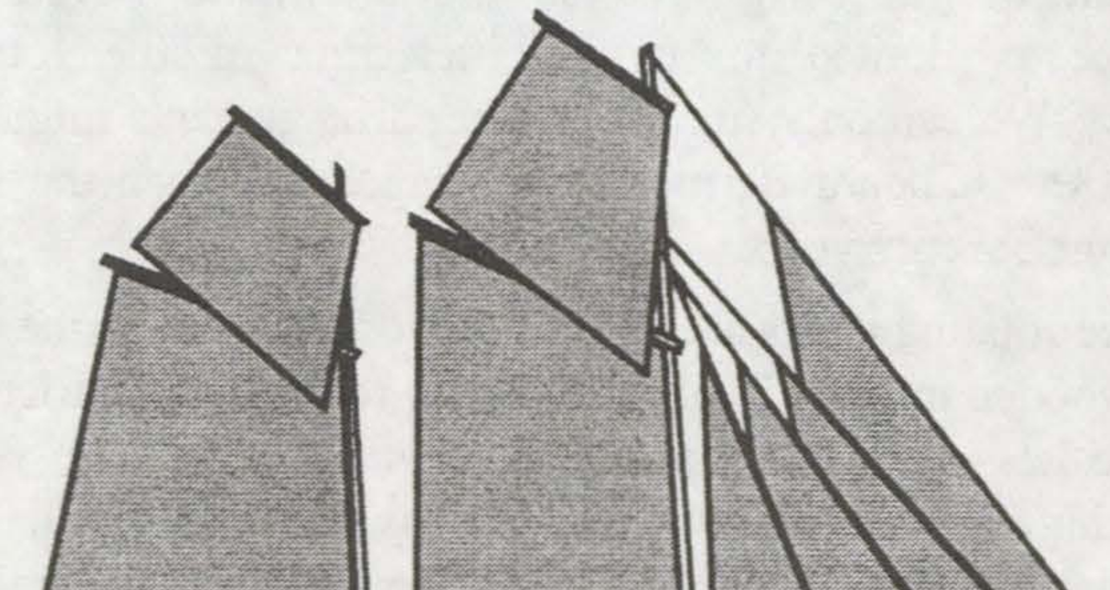
Racing started to become popular towards the end of the last century and inevitably winning became very important. Leading to the development of some unsafe yachts and forced the governing bodies of yacht racing to put more and more restrictions on hulls and construction as well as the size and type of sails that could be set, resulting in the 6, 8 & 12 Metre Classes etc.

Since early this century the racing rules have effectively restricted the free development of yacht rigs and so the information available on sail performance is limited to a small selection of the total range of possibilities. We can only surmise if other arrangements might been better better than the standard Bermudan rig, which has been the standard sail plan for some seventy years.

For instance rotating masts are banned in most classes. In the era of cotton sails and wooden masts this was probably a reasonable restriction, but now that composites are in everyday use is this still a realistic restriction for serious racing yachts? This is rather like insisting that all racing cars must still use sidevalve engines because that was what was used at the beginning of the century! We are now only just getting away from symmetrical spinnakers and short spinnaker booms on racing boats. With the forestay always having to be on the centreline and headsails triangular the development of rigs has always been very restricted.

In recent years only the sailboard rig can be said to have been developed free from artificial preservatives. They have found the factors that really matter in achieving performance from a simple single sail rig, but it must be remembered that the style is still dictated by the handling and manoeuvring requirements of the board sailor. Although this rig is no doubt efficient and can teach us many very useful lessons, it will almost certainly not be the best on other types of larger and more stable craft. ✔





Rig Limitations

Before discussing the shapes, styles or efficiency of rigs it is important to have a clear understanding of what the limiting factors are in the design of any rig. In all cases in this publication we are considering optimum performance. The problems of handling and practical engineering come later when developing these theoretical ideas for use on real boats.

Strong winds

This situation is relatively straightforward as there is more than enough sail available. We just want to know what shape and arrangement the limited sail area should have to either drive the boat to windward or sail off the wind at speed. Reducing speed generally only requires a reduction in sail area, but the windage of the hull, superstructure, rigging and crew, will have a more dominating effect as the wind gets stronger and imposes a minimum effective sail area which will successfully propel the craft to windward. The main problem is to minimise drag.

Light winds

This situation is more complicated and splits up into several factors. The most usual limitation for racing craft is that the sail area is controlled. The problem then becomes how to make best use of the sails within the limits imposed by the rules. This development can be distorted by 'free' area allowed under many measurement systems. This practice came about simply because cotton sails were difficult to measure accurately, so the length of the spars and area of the fore triangle were used to control sail area, this resulted in the overlap of headsails and the roach on the mainsails being unmeasured.

With the advent of artificial fibres and more stable sail shapes recent rules now measure the sails directly, but still use traditional limitations such as the size of headboards, length of battens and insist on only triangular headsails. These factors are mainly cosmetic in nature when the sail area is measured directly. With the area limited the aim becomes to obtain the maximum useful driving force from the sails.

As the wind strength increases or the apparent wind becomes more towards closehauled the desire is not so much for maximum drive but to reduce drag. Windward performance is dominated by the height of the rig (and depth of keel), Provided there is enough righting moment available, Velocity Made Good (VMG) will potentially be improved by any increase in the effective height of rig or depth of keel.

Just as racing cars try to obtain the maximum power out of a given engine size so racing rigs are almost always designed to get the maximum power from of a limited sail area. This often means that very considerable effort is required to achieve the last fraction of a % in performance and can be so labour intensive that it is totally impractical off the racing course.

Non- class rigs

Boats that do not have to comply with any particular class racing rules unfortunately tend to follow the fashion of the racing yachts despite the fact that the requirements may be very different. There is no restriction on the total sail area that may be set at any one time, though the total available may be limited only by the generosity of the mortgage manager.

Mainly due to the difficulties with traditional reefing, up to the early 1970s a good cruising yacht was expected to be able to carry full sail in winds of up to 25 knots. Now the situation is better, but the tendency is still to have too little sail available for the gentle days and off the wind. It is similar to having a car with a small engine, that does not have any extra power available when wanted. Racing car engines are limited in capacity and everything is done to optimise the power from the limited size, but the production cars simply fit larger engines when more power is required. The same should apply to the design of sailing craft.

As a general principle, non-racing boats should be able to set more sail area than their class racing contemporaries particularly in light winds.

The tendency is always to fit bigger auxiliary motors. Why not do the same with the sails? The modern sail handling systems have transformed the potential for cruising yachts as it is now possible for all reefing to be done by one person from the protection and comfort of the cockpit.

The aim for all craft should be to set the most effective sail within the length of spars available. Multiple sail arrangements are in the main chosen for handling rather than efficiency because this can be far more important than looking for the last little piece of efficiency.

As will be explained later the optimum rig is tied in closely with the efficiency of the hull and keel which it is propelling. ✔

Relative levels of performance

When looking for performance improvement it is important to ascertain the level which is of interest. The racing fraternity will spend fortunes to try for a 0.1% improvement in speed, this represents 3.6 seconds per hour or 10 minutes in a week's sailing ! In this situation anything that might improve performance is significant, even persuading the crew to have a haircut !

In the real world the smallest practical measurements from wind tunnel or tank testing is normally limited to about 2% (± 1%) in absolute terms. It is difficult to achieve any better results because the differences with the same model on different runs can be more than that between the various models. There are also empirical corrections required to scale the test results up to full size and these also limit the degree of accuracy which can be achieved.

It is possible to detect smaller differences but not to measure the absolute results. Computer simulation is one way of analysing the situation and indicating what the effect of small changes might be, but this approach depends very much on the validity of the computer program. Unfortunately the general tendency of their creators is to claim a great deal more for them than they can actually achieve. In practice very small improvements in performance are more usually achieved by intuition.

To achieve something like a 10% improvement in performance could require drastic measures with both the boat and crew. Sailboards improved their performance by some 230% over twenty years, but this was as a result of millions of hours of development and millions of dollars in investment. Regrettably it is not usually possible to achieve any great breakthroughs in performance without considerable time and effort. Australia II with its winged keel was only marginally faster than the other 12 Metres (and certainly less than 1%). The real advantage was in the psychological battle where having something completely different worked wonders !

For non-racing craft it is probably only worth considering a performance package that affects the performance by at least 2%, that is about a minute an hour, 30 minutes a day or 3 hours over a whole week's sailing. For those crossing the Atlantic that is something like half a day.

Apart from using the rig more efficiently this level of performance improvement might be achieved by increasing the length by 5%. Or, if the craft is not up to hull speed, increase the height of the rig and depth of keel by 2%, provided of course that the necessary stability is available without adding to the total resistance. ✔

Fundamentals of Performance

There are some simple principles that physically limit the performance of any sailing craft. These are the factors that the rating rule makers basically try to control and designers use their ingenuity to circumvent!

The parameters that directly affect performance are:-

Primary:- **Stability**
Weight
Length

This is in effect the vehicle that is to be propelled. The primary information, combined with the wind strength effectively defines the maximum possible performance that can be achieved from a given hull and this is basically regardless of the style or design of rig used.

Secondary:- **Effective height of rig**
Effective depth of foils
Sail area

The secondary factors define the basic efficiency of the rig-keel combination which is the mechanism (or engine) that propels the boat. The Sail Energy Transfer (SET) system or rig is only aware of the stability along with the strength and direction of the apparent wind. This energy is transferred by the hydrofoils by what we might call the Water Energy Transfer (WET) system.

Tertiary:- **Foil shapes.**
Style of sails, spars and rigging
Hull lines
Surface finish
Drag from appendages
(propellers, cabin tops, crew etc.)

This is where the designer, builders and sailmakers generally express their individuality and although these factors can detract from the performance achieved, it is not possible physically to exceed the limitations imposed by the primary and secondary factors listed above.

In practice it is not possible to totally isolate each individual factor because they are in many ways all interdependent. But to improve performance first look at the primary and secondary factors before optimising the remainder. For instance, if the rig is not big enough, too much stability or weight will reduce performance. For optimum performance all these factors need to be matched to the weather conditions and to each other.

Stability allows the wind to fill the sails and therefore the rig to develop the power to propel the craft. Without stability there can be no pressure in the sails and therefore no sailing. The maximum power is available at the optimum angle of heel (which will be explained in more detail later).

Weight is always with us. It causes wave making resistance and defines wetted area or surface friction. The only place where weight is advantageous is in reasonable quantities at the bottom of the keel on mono hulls. In any other place it only contributes to a reduction in performance.

Length reduces wave making at the expense of extra wetted area. It is used for longitudinal stability and on high speed craft the effective wetted area can be reduced by using planing surfaces or hydrofoils. An extreme case is the Y framed sailing machine *Yellow Pages Endeavour*.

Height of rig controls the heeling moment and the induced drag. Doubling the height of the rig will cut the induced drag to a quarter for the same sail load, but to do this there must be enough stability available.

Depth of foils is similar to the rig with added depth increasing efficiency at the expense of increased heeling moment. If there is a reasonable amount of ballast at the bottom of the keel, then performance will improve by increasing draft and therefore the righting moment. It is practical considerations which usually limit this approach, but the tendency amongst racing classes is to go for the maximum draft possible. The combined effect of the effective height and depth is to define the limits on VMG.

Sail area defines the light weather and off wind performance, but as stated above has less effect than height and depth on windward performance (VMG). Cruising boats may be limited in draft and mast height for entirely practical reasons, but they should always be generous with their sail area.

The error in most rating rules is that they put sail area too high up the agenda and attempt to mix primary and secondary factors. Unfortunately these can only be truly combined for one set of conditions. A long boat with little sail area in strong winds will be fast and in light winds a shorter craft with lots of sail will be faster. These boats will very rarely be racing close together. A third boat with moderate length and sail area would always be expect to come second and it is only in one set of conditions that it would be possible to create a fair handicap for all three craft. It only requires the conditions to change slightly – more windward work or a change in wind strength – for the assumptions made in the rating formula to be invalid. All else being equal these race results would depend only on the weather – not an entirely satisfactory situation.✔

Stability – the root of all sailing performance

Any form of sail, kite or windmill propulsion is an energy transfer system and will only work if the wind is moving relative to the water. With the wind blowing above the water there is always a heeling moment produced by this transfer of energy. It is not possible to propel any form of sailing craft without causing a heeling moment and therefore all sail powered craft require some form of stability for them to be able to do any useful work. Yes, even kites and so-called non-heeling rigs, these simply use the inclined angle to produce a vertical righting force that counteract the heeling moment produced by the horizontal driving force.

Stability comes in two forms – **Static** and **Dynamic**

Static stability is used by classic boats (mono or multihulled) where the righting moment is produced by moving the centre of buoyancy to leeward of the centre of gravity as the craft heels to the wind. This force can be measured with the boat afloat in calm conditions.

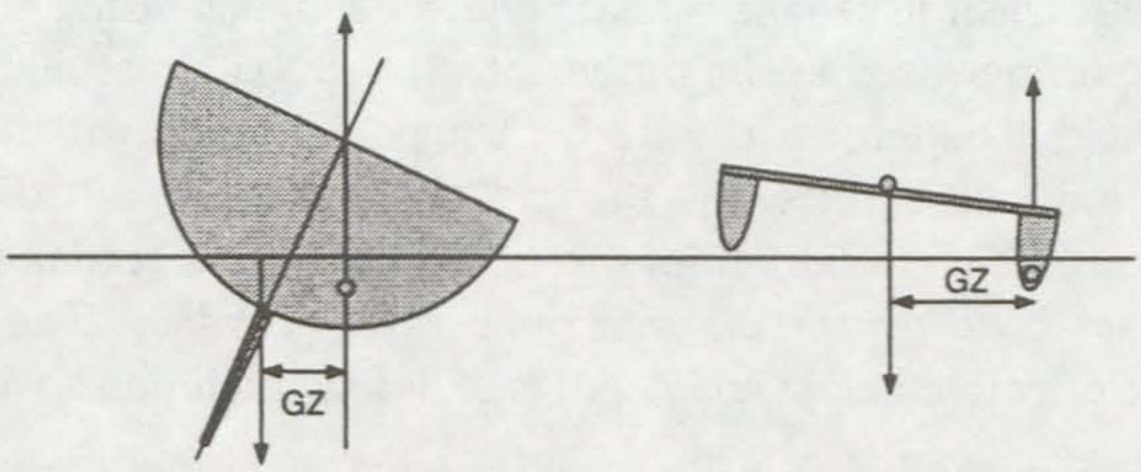


Figure 1 – Static stability created by horizontal distance between centres.

Dynamic stability can be produced by the flow over the hull, foils, sails or any other suitable device. It is entirely dependant upon the dynamic forces being produced at any particular moment and ceases when the flow ceases.

Inclined rigs, kites and hydrofoils all produce forms of dynamic stability, with the vertical components of their total force being used to counteract the heeling moment which they produce.

Figure 2 shows how the forces on a kite and hapa combination are in balance. The horizontal couple K_y, H_y is equal to the vertical K_z, H_z. Only part of the horizontal force K_y can be used for propulsion and none of the vertical one K_z, therefore the vertical component becomes in effect 'wasting' energy as it is not used for propulsion. The inefficiency of any inclined sail is directly proportional to the angle of inclination (Cos θ). The exposed area is also reduced by this angle, so if the area is fixed the horizontal force available for propulsion is proportional to Cos θ^2. At 45° the available horizontal force is reduced by 50% and the foil is creating 41% more force than can be used for propulsion. The drag is therefore 41% higher than it need be for pure propulsion purposes and the potential performance is reduced accordingly.

In conventional displacement designs dynamic stability is usually ignored by all regulatory and racing authorities despite the fact that these forces can be the dominant factor in smaller craft. The reason being that the flow along a surface and the magnitude of the forces produced are almost impossible to measure or predict with any reasonable degree of accuracy.

Inertia, damping and hysteresis also play important parts in determining the stability characteristics of any craft since they control the speed at which events happen and may help or hinder the main stability factors

For a simple demonstration of the powerful effect of the dynamic forces at slow speeds one only has to paddle a canoe or row a dinghy to notice how much more stable it is once it is moving through the water.

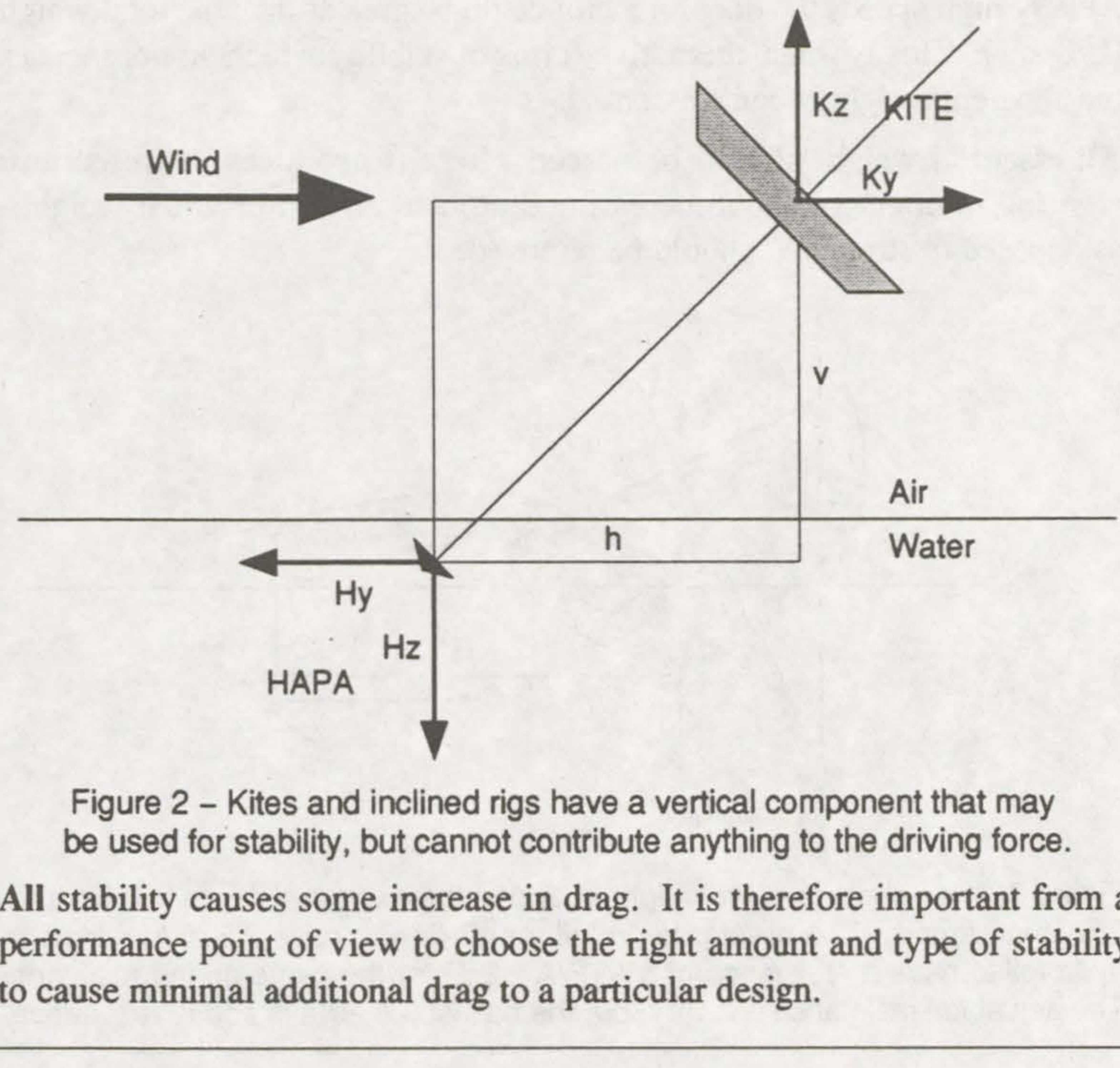


Figure 2 – Kites and inclined rigs have a vertical component that may be used for stability, but cannot contribute anything to the driving force.

All stability causes some increase in drag. It is therefore important from a performance point of view to choose the right amount and type of stability to cause minimal additional drag to a particular design.

For example ballast may be added, but this will create permanent additional resistance. On the other hand a foil at the end of an arm can produce a useful force that is proportional to the square of the speed. The problem with foils is that they do not produce any force when there is no flow and this can cause stability problems when manoeuvring or accelerating.

For craft sailing at below hull speed, i.e. at a Froude number (Fn) < 0.3 [2.0$\sqrt{L}$(m) 1.1$\sqrt{L}$(ft)], the most useful stability is usually in the form of ballast (or cargo) as the additional drag is < 2% [Weight/Drag > 50/1] and this sort of ratio is difficult to achieve by dynamic means. The lower down the weight the more effective it is. Ballast should always be at the bottom of the keel to optimise performance.

The next step is to shift the movable ballast (crew) to windward by using trapezes or outriggers, the alternative being to move the centre of lift (buoyancy) further to leeward by the use of floats. Most performance craft use a combination of these factors to obtain the maximum righting moment for a given all-up weight.

At very high speeds the drag on a hull could be greater than the total weight [L/D < 1]. This is when alternative forms of stability which do not increase the apparent weight become essential.

All essential weight should be placed where it produces the maximum righting moment (without increasing drag) and all non-essential weight – as opposed to strength – should be removed.

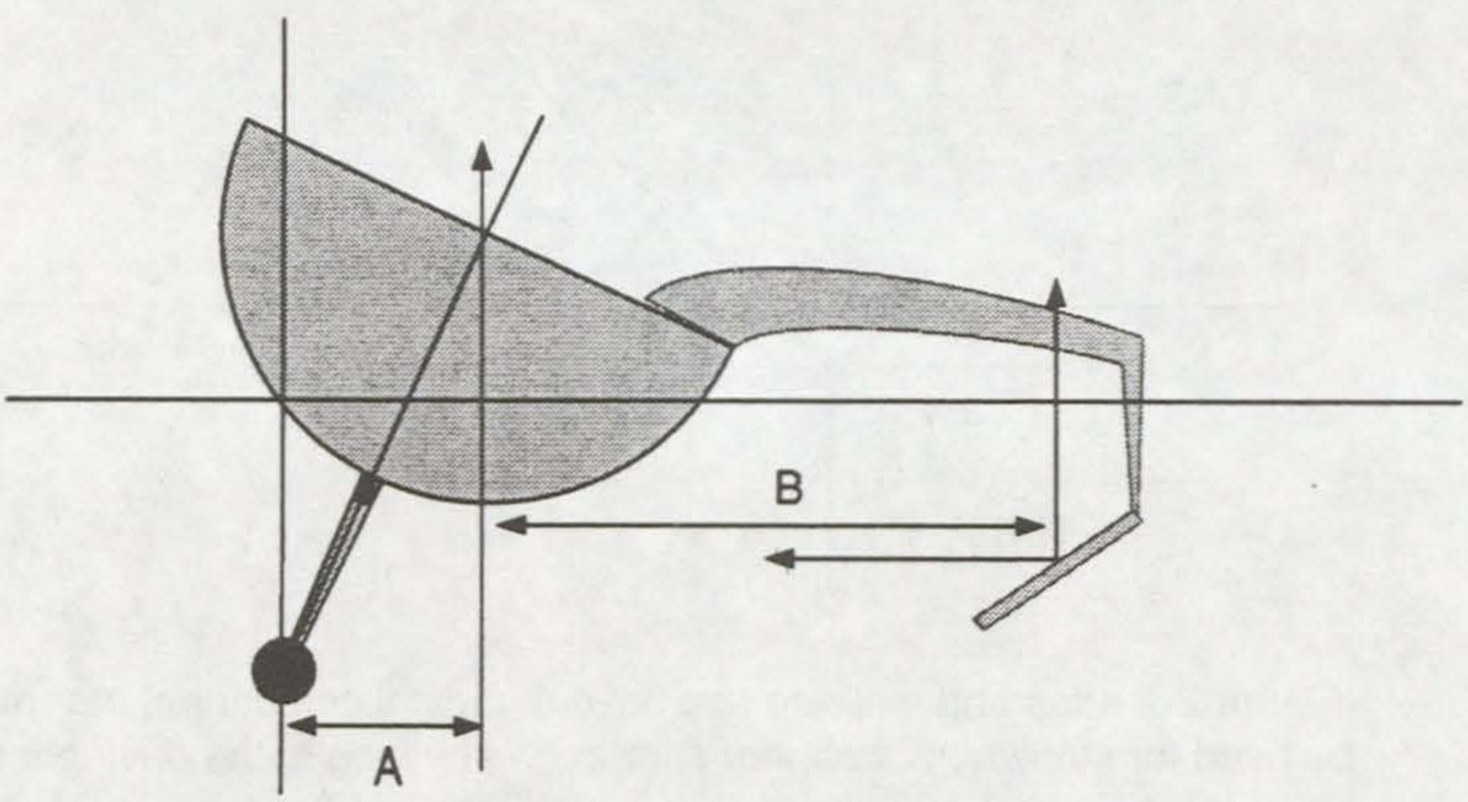


Figure 3. – If ballast or crew weight is added the extra resistance will be about 2% on an arm A. The greater hydrofoil arm B (in this case 2.5 X A) allows the hydrofoil to have a resistance of 5% (B/A x 2%) for the same added resistance. The actual foil resistance will vary, but the ballast will always add to resistance.

Hydrofoils can have a drag as low as 5% of lift [L/D 20/1] in ideal conditions, but the additional drag caused by the supports and ventilation can very easily double the resistance to 10% [L/D 10/1]. Cavitation and ventilation of foils will increase the drag to that of a simple planing surface.

A fully ventilated foil or planning surface can be expected to have a minimum drag in the range of 14%-20% of loading [L/D 7/1 - 5/1], with spray and support struts causing noticeable additional resistance. In order not to be disappointed, high speed designs need to take these additional resistance forces fully into account.

Spray may be good for photographers, but it is also an excellent measure of inefficiency as it wastes energy and not only increases the wetted area (friction), but upsets the airflow around the hull(s) and into the sails. The fastest craft are often the un-spectacular ones because they create so little spray and wash.

When it comes to increasing stability to improve performance it is important that the total additional resistance is significantly less than the increase in thrust. On very high stability yachts such as the Whitbread 60s and the America's Cup yachts not all the ballast is put in the bulb at the base of the keel because the torpedo shaped bulb increases the drag enough to significantly reduce the light weather and off wind performance. Part of the problem is the interference caused by the fin, particularly when producing a side force.

Interference drag is always difficult to predict and has an unfortunate habit of being much larger than predicted. In the aircraft world it can take many hours with full size tests to make significant improvements. Despite the theoretical end plate effect of wing tip tanks, it has been found that the drag can only be minimised for one set of conditions. In all other cases they create a significant increase in drag. This is an area where some systematic research might produce some useful breakthrough for designers.

Using computers to calculate flow predictions is rather like Dead Reckoning (DR) navigation. It is only as good as the information put in and the assumptions made. The actual results have to be compared with the real world and real results. Their predictions are only valid if there is some form of confirmation from the real world. Unfortunately computers do not have their own internal version of the Global Positioning System (GPS) that will check that what they calculate is reasonable or reliable. All unconfirmed computer predictions should be used with great caution. ✔

Optimum angle of Heel

This is when the righting moment and sail forces are optimised. In general the greater the angle of heel the greater the righting moment, but on the other hand the efficiency of the rig is reduced with increasing angle of heel.

For multihulls the optimum angle of heel is normally at the minimum angle at which the entire displacement is taken on the lee hull or foils. In practice, not all this stability can be used if there is to be some safety margin available against unexpected gusts. Monohulls have the advantage that additional stability is available well beyond the optimum angle, but this is at the expense of greater weight and less performance.

For ballasted monohulls, the righting moment initially increases directly with the angle of heel (a straight line on the graph). As the righting moment increases so the corresponding load on the sails also increases and as the sail load increases so the side load on the keel also increases. The load on the sails and keel causes the induced drag of each to increase as the square of their loading. The total additional drag due to the induced drag increases by the fourth power of the angle of heel (θ^4).

Only part of the horizontal component of the sail force can be converted into useful forward thrust. Any vertical component can be used for stability but will only lift or depress the boat and reduce propulsive efficiency.

With the apparent wind on the beam ($\beta = 90°$.) the projected area reduces with the angle of heel, the flow changes from across to up, but with the wind directly ahead ($\beta = 0°$) there is no reduction in apparent area, the effective area reduction with heel is close to Cosine θ (the angle of heel). The angle of attack of the sails is also reduced by Cosine θ which has the effect of reducing pointing ability. At 25° of heel β is effectively increased by 10% and thus VMG is reduced by a similar amount. The propulsive force of the sail varies as the Sine β (apparent wind angle) and also reduces as the Cosine$^{(1+\cos\beta)}$ θ. The basic theory is therefore that the total net sail driving force reduces as approximately the sixth power of the angle of heel (Cosine^6 θ). *(A paper model can be used to visualise what is happening).*

In practice the situation is slightly different as the induced drag on the keel and the heeled resistance on the hull do not normally increase as rapidly as that of the rig. This is due to their better Lift/Drag ratios at which they operate and therefore the range of the correction will be within θ^4 & θ^6.

In figure 4 the reduction in sail efficiency is plotted against the angle of heel for these two values, the real situation being slightly greater than θ^5.

The total effect is that the net effective sail force is approximately:-

$$\textbf{Cosine } \theta^{(a+\cos\beta)}$$

∴ the approximate optimum angle of heel is when:-

Righting Moment x $(\cos\theta)^{(a+\text{Cosine}\,\beta)}$ **is a maximum.**

Where **a** is approximately 5

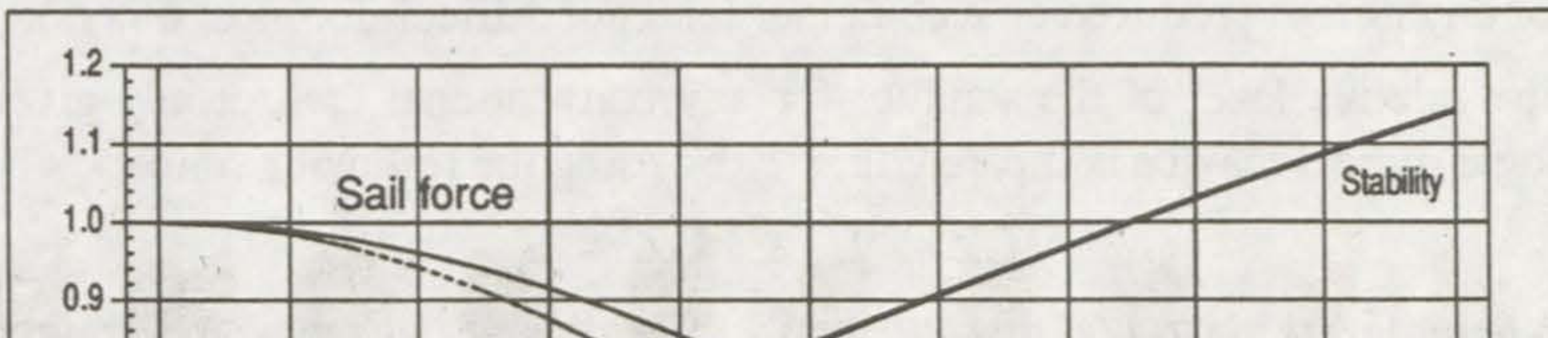


Figure 4 – Optimum angle of heel for stability with and without crew assistance. The sail power curves are plotted between θ^4 & θ^6.

There are two stability curves, the lower one for a conventional monohull without any additional stability from the crew. The upper one where crew and/or water ballast provide a substantial righting moment when upright.

The two stability curves are combined with the sail curves to produce an optimum angle of heel. For θ^6 this is about 22° and for θ^4 27° for a conventional monohull. With help from the crew or water ballast the this reduces to 15,° for the example shown above (with θ^5).

The optimum angles of heel for monohulls is < 20° for a shallow low efficiency keel system to near 25° for a deep efficient one. The optimum reduces to less than 14° for dinghies with the crew providing most of the righting moment. In practice the optimum angle of heel is not critical as the curves are close to optimum over a range of about 5°. For want of any better figures use 25° for cruising yachts and 20° with crew assisted stability. For multihulls the problem is more straightforward. ✔

Stability factor (Gf)

One of the conventional measures of stability is to use ballast ratio.

$$\text{Ballast} \div \text{Displacement} \times 100$$

This tells us nothing about the ballast's position or usefulness. A more practical figure is the Stability factor (Gf), this may easily be calculated for any design produced on a computer (and not difficult for most others).

The relative level of the stability for any conventional craft at any given angle of heel may be compared directly by using the following ratios:

$$\mathbf{GZ \div L \quad \& \quad GZ \div h}$$

Where GZ = horizontal distance between centres of buoyancy and gravity,
L = effective Length of the craft (somewhere between LOA & LWL)
h = ht. of Centre of Effort (CE) above Centre of Lateral Resistance (CLR).
Righting moment (RM) = Displacement (Δ) x GZ

These ratios unfortunately give no information on the weight of the craft or any indication of the actual righting moment available.

GZ needs to be compared with the weight and it is also more useful if the ratio can be made non-dimensional, therefore $\sqrt[3]{\Delta}$. is used.

GZ divided by $\sqrt[3]{\Delta}$ (cube root of the displacement in metres^3 or feet^3).

$$\mathbf{Gf = GZ \div \sqrt[3]{\Delta}.} \qquad \textbf{[1m]}$$

from above

$$GZ = RM \div \Delta$$

$$\mathbf{Gf = RM \div \Delta^{(4/3)}} \qquad \textbf{[1b]}$$

Righting moment divide by displacement (cubic units) to the power ($^4/_3$)

The weight is measured in tonnes (1000kgs), if using lbs & ft, divide by 4 (or 3.967 for academics) to keep the ratios similar. The Righting Moment should be taken at the designed or optimum angle of heel up to a practical maximum of 0.5 radians (28.6°).

The values of GZ / L are in the range of about 0.01, for a square rigger, to > 0.5 for a '*square*' (beam = length) multihull with movable ballast.

The values of GZ / h are in the range of about 0.05, again for a square rigger, to almost 1.0 for a beamy multihull with movable ballast.

On conventional boats **GZ** is the athwartships horizontal distance between a vertical lines through the centre of buoyancy and centre of gravity. With other types of craft **GZ** is the athwartships horizontal distance between the centre of the vertical upward forces (lift & buoyancy) and the centre of the down forces (weight & down loads). The total weight in this case should include all the downward loads acting on the water, as they increase the apparent displacement of the vessel and therefore the drag.

The **Gf** range is approximately:-

Cruising keel boats	0.2
Performance keel boats	0.5
Dinghies	1.0
Sailboards	2.0
Multihulls	3.0
Yellow Pages Endeavour	9.0

Gf will be increased if **GZ** is increased without adding to the total weight.

Gf expresses how the weight contributes to the stability and can be considered to be a more informative version of ballast ratio because it takes into account where the ballast is placed and the actual form of the hull. A convenient outcome is that the figures produced for conventional monohulls are in approximately the same range as the traditional ballast ratio.

Where the structural weight is known it is straightforward to calculate the maximum useful crew and/or ballast weights to achieve the optimum stability, but for fixed ballast and crew weights the overall optimum will in practice usually be less than the maximum figure given by this formula. This is because the increase in weight will increase the displacement/length ratio and also wetted area and other beneficial ratios can deteriorate.

The other important factor in the allowable sail power is the ratio of righting arm (GZ) to heeling arm (h). This represents the ratio of sailforce to weight, but is more difficult to calculate as the centre of effort of the sails moves with changes in twist of the sail and the ratio may be increased by as much as 50% (lower CE) from that calculated from drawings.

For high speed sailing the above may be combined with the stability factor to give a potential speed factor that we might call the **Warp factor (Wf)** and is as follows.

$$\mathbf{Wf} = GZ^2 / (h \times \sqrt[3]{\Delta}) \qquad [2]$$

For a keel boat this is about	0.1
For a sailboard	1.5 +
Yellow Pages Endeavour,	10 +
Y P Endeavour fitted with biplane rig,	16 +

For performance maximise this ratio. It is noticeable how much higher these ratios are for *Y P Endeavour* when compared with any other craft. ✔

Energy Transfer System

Sailing is an energy transfer system that will only work if there is movement of the air relative to the water. The power system consists of the aerofoils (sails and spars) and hydrofoils (keel and rudder). The net forward thrust of this system is used to propel the hull with each factor having an efficiency of less than unity(<1). The thrust that propels the craft will always be less than the total energy input and in most cases much less.

The fundamental task of the rig and foils is to use the available wind and righting moment to produce forward thrust. For maximum performance this force this should be optimised, by means of the size and shape of rig.

The rig only responds to the effect of the strength and direction of the apparent wind being opposed by the available righting moment, but the optimum rig is directly affected by the type of hull & keel used.

Since the righting moment is limited there is a maximum force that the rig can develop for any given wind strength and direction and from this there is a maximum thrust that it can produce.

To simplify the description, the range of conditions where the apparent wind is forward of the beam will be considered, i.e. when the drag forces oppose the forward thrust (F_R). When the apparent wind is aft of the beam drag contributes to the forward thrust, so there is not the same requirement to minimise it.

On aircraft, and particularly gliders, the wing span is increased to reduce induced drag, but the penalty is increased weight and structural complexity.

From an aero-hydrodynamic point of view the greater the height of the rig and depth of keel, the smaller will be the induced drag, reducing as the square of the increase in height or depth. A tall rig and deep fin will have a large capsizing moment, so this option is only available in light winds. In stronger winds there has to be a balance between a reduction in heeling moment and increased induced drag.

The most efficient or useful rig is not the one with the highest lift/drag ratio but the one that produces the maximum forward thrust within the available righting moment.

In practice the optimum lift/drag ratio and therefore aspect ratio varies with the apparent wind direction and the dimensions vary inversely with the apparent wind speed. The sails, are unaware of the hull below and only know the righting moment along with the apparent wind speed and direction. It is therefore possible in principle, to define the basic ratios of a rig from these three functions only. There is an optimum rig for each strength and direction of apparent wind for any given heeling moment, as shown below.

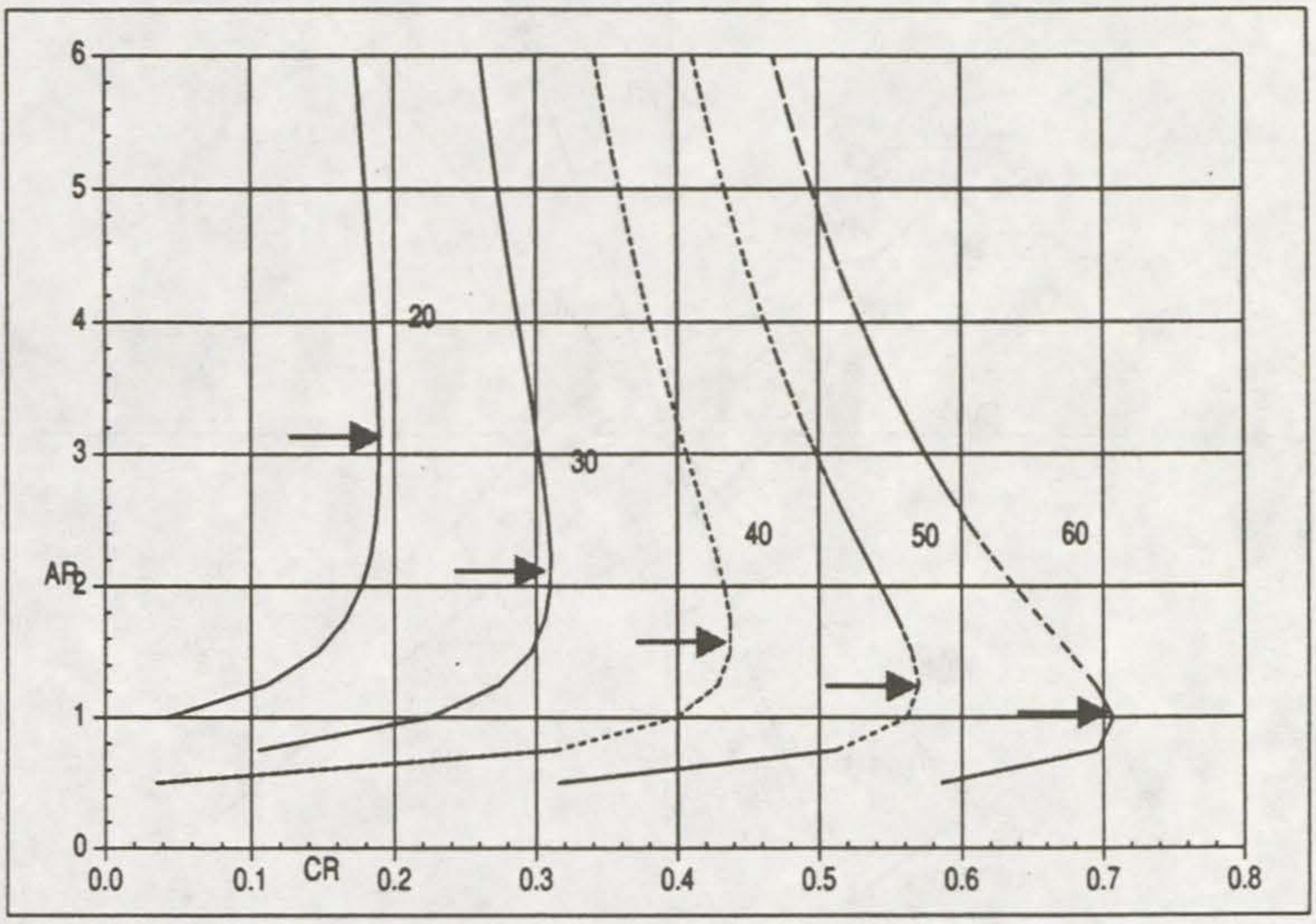


Figure 5 – Optimum aspect ratio for apparent winds from 20° to 60° plots [Lift . Sin β - Cos β . Lift² /(π . AR)] for a constant heeling moment. This is a simplified calculation, but shows the general trend. Note how at 60° the maximum thrust is with an aspect ratio of only 1 and even when closehauled at 20° the optimum is about 3. Also note how much the performance falls off when the rig is the wrong height. This demonstrates the importance of twist control.

These figures are on the whole lower than we are used to. On the other hand ice and land yachts are close winded due to their high speed relative to the wind but use lower aspect ratio sails. They appear to have discovered what 'wet' sailors have not – that if heeling moment is limited a low aspect ratio rig will give more thrust even when sailing closehauled.

The power produced by the rig needs to equal the resistance of the hull. A conventional hull when going to windward at optimum speed [Fn = 0.3 2.0√L(m) 1.1√L(ft)] has a drag of about 2% of displacement, plus the drag of the keel, rudder etc. Performance multihulls can go to windward at near twice this speed and the hull resistance is more likely to be in the order of 10% of weight plus the induced resistances. ✔

Course Theorem revisited

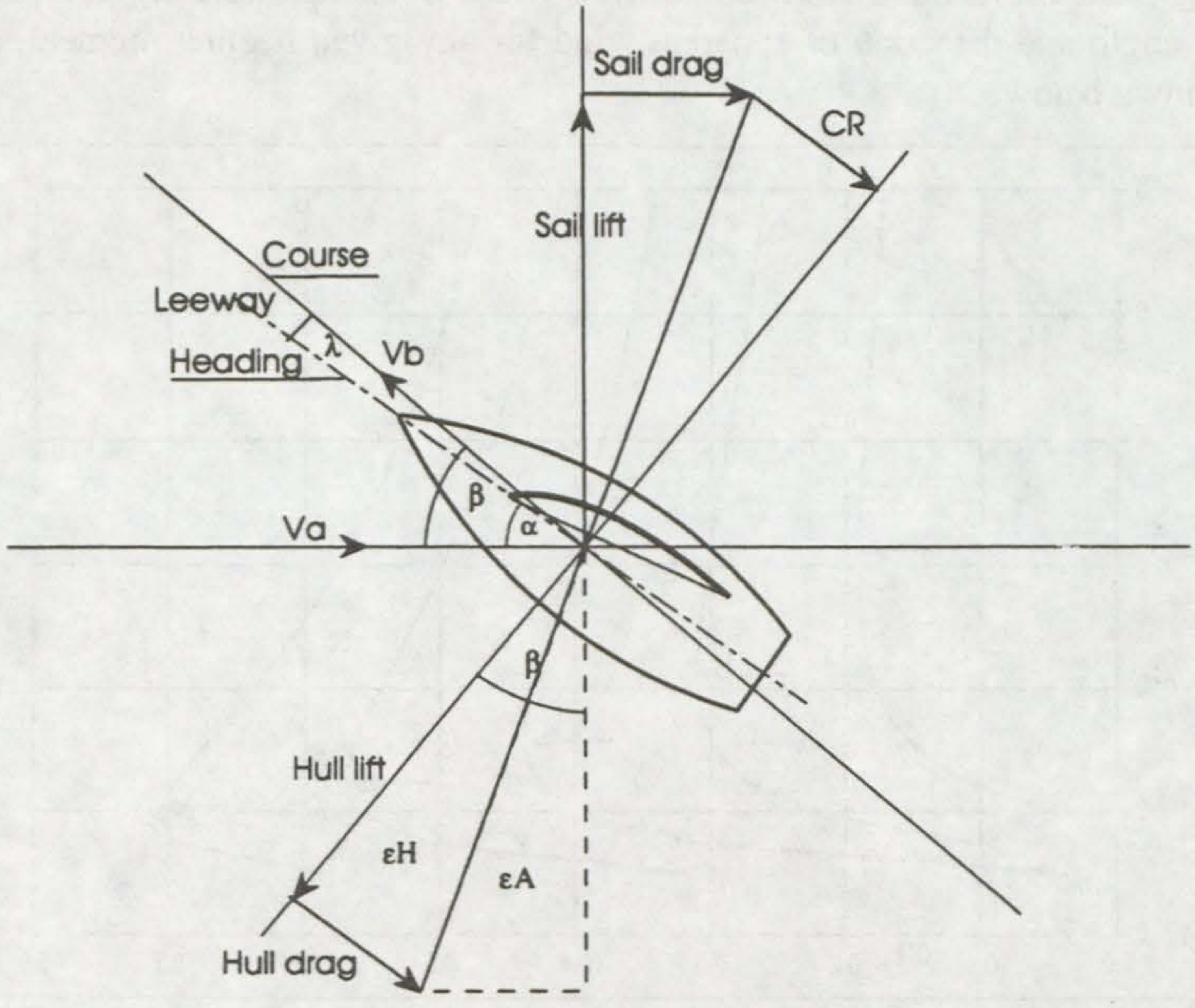


Figure 6 – On any heading, the angle β between the apparent wind direction and the course sailed, equals the sum of the drag angles.

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

and is optimum when $\varepsilon_A = \varepsilon_H$

ε_A	=	Aerodynamic drag angle,
ε_H	=	Hydrodynamic drag angle
V_a	=	Velocity of Apparent wind
V_b	=	Velocity of boat in direction of Course (not Heading).
α	=	Angle of attack of the sail
β	=	Apparent wind angle relative to Course
λ	=	Angle of Leeway, difference between Heading & Course
C_R	=	Hull resistance coefficient relative to Course
C_X	=	Force coefficient along the fore and aft axis of the hull
C_Y	=	Force coefficient across the axis of the hull
C_Z	=	Vertical force coefficient relative to the horizontal

(C_X, C_Y & C_Z, are the coordinates used in wind tunnel testing).

The traditional course theorem approach is as in fig 6. When optimised the aero and hydrodynamic drag angles are equal. If we look at this in a slightly different manner; we want to maximise C_R. For this we need the polar curves (lift against drag) of the rig and the underwater foils. These are plotted on the wind and course axis respectively and are represented by curves OAC & OBC below.

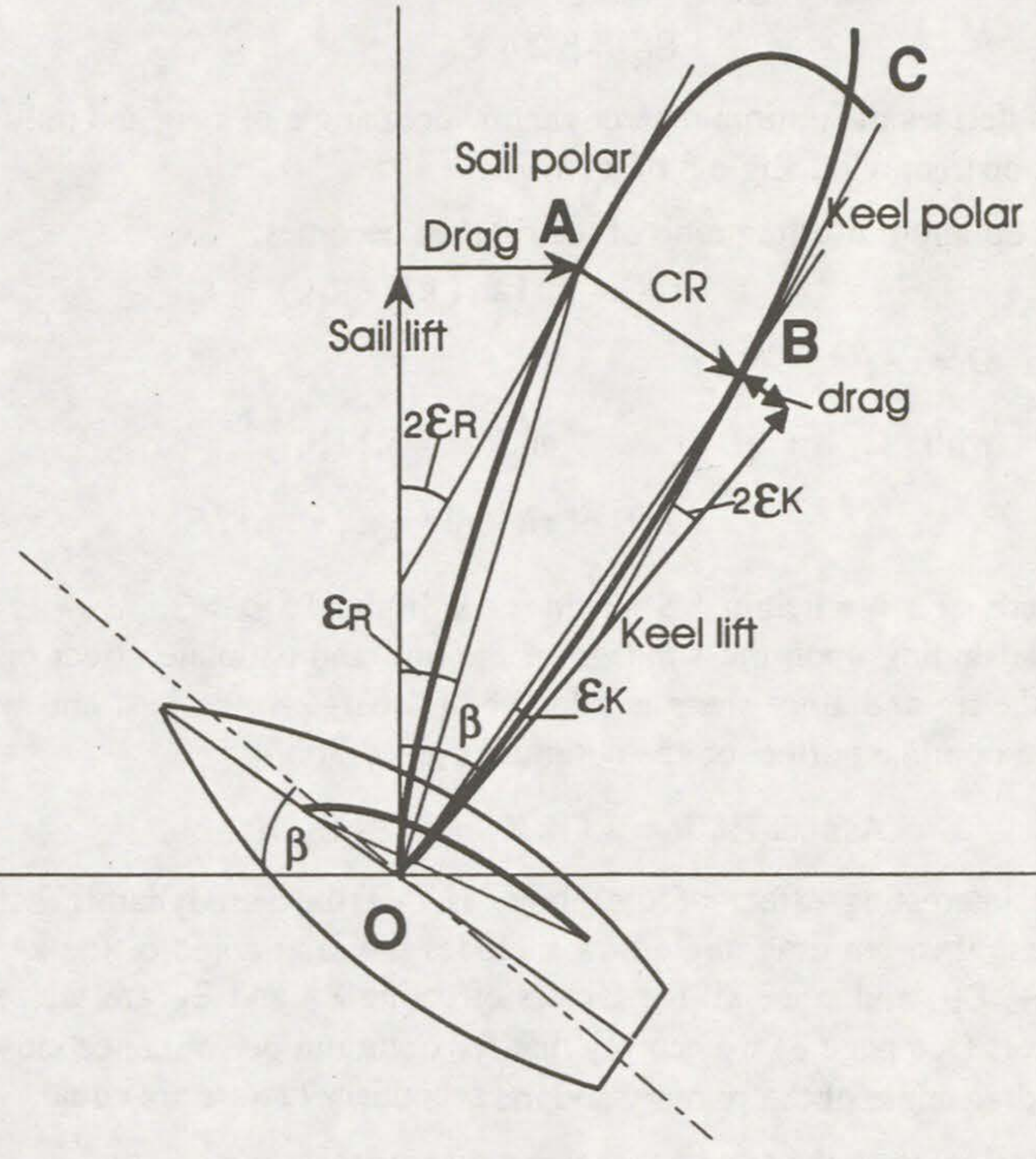


Figure 7 – The optimisation of the sail and keel polar curves.

The polar curves of the rig and keel are plotted for a given apparent wind velocity and boat speed. For this it is assumed that the drag increases as the square of the lift and therefore these curves are taken to be parabolic (within the part that is of interest). If the loads are allowed to become too large the two curves meet at C and there is no propulsive force available.

The drag angles of the rig and keel are represented by the angles ε_R & ε_K. The maximum thrust from the rig is when the length C_R is a maximum.

This will occur when the two curves are parallel at points A & B and the slope of the curves is represented by the angles 2 ε_R & 2 ε_K, and equals angle β.

Therefore;

$$\beta = 2\,\varepsilon_R + 2\,\varepsilon_K \qquad [3]$$

and thus the drag angle of the rig

$$\varepsilon_R = \beta/2 - \varepsilon_K \qquad [4]$$

This defines the optimum aerodynamic drag angle of a rig and hull for apparent wind angle β of up to about 40°.

The optimum lift/drag ratio of the rig then becomes;

$$L/D = 1/\,\mathrm{Tan}\,(\beta/2 - \varepsilon_K)$$

with $D = L^2/(\pi\,AR)$

with $C_{Lift} = 1.0$ and $\pi = 3.1416$

$$\textbf{L/D of rig only} = \pi\,.\,k\,.\,h^2 / S \qquad [5]$$

Where h = height S = area k limits 0.5 <–> 2,
(k depending upon the windage of the hull and endplate effect of the hull on the rig and since there is a factor of 4 between the best and worst this has a dominant effect on the optimum aspect ratio.)

$$\textbf{Aspect Ratio} = 1 / [k.\mathrm{Tan}\,(\beta/2 - \varepsilon_K)] \qquad [6]$$

The interesting effect of the above is that the aerodynamic half of the course theorem drag angle now includes the drag angle of the keel ($\beta/2 = \varepsilon_R + \varepsilon_K$) and since all the factors effecting ε_R and ε_K are the secondary factors (see page 8) we can say that for optimum performance close hauled the drag angle of the primary and the secondary factors are equal.

The addition to the course theorem now reads:-

On headings on or near closehauled, the angle between the apparent wind direction and the course (β) equals the sum of the drag angles of the Primary and Secondary factors.

This is only valid as long as the polar curves are approximately parabolic. The more general term is to take the slope of the rig and keel polar curves and F_R will be a maximum when:-

$$\beta = \tan^{-1}(\delta D_{rig} / \delta L_{rig}) + \tan^{-1}(\delta D_{keel} / \delta L_{keel}) \qquad [7]$$

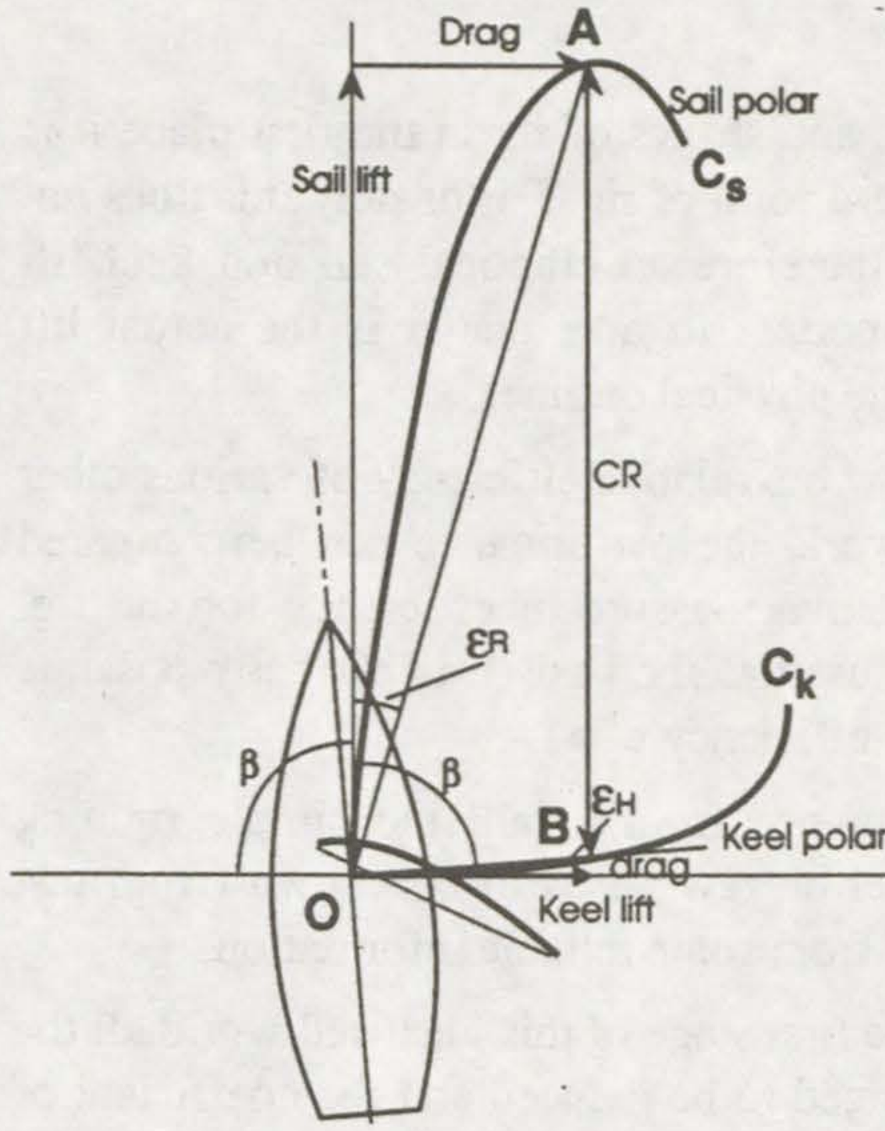


Figure 8 – With β at 90° the assumption that the polar curves are parabolic is no longer valid and therefore the drag angles are no longer equal. But for maximum C_R the curves at points A and B will still be parallel. At this point the sail will be partially stalled.

With the point C_S and C_K far apart it is difficult to obtain a setting of the sail that will produce no drive, except by releasing the sail completely and obtain zero thrust at point O.

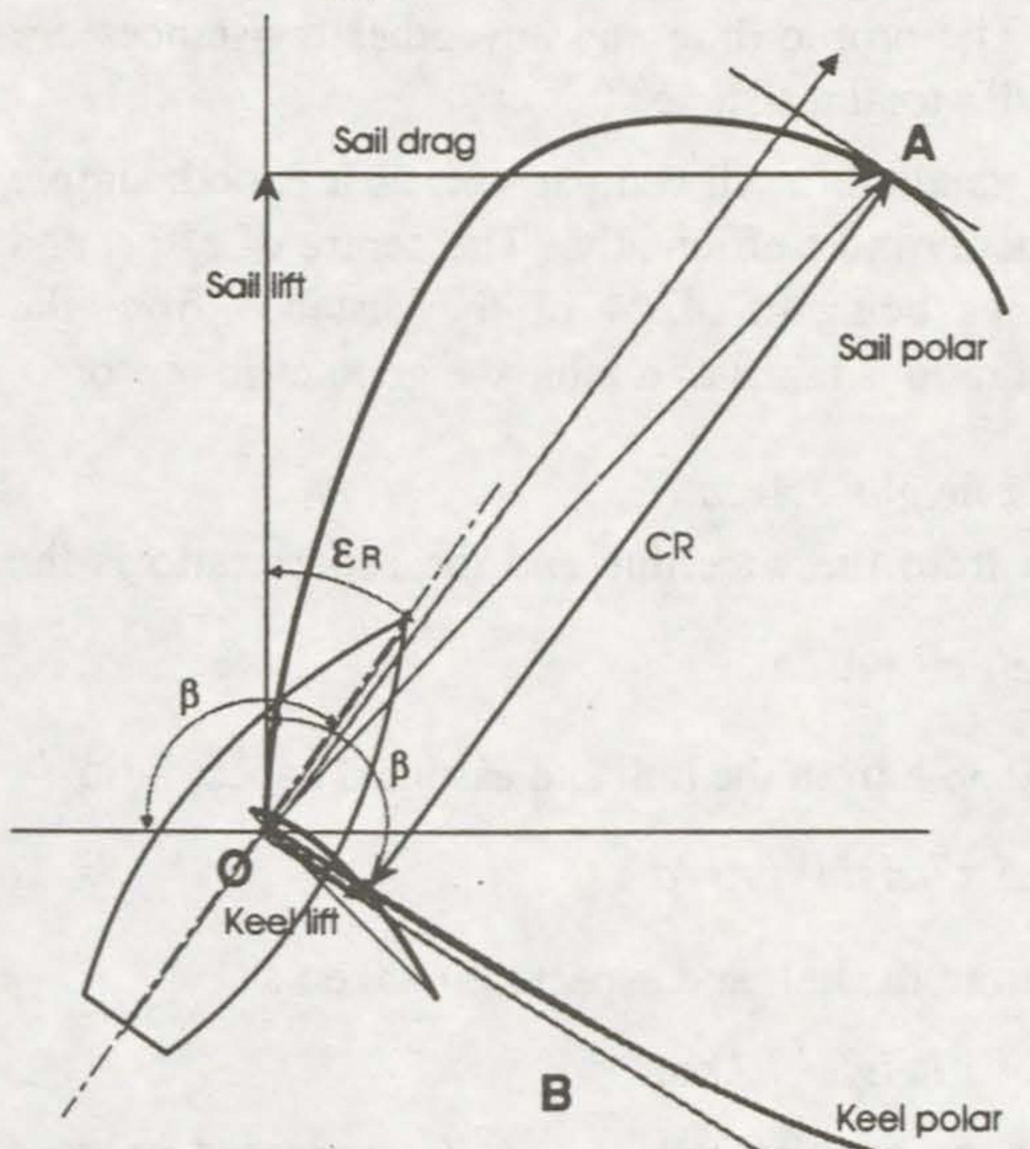


Figure 9 – with β at 130°. The polar curves of the rig and keel are still parallel at points A and B. In this case the drag of the sail is contributing to the total thrust (C_R).

The aerodynamic requirements are therefore for the optimisation of both the lift and the drag. This is an unusual requirement, but would indicate that vortex lift would be best for this and would indicate an aspect ratio of about 1 would suit this best. Neither a conventional mainsail nor tall spinnaker would be expected to be efficient in these conditions.

The course on which the sail force is all forward, with no heeling is when:

$$\beta = 90° + \tan^{-1}(C_{Drig} / C_{Lrig}) \qquad (\varepsilon_K = 0) \qquad [8]$$

With optimum C_{Lrig} about twice C_{Drig} $\beta = 115°$. ✔

Standard Rigs

In order to compare different sizes and shapes of rig in the first place it is first necessary to establish a standard form of rig. Fortunately this does not have to be practical or real and therefore an elliptical sail and keel lift distribution is assumed. It is important to note that it is the actual lift distribution that is important, not the physical outline.

The standardised rig is used to show the relative efficiency of various other rig options and then in the real world the performance can be compared with the predictions to give a relative measure of efficiency for the rig. Since a single simple sail form is used as the basis it is perfectly possible that a real rig could have a relative efficiency of >1.

To calculate the standard performance from a hull the simple running resistance of the hull, with no heel or yaw needs to be known (from test tank results etc) or estimates made from some reliable information.

To simplify the calculations for the first stage of this idealised world all the drag from the rig and foils is assumed to be induced and the coefficient of lift is taken as 1 ($C_L=1$). The profile drag and any other resistances are assumed to be part of the hull's total resistance (C_R).

The Mk I rig is used as the standard for all comparisons as it is both simple to define and fits in with theory most efficiently. The centre of effort and lateral resistance is taken as being at .4244 of the distance from the waterline (WL). The aspect ratio is taken as double the geometric one or

$$2 \times height^2 / Area.$$

Mk II has centres at 0.5 h from the waterline and the aspect ratio is the geometric one at

$$height^2 / Area.$$

Mk III centres are taken at 0.38 h from the hull and assumed aspect ratio

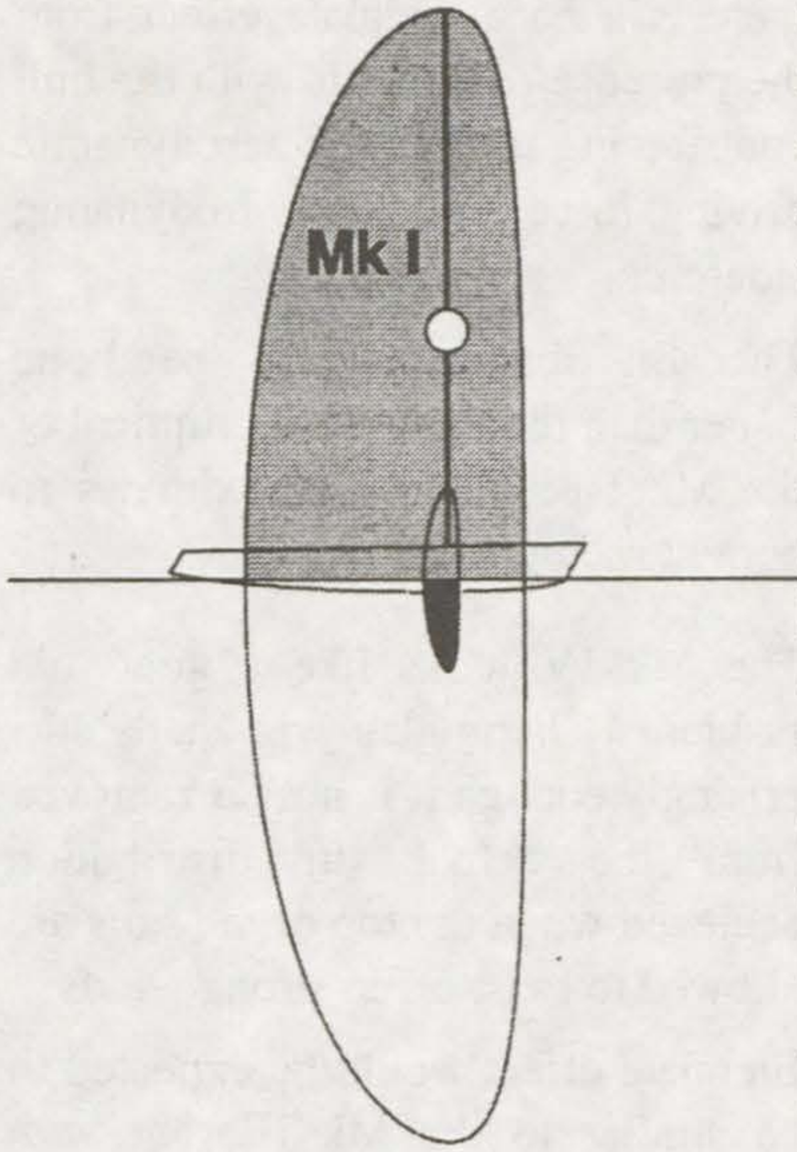
$$1.5 \times height^2 / Area.$$

Mk IV centres are at .33 h from the hull and aspect ratio taken as

$$1.4 \times height^2 / Area.$$

1.5 is used with Mk III for the endplate effect and 3% increased induced drag over Mk I. For the Mk IV 1.4 allows a further 6% for the induced drag of the triangular sail form. This is nearly twice that quoted in ref 1 p17 and therefore the figures will underestimate the efficiency of these two rigs.

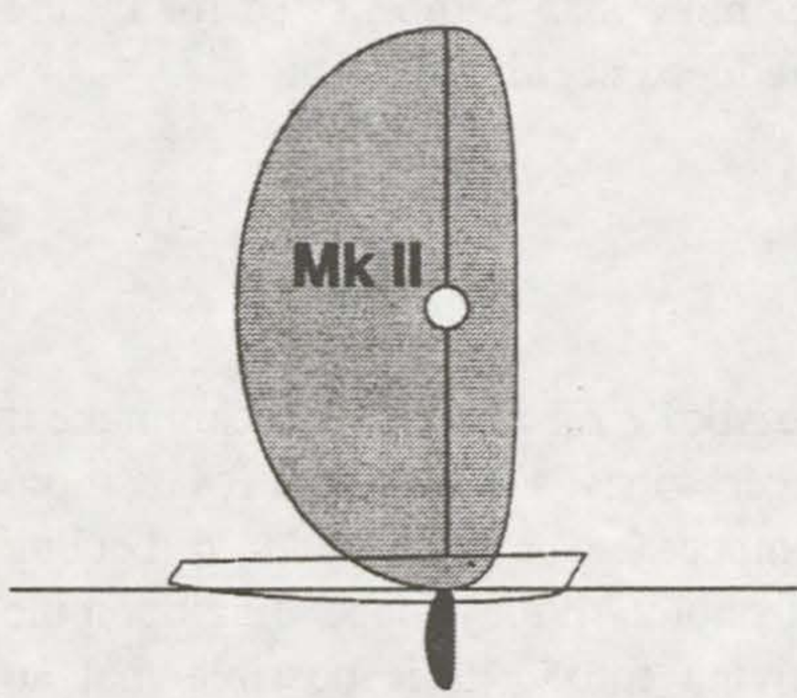
Conventional aerodynamic theory states that if one end of a wing is put up against a surface such that there is no leakage of air around the end the aspect ratio will be doubled. This assumes that there is another half to the wing creating a mirror image.



Again using the conventions of aeronautics, both foils below and the sails above are considered to continue to the surface and the shaded part of the hull contributes to the forces developed by the sails and keel.

The Mark I rig also assumes the theoretically ideal semi-elliptical lift distribution with the water surface giving a full mirror image effect.

Assuming no twist in the sail both the centres of pressure are taken as being at 42.4 % of height above and below the waterline.

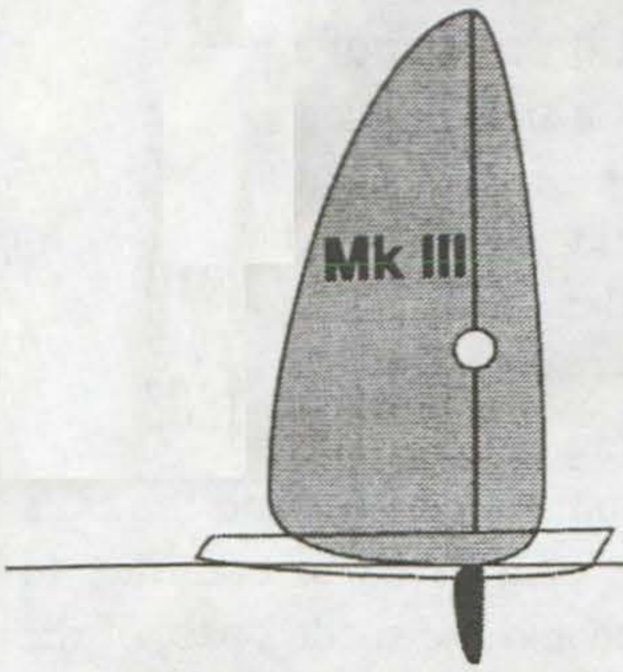


Figures 10 & 11 – All rigs (and keels for that matter) have a theoretical mirror image as shown in fig. 10. These have been omitted from the following drawings for sake of space and clarity.

The Mark II rig assumes that there is no end plate effect from the sea surface and therefore both the sail and keel have half the effective aspect ratio of the Mark I rig.

This is less efficient due to higher heeling moment and increased induced drag and is probably close to the case of rigs where the sails are set clear of the deck and when reaching.

The centre of effort is at mid height.



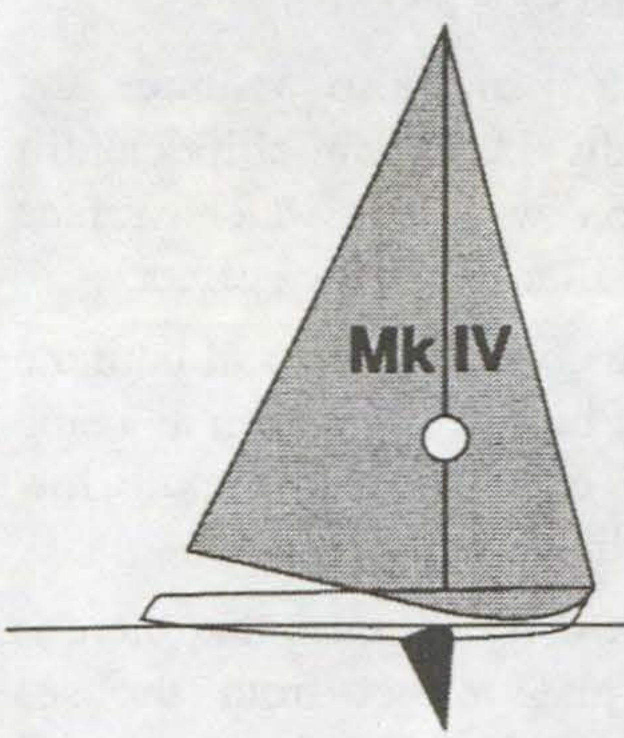


Figure 12 & 13 – these rigs are assumed to have an endplate blocking factor of 55% and to this is added the increased induced drag over the Mk I rig.

The Mark III rig is nearer to the true situation in that it is assumed that there is a 55% endplate effect from the presence of the hull, with the hull contributing to both the aerodynamic driving force and the hydrodynamic sideforce.

The lift distribution is parabolic rather than the theoretical elliptical of the Mk I & II and approximates to current racing rigs.

The Mk IV looks like a good old fashioned bermudan rig and surprisingly enough it is not far removed from the actual lift distribution achieved when the top of the sails are allowed to twist off in strong winds.

Endplate effect would be expected to be similar to the Mk III, but with slightly increased induced drag due to the triangular lift distribution. This is more than compensated for by the reduced heeling moment.

The reduced heeling moment from the Mk IV rig combination can make it a competitor to the Mk I rig in stronger winds. For although it has more induced drag this is more than compensated by the reduced heeling moment, so that for a given amount of stability it may (depending upon the hull configuration) produce more driving force. It is possible that an optimised rig may produce a better performance than the idealised Mk I rig and the relative efficiency would then be > 100%. One of the ways which this can be achieved off the wind with relatively unstable boats is with a multi masted low rig that can produce more thrust for a given heeling moment than a single tall one (AYRS 111 pages 53 - 54).

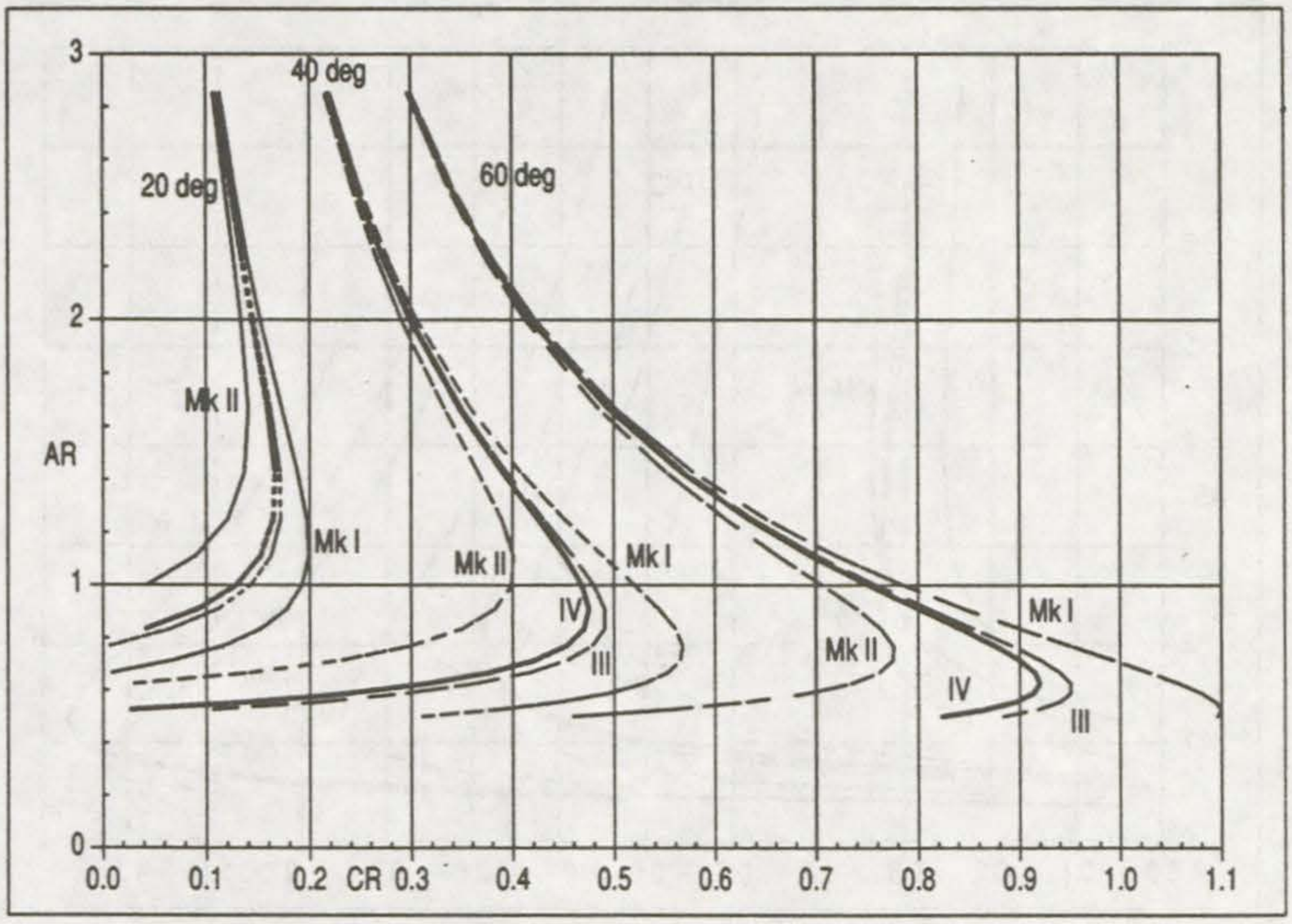


Figure 14 – Plots forward thrust against Aspect Ratio for apparent wind angles ($\beta - \varepsilon_k$) of 20° , 40° & 60° for a fixed height of rig. The message here is that it pays to pile on the canvas, even closehauled, if you can find a practical way of so doing.

The above shows that the Mk I rig is the most efficient, but once sheets are eased the endplate effect of the hull is lost and it is likely that the performance of any real rigs would be nearer Mk II. In all cases the optimum aspect ratio is low and it pays to set large amounts of sail, even when close hauled.

There are severe limitations to low rigs because once the sail starts to spill beyond the ends of the hull their efficiency drops off noticeably. Thus there are practical limits to low aspect ratio rigs for going to windward.

The rule of thumb for the sail area on square riggers was length^2, which gives in practice an aspect ratio of a little over one. This is not far removed from the conclusions of the above graph. So our ancestors found out by trial and error what we can now deduce by computer!

In all the discussions here the geometric aspect ratio is taken as that of the whole rig and not that of individual sails. The calculation includes the total height and the total area and not just the nominal measured areas.

$$\text{Geometric Aspect Ratio} = \text{Height}^2 / \text{Total Area}$$

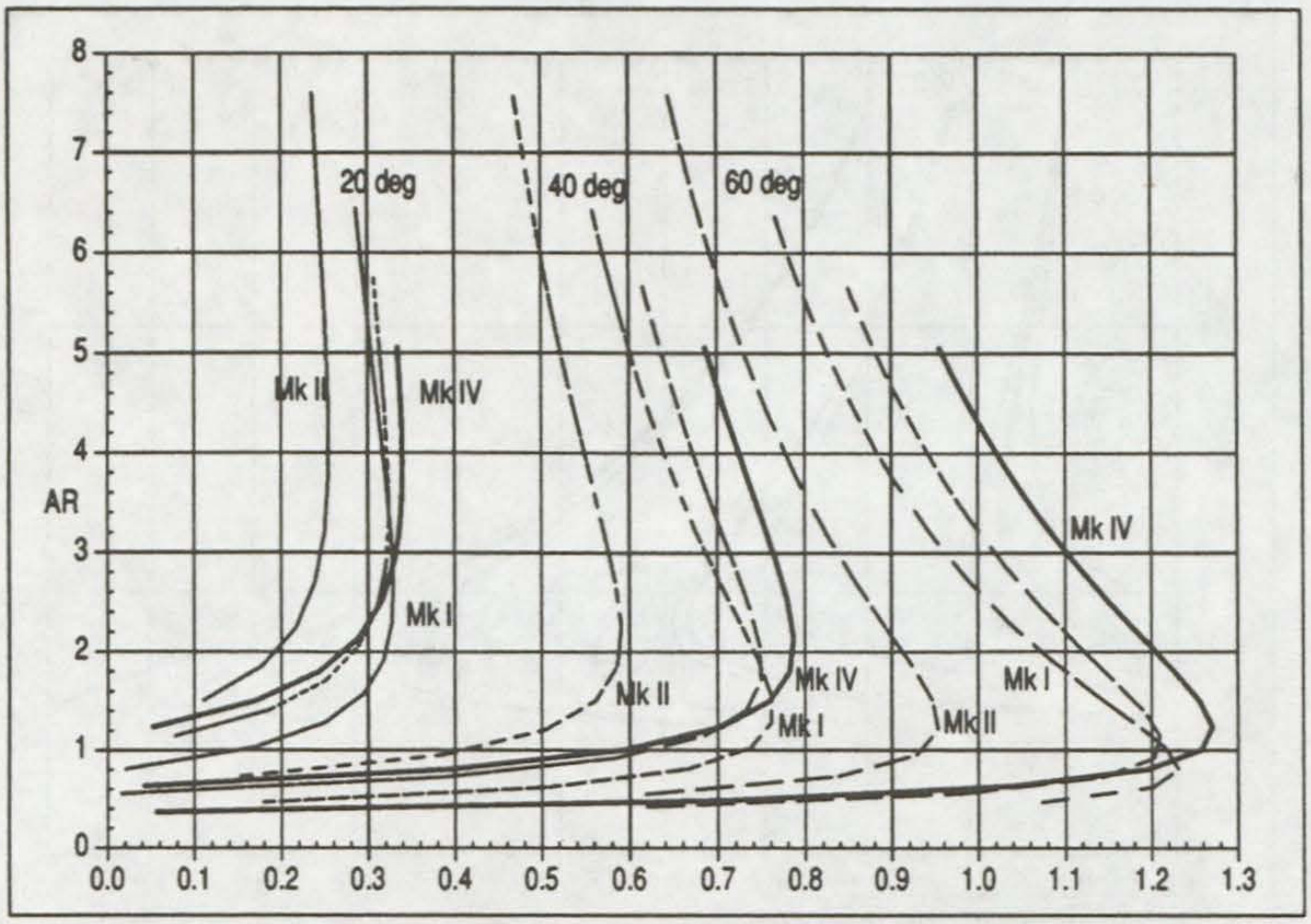


Figure 15 – The net thrust from the rig with a constant heeling moment, for apparent wind angles ($\beta - \varepsilon_k$) of 20°, 40° & 60°

The notable result from the above graph is that the Mk IV (the triangular bermudan) rig provides more thrust than the theoretically ideal Mk I. This is basically due to the fact that although the induced drag is greater the reduction of heeling moment more than compensates. The triangular rig has a higher aspect ratio for any given heeling moment.

This is in fact borne out in practice as we know that a near elliptical sail is good in lighter conditions, but when the wind starts to freshen the top of the sail is eased out and the wind spills from the top of the sail giving a nominal triangular lift distribution.

The optimum power occurs when the maximum of the allowable drag is used as induced, rather than profile and surface drag. Thus boats with low windage and a low drag wing mast should have a lower aspect ratio than a conventional boat for the same apparent wind angle of ($\beta - \varepsilon_K$).

The windage of the hull and crew will increase the drag and mean that the real AR would have to be higher than the figures suggested in order to compensate. It is thus equally important to reduce wind resistance of the hull and crew as it is for any component of the rig. It is surprising how often one sees a racing boat with a light weight low windage rig, only to find that the crew are dressed up in a high fashion, high windage mode !

If the lift/drag ratio is lower than required then β will be increased to compensate. Equally if the ratio is higher β will be reduced – yes the crew's dress has a direct bearing on β and VMG ! When is sailing going to catch up with the cycling world and realise that the windage of everything is very important for performance ?

Only if sail area is limited does it pay to use a higher L/D ratio (taller rig), but this will inevitably produce less performance than an optimum area, low rig. The optimum L/D ratio for the sails is lower than is the standard today because we are used to the racing rules limiting the sail to well below the ideal area for maximum performance.

As the area is reduced by reefing, so the fixed windage of the hull becomes a greater proportion of the total resistance and the L/D ratio of the sails needs to be improved when reducing area (or the apparent wind angle β has to be increased, or both). .

Designs free from restrictions should go for plenty of sail area low down and minimum windage from everything and everybody. Performance machines such as land and ice yachts as well as classes such as the International 14s and the Ultra/Ultimate 30s all go in for low aspect ratio rigs with lots of area. This is what is needed for real performance. ✔

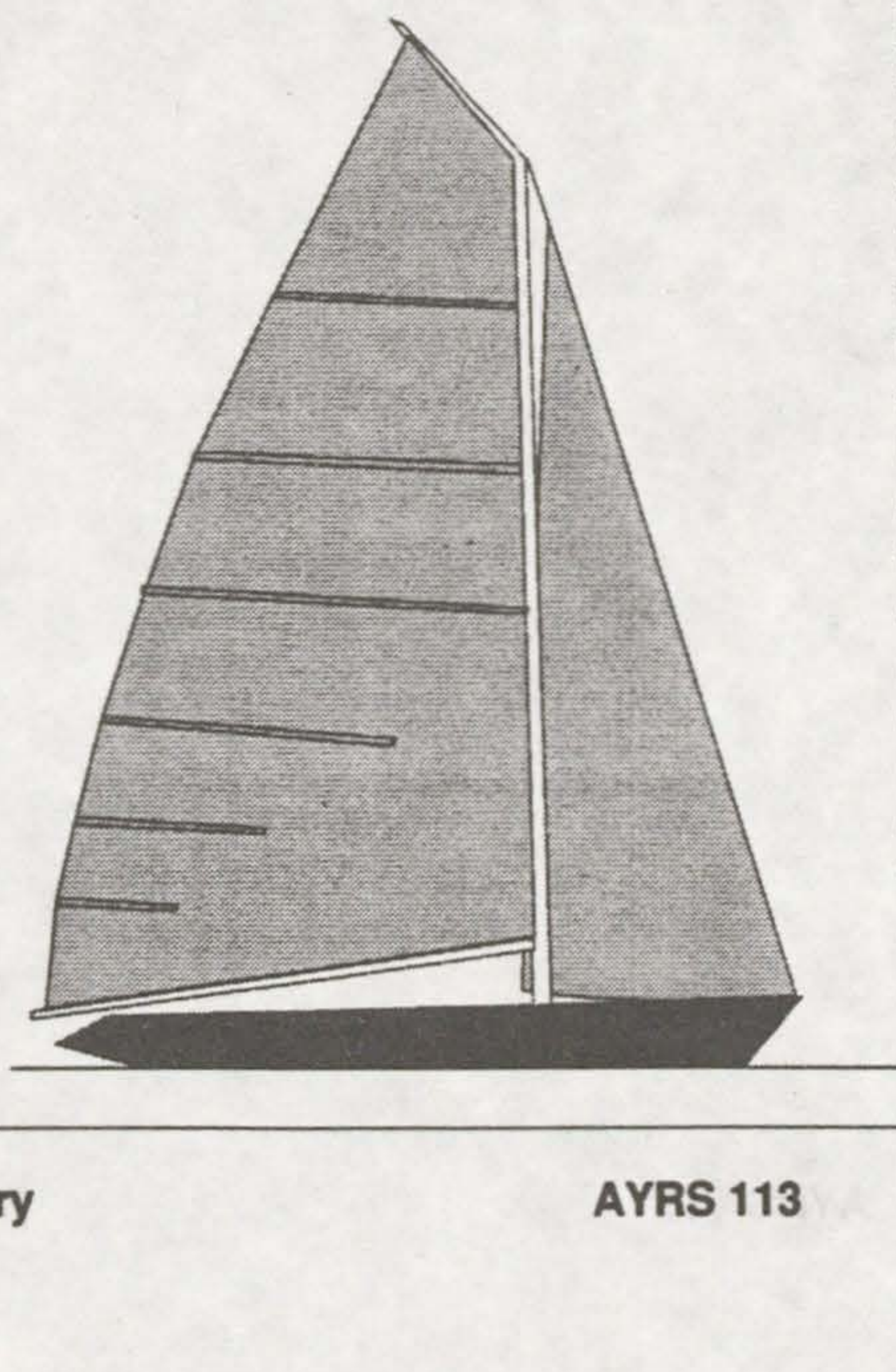


Figure 16 –
Some features of an aerodynamically efficient sail plan:- Large area, low aspect ratio with over rotating mast. 85% forestay for windward work. Raked mast head for both windward performance and vortex power off the wind. Maximum length leeches. Tacks of each sail in clear air. Jib tacked to bow, but clew and 20% forward of it clear of the deck to allow a powerful lower vortex. Main boom drooped. The positioning of the battens can have a marked effect on the development of the trailing vortices and the total drag. Deck, cockpit and crew should all be aerodynamically clean.– Practical solutions may reduce efficiency.

Sail forces

All aero or hydrodynamic forces come from the difference in pressure between the two faces of a foil. Anything which reduces this pressure difference will reduce the lift force produced.

Drag is the force produced in line with the flow and it is divided into frictional, profile and induced. The maximum theoretical coefficient of drag (C_D) is 2.0, but in practice it is usually less than 1.2.

Frictional and profile drag are due to the shape and finish of the surface. Anything done to minimise these will help performance.

Laminar Flow is possible around the foils and hull in calm and still waters (lake sailing), but in tidal waters it is probably not achievable due to the natural turbulence of the water. The maximum force produced by sails is limited under laminar flow conditions to C_L less than1. Anyone interested in this area and operations at low reynolds numbers should consult one of the many good books on model aircraft aerodynamics.

Induced drag is the drag caused by the leakage around the ends of a foil. It is proportional the square of the lift force and can only be reduced by increasing the effective span of a wing or height of a rig (and keel).

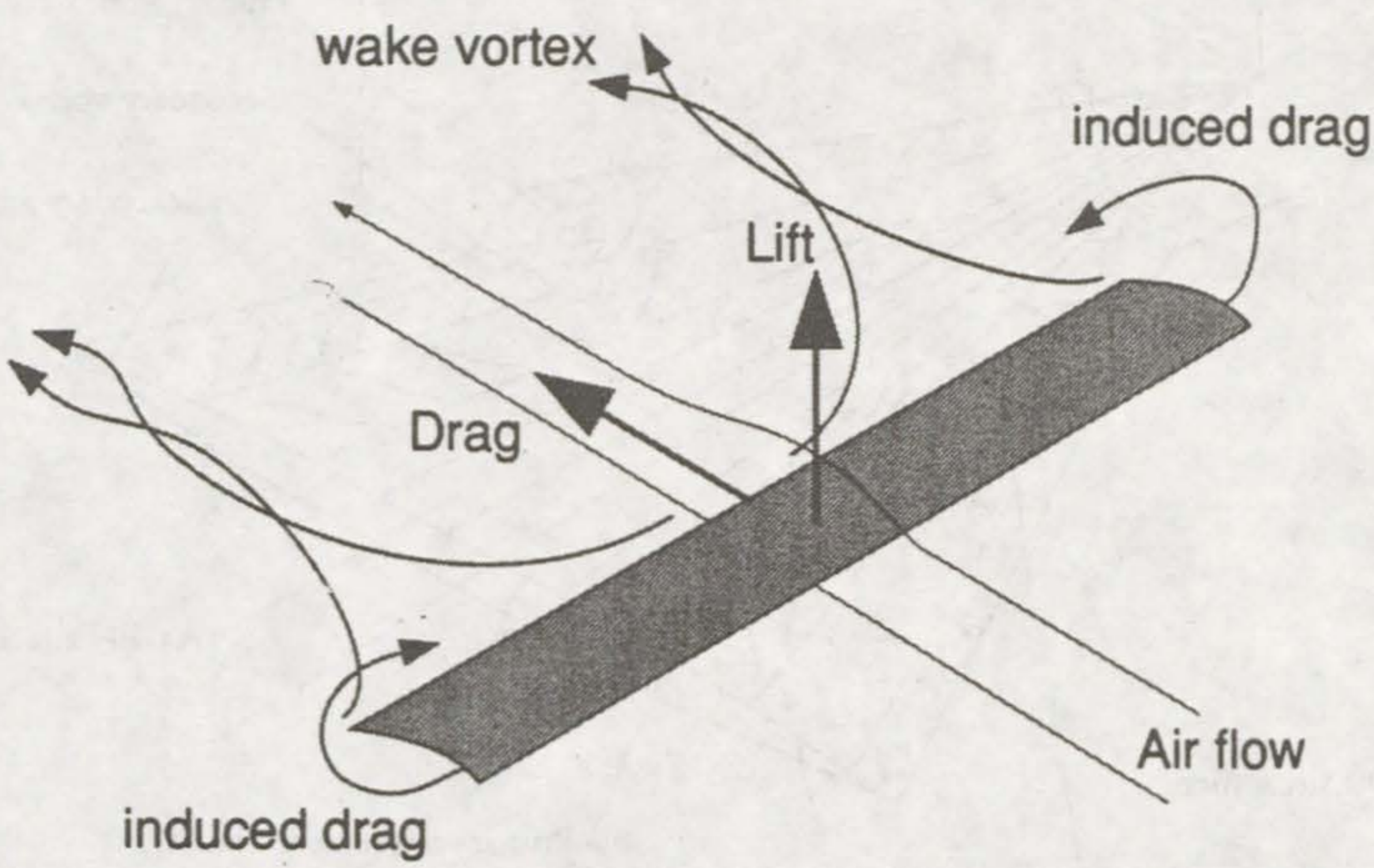


Figure 17. – Lift, Drag and induced drag conventions on a wing.

Lift is the force produced perpendicular to the flow (and need not be vertical). In most cases it is considerably larger than the drag force, with a physical maximum of $C_L < 4.0$ and more like 1.0 – 1.6 for any real sail.

Lift comes in two forms: potential and vortex.

Potential lift is caused by the difference in pressure on either side of the foil and is caused by the flow on the leeside having a longer path and higher speed of flow. This is normally termed two dimensional flow and is what is demonstrated in wind tunnels when the test piece runs from wall to wall.

Vortex lift is caused by the flow around the the ends of a foil and produces its force with the low pressure in the centre of the swirling flow.

High aspect ratio foils (glider wings) have predominantly potential two dimensional flow at all angles of attack up to the stall. Low aspect ratio foils such as Concorde have predominantly vortex lift at higher angles of attack and are much more difficult to stall. In practice all foils have a combination of both types of lift. Potential lift also produces a series of small vortices on the trailing edge. ✔

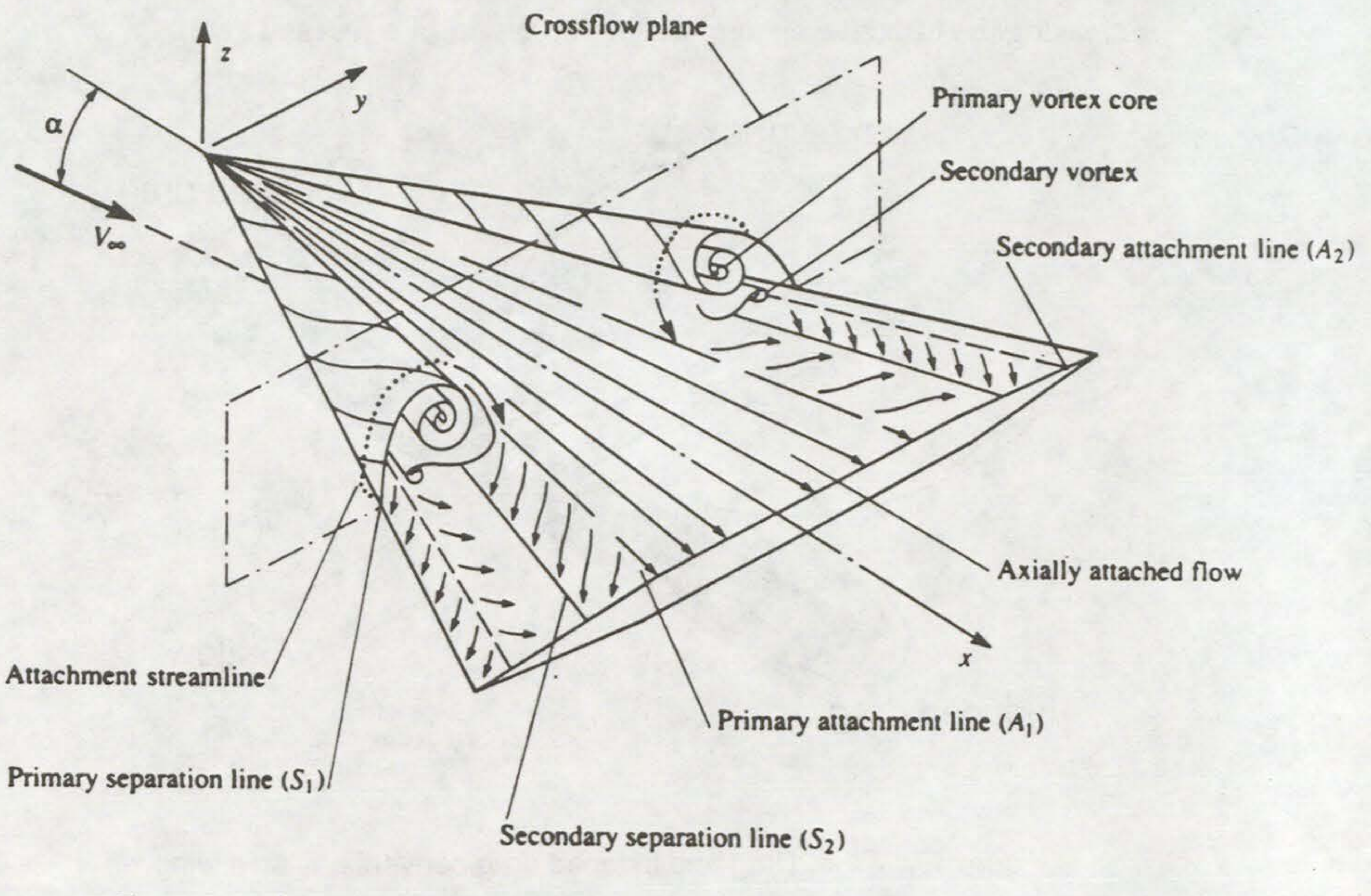


Figure 18 – Vortex flow over a delta wing (by John Stollery, Cranfield)

One or more Sails

Which is more efficient one sail or a multi sail system? There are two reasons for splitting up the sails, apart from the practical one of handling.

When trimming headsails there is frequently talk of closing the slot in light conditions and opening it in stronger winds, but what does this really means in practical terms, what is actually happening?

There are two different and opposite effects with slotted foils and biplanes.

Biplane theory

Less induced drag for a given (span) heeling moment.

Induced drag (caused by the lift) is dependant upon the span squared of the wing as this controls the leakage of pressure around the tip and therefore the drag produced. The greater the wing span (for the same load) the less is the induced drag.

When span is limited the induced drag may be reduced by splitting the total load between two (or more) wings (usually of approximately the same span), but the closer the wings are together, the more is there mutual interference and results in less benefit.

The benefits of the multi-planes reduction in induced drag comes from keeping the foils apart (measured across the flow).

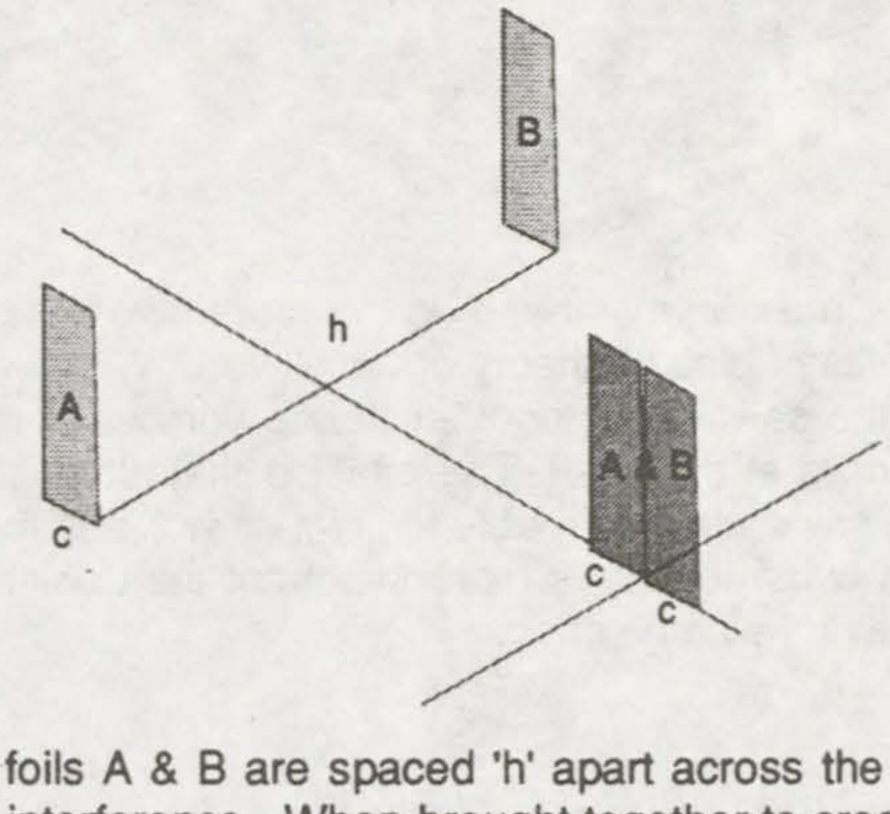


Figure 19 – Two foils A & B are spaced 'h' apart across the line of flow with virtually no mutual interference. When brought together to create AB they have the same total load but double the induced drag. The level of interference is shown in the following graph and it assumes that the loading and dimensions of the foils are identical. Biplane theory indicates that it is only the across flow dimension that matters. The stagger up or down the flow has virtually no effect on the total drag.

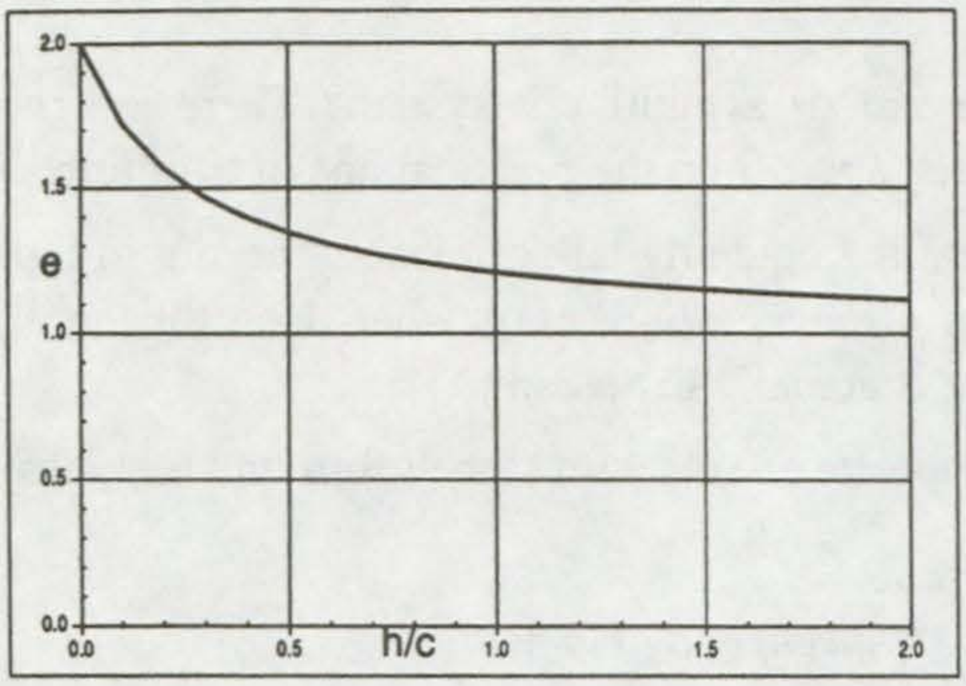


Figure 20 – Biplane factor 'e' (1+ σ) is plotted for h/c (distance apart / chord).

The interference effect is:–

$(1+\sigma) \div (\pi \times AR)$ [9]

where

$\sigma = AR \div (AR + 12 \times h/c)$

With the distance at two chords the interference is only an additional 10% and the heeling moment reduced.

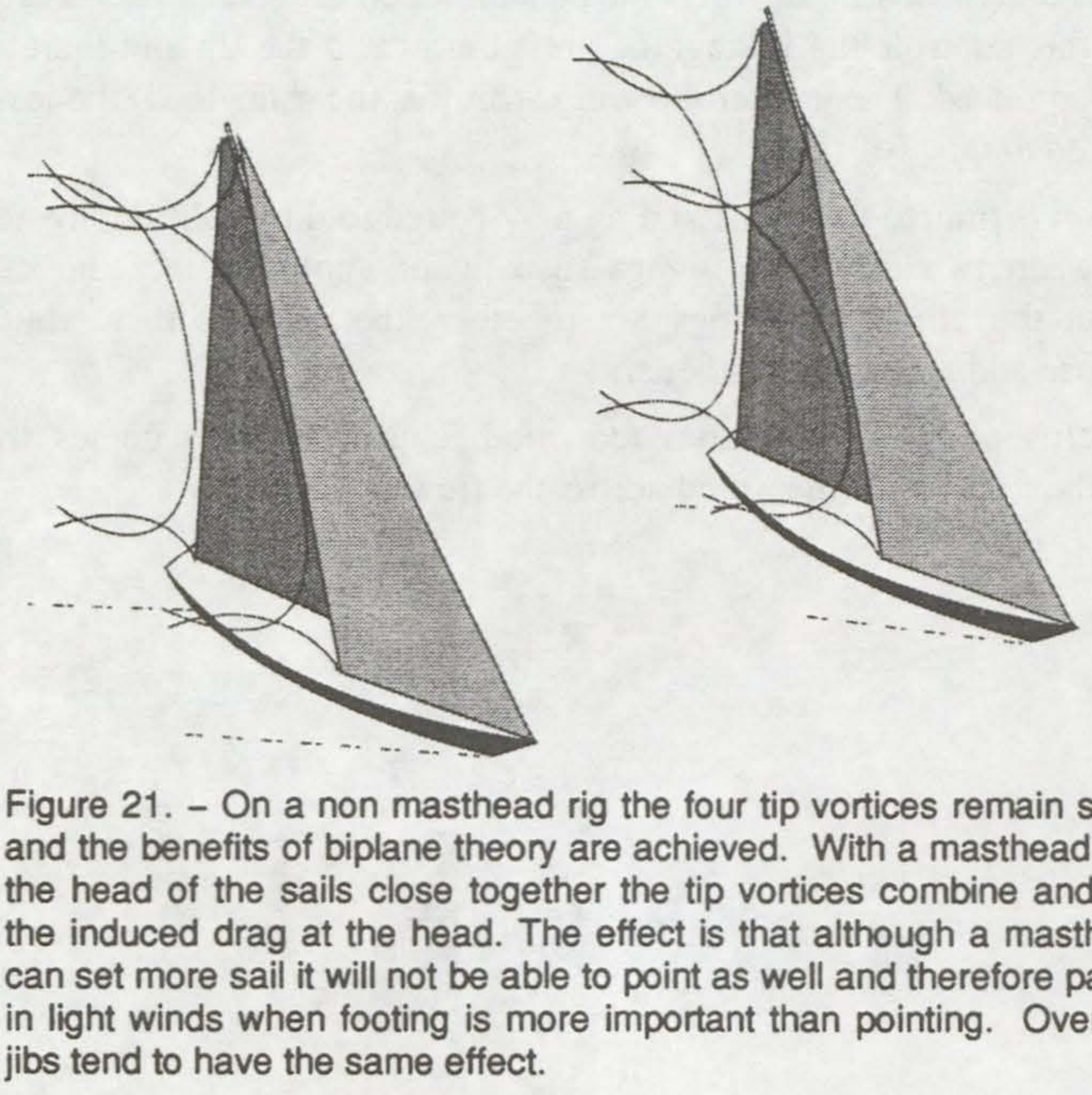


Figure 21. – On a non masthead rig the four tip vortices remain separate and the benefits of biplane theory are achieved. With a masthead rig with the head of the sails close together the tip vortices combine and double the induced drag at the head. The effect is that although a masthead rig can set more sail it will not be able to point as well and therefore pays only in light winds when footing is more important than pointing. Overlapping jibs tend to have the same effect.

Slotted Foils

Increased lift available with some increase in drag.

The maximum coefficient of lift (C_L) of a single sail or aerofoil is in the order of 1.5. Aircraft use slotted flaps to increase C_L to around 3.0. Achieving this extra lift is the converse of the biplane effect. The closer the foils are together the greater the interaction between the surfaces and the maximum lift increases with one foil improving the flow over another. The optimum gap to achieve maximum lift is in the order of 2%-5% of the total chord (width) and is dependant upon the thickness of the boundary layers.

This is why it pays to close the headsail slot in light conditions to increase the total force produced and to open the gap in strong winds, to reduce the lift and total induced drag.

The headsails cannot be moved too far away as they also play an important part in stabilising the flow around the masts and prevent separation of the flow just aft of ít. Rigs without a headsail in front of the mast tend to have reduced power and increased drag (unless the mast is over-rotated to have the sail coming off the lee side in a fair curve.

Figure 22 – Only an over rotated mast gives a fair flow onto the lee side of a sail and this increased performance has been demonstrated frequently in practice. Free rotating masts are only slightly better than fixed ones.

The optimum lift coefficient is generally around 1.0 and jibs should therefore not be needed to create extra lift, but they are required to improve the flow around the lee of the normal type of non-rotating mast. Unfortunately when reaching, the jib and mainsail are generally not close enough to give much slot effect and this can be seen in the AYRS 111 data, by the reduced reaching performance of the more conventional rigs.

From the data used in AYRS 111, C_L of all rigs varies with the apparent wind angle at an approximate rate of 0.04/deg, so that at 20° $C_L = 0.8$ and increases up to the maximum of about 1.5 at around 40°(vortex powered rigs such as the Crab Claw can go higher than this). Figure 23 shows the effect of theses assumptions and varying 'k' (efficiency factor) from 2 (good) to 0.5 (poor) – note an almost constant aspect ratio for apparent winds of less than 40° for the ideal efficiency factor of 2.

The higher the windage from the hull, rigging and crew the higher the lift drag ratio of the sails (and therefore aspect ratio) has to be to compensate. Conversely the lower the wind resistance of the crew, hull and rigging the lower is the optimum L/D and aspect ratio of the rig, for a given angle of β. In practice the optimum β is lower for efficient designs. High windage, low stability designs need biplane rigs for good performance.

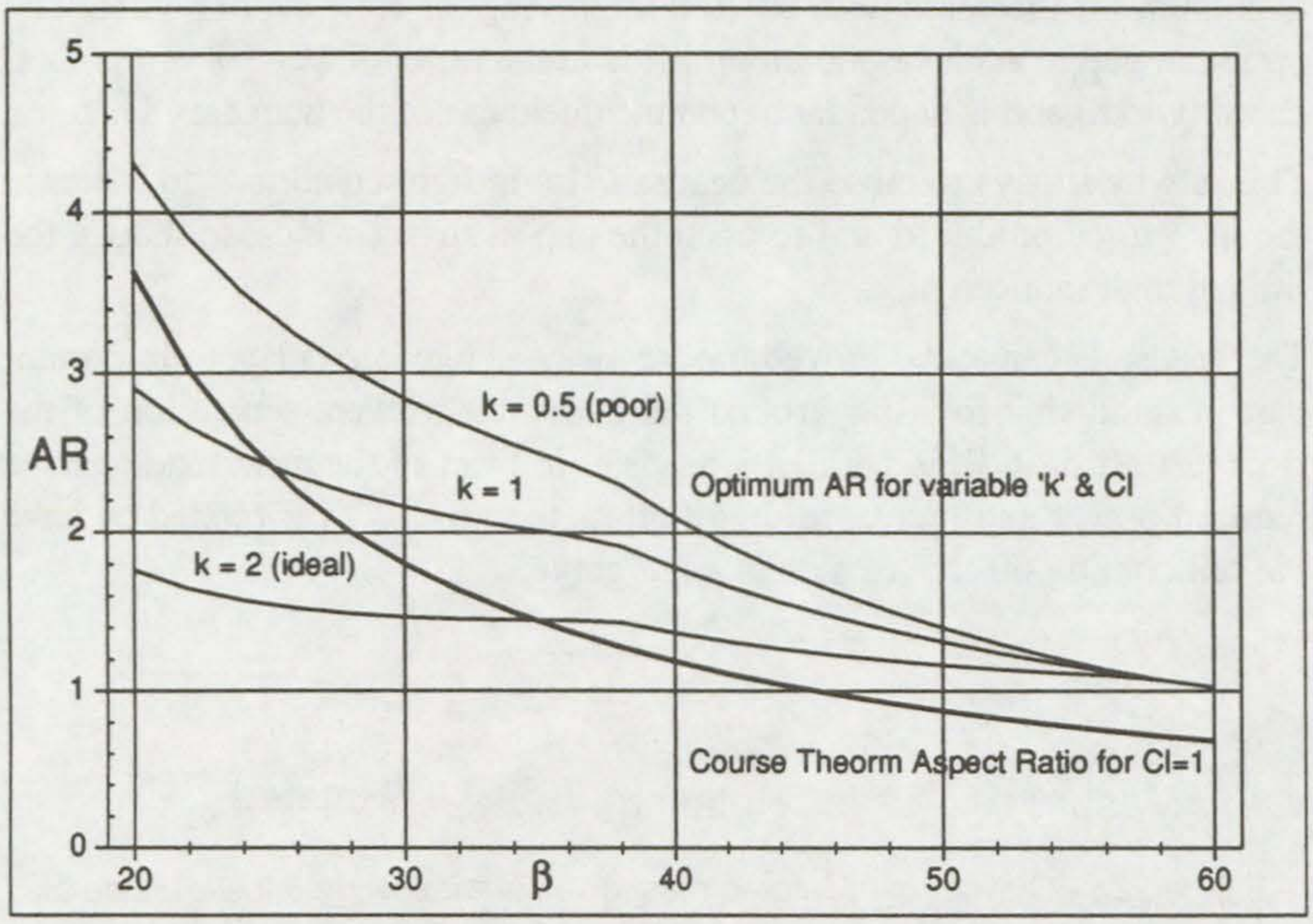


Figure 23 - Optimum Aspect Ratio from modified Course Theorem

If the aerodynamic drag of the hull and crew equals the induced drag of the rig then the L/D ratio of the rig will have to be doubled (or the height will have to be increased by 40% for the same area – in the calculation above 'k' is halved) in order to increase the aspect ratio enough to compensate. The windward performance is controlled not only the drag of the rig but by the aerodynamic drag of the hull, rigging, deck structures and crew as well.

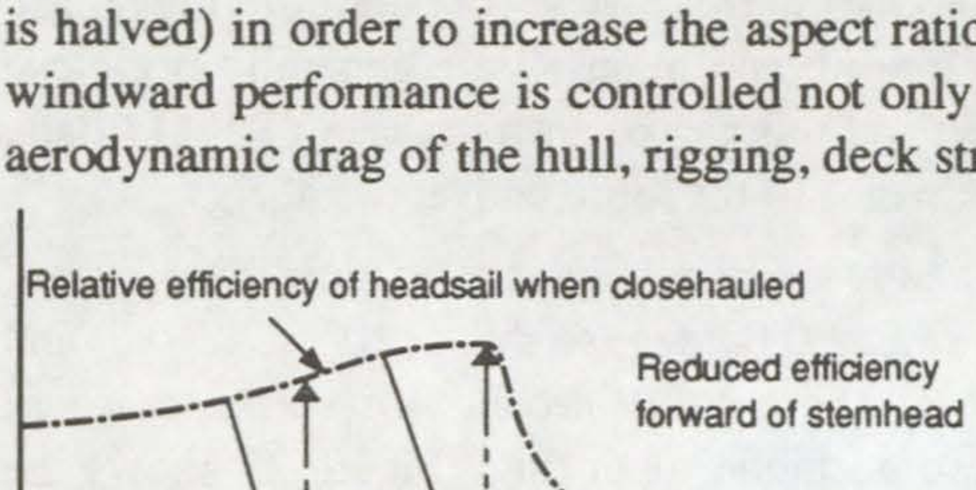


Figure 24 – Efficiency of headsail tack position

The efficiency of a headsail to windward is affected by the relative position of the tack and the stem head. Fig 25 shows the approximate change in effective aspect ratio (and therefore induced drag) with the position of the forestay. Going forward the efficiency rapidly halves, while moving aft is affected by the thickening hull boundary layer.

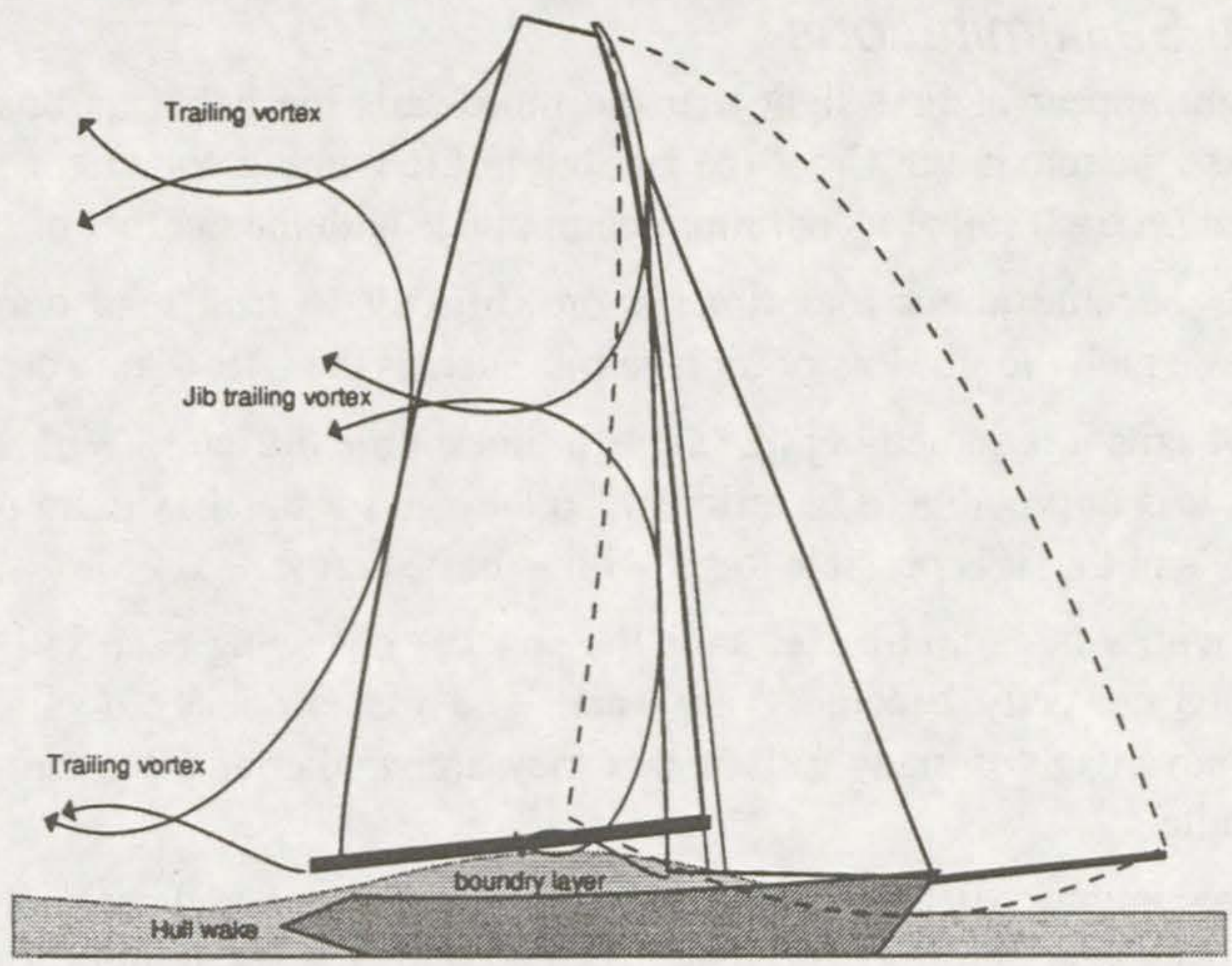


Figure 25 – The tack of all sails should be clear of turbulent boundary layer.

Off the wind the sails no longer have the beneficial influence of the hull and the induced drag increases rapidly once sheets are eased, and becomes similar to that of a headsail tacked onto a bowsprit.

There is an area of disturbed air near the surface which the sails need to be kept clear of for maximum efficiency (see AYRS 111 pages 29 - 30). This area of turbulence is increased by the presence of the hull.

The tack of each sail should be in clear air and by drooping of the main boom the wake turbulence of the hull is suppressed. An open transom also helps reduce hull aerodynamic drag, provide that it is kept clear of junk.

Raking the mast back has the effect of encouraging the top vortex to leave nearer the head of the sail. This slightly reduces the induced drag and the aim is to keep the pairs of trailing vortices as far apart as practical.

It is important that the lower edge of a sail is steady and reasonably straight so as to allow the lower vortex to develop properly. The shape of the boom has an effect on this and it is one of the reasons why it is better to fit a central mainsheet with the minimum number of parts on it. There is also an advantage in extending the boom for a short distance aft of the clew and keeping it smooth and clear of fittings and holes,

These are only a few of the very many subtle refinements that will improve performance without having to go for a complete redesign. ✔

Multi Sail limitations

It might appear at first sight that the more sails the better as this would increase the maximum C_L of the rig, but in life nothing comes for free. To cut and set each sail at its optimum compounds with the number of sails.

2 sails become about four times more difficult to trim than one, This applies equally to jib slots or biplane rigs such as the IOR Maxi ketches.

With 4 sails it is something like sixteen times more difficult. With a square rigger it is impossible to be efficient, so they go for the maximum practical area of sail that it is possible to set with a limited crew.

Thus with a large number of sails the chances of having each sail cut and trimmed correctly becomes very small and the efficiency declines. The main advantage of many sails is that they are smaller and generally easier to handle.

The maximum coefficient of lift (C_L) of a single cambered aerofoil section or sail shape is limited to around 1.0 - 1.5. This the maximum lift that can be achieved before the flow begins to separate from the upper surface. The separation may be prevented with the introduction of

suitably shaped flaps and slots to re-energise the boundary layer . This can be seen on aircraft wings in the form of trailing edge flaps and/or leading edge slats.

The maximum possible Coefficient of Lift (C_L) is less than 4.0 and more likely to be around 2.0 for any real sails. The addition of the slots increases the drag as well as the lift, it therefore pays to achieve the additional lift with the minimum number of slots (or sails). The size of the slot also has an effect on the result. For aircraft this is optimum with the slot around 2% of the wing chord (length of foil in the direction of the flow) and falls off noticably above 5%. The thicker boundary layer on sails caused by the rougher surface and seams prevents any truly narrow gaps.

It is unlikely that more than three sails are ever required for maximum aerodynamic efficiency as opposed to making the most of a particular measurement system, to ease of handling or reducing heeling moment.

On aircraft the settings between each foil are controlled to maintain an optimum setting for each air speed and at slow speed (high lift) the setting is altered for every 10% change in speed. In sailing this is achieved by trimming the sails to satisfy the frequently altering strength and direction of the apparent wind. ✔

Sail Plan Design

Any seagoing sail plan needs to be effective in a wind speed range from below 5 kts to over 50kts and although it is fairly easy to design a rig which will give optimum performance in any one set of conditions it is the 'off design' conditions that usually dictate the dimensions and style used.

The following factors should be taken into account with any new rig.

Cost. What funds are available to make the rig and what is available for research and development, both before building and after launching.

Technology available. Standard production layout or something new and more exotic?

Manufacturers. What is the experience of the spar and sail makers?

Risk level. Using proven systems only or is it acceptable to include some new and less proven factors?

Time available. A short time scale will limit the variations possible.

Rules,. Do any regulations limit the size or type of rig?

Lightest wind what type of sail(s) and extra area is available.

Optimum design conditions. This will depend on the waters that the boat is likely to be sailed in.

Strongest winds & roughest sea state. Where survivablity and managing to make to windward becomes very important.

Windward performance

If the masts over rotates such that there is a smooth flow onto the lee side then a jib is not required as it would appear (from the data used in AYRS 111) that C_L is not a critical factor when close hauled. The optimum is around one and is well under the maximum for a single sail. The presence of a jib will improve performance with either a free rotating mast or a non-rotating one. From a collection of data and observation it appears to improve windward performance to rake the mast and bend the top of the mast well back and have the leeches of the sails near vertical. Induced drag is reduced by maximising the length of the leech, therefore droop the boom as much as is practical. The tack of each sail should be mounted in clear air and away from the hull boundary layer (see figure 24).

Reaching performance

Again from AYRS 111 there is a great deal of difference in the performance of rigs when the apparent wind is less than60°. It would appear that for these conditions the sails should have a spar on both the head and foot to help develop vortex lift and greater power at high angles of attack.

Care needs to be exercised when using more than one sail so that the various vortexes do not interfere with each other, otherwise the results could be disappointing. Spinnakers are not particularly powerful sails on an area for area basis, but rely on their large size to achieve performance.

There is a lot of potential performance benefits could be obtained from developing new forms of reaching sails and rigs. The traditional bermudan rig and symmetrical spinnakers are particularly poor in this respect.

Running performance

In this situation it is simply a matter of spreading as much sail as possible, shape and cut have very little to do with it. For most craft the performance is increased by tacking down wind and therefore it is better to arrange the rig for broad reaching, as the square riggers did. It is only when it blows hard that it is worth sailing straight downwind, but this can cause rolling and make life uncomfortable. Downwind rigs need something to dampen out rolling, once again the conventional bermudan sails and balloon spinnakers are great roll inducers – new ideas are needed urgently !

Light Conditions

When the heeling moment or control is not limiting on the point of sailing is being considered: Extra sail will increase power available

If area is limited it may be possible to increase power from the sail C_L by increasing camber and ensuring a fair shape: Extra sail force (via C_L or area) will increase induced drag. Extra height will reduce induced drag.

If the effective height of the rig is limited when going to windward there is an optimum sail force and any increase or decrease in the forces produced will cause a reduction in performance. This can be seen in high performance boats that now change down from overlapping large genoa jibs in comparatively light conditions (true wind less than 10 knots), where as the older heavier style of yachts kept full size headsails until the wind was over 20 knots.

Strong winds and/or Rough Conditions

In a seaway the resistance of the hull can more than double and so an increased driving force is required within the same heeling moment. this can be achieved by:- Lower centre of effort (reefing). Reduce windage and pitching inertia.

The windage of most craft is fixed and as sail area is reduced in strong winds the windage becomes a greater factor. **For any sailing craft there is a minimum effective sail area that will drive it efficiently to windward.**

An important safety factor is the maximum wind strength that this Minimum Effective Windward Sail area (MEWS) may be carried. The higher this wind speed is the better is the survivability of the craft.

In some ways many modern designs rely upon the reliability of a single engine installation and its fuel supply. Many modern auxiliary "comfortable sailing cruisers" would be unable to beat off a lee shore in a strong wind without help from the engine and therefore should in truth be classed as "single screw motorboats with auxiliary sail", not "sailing yachts".

The MEWS could be partially demonstrated in lighter conditions by finding the minimum sail plan that will allow the yacht to have say a VMG >=1 kt. and then from the stability information find out what is the maximum strength of wind that this area may be carried.

There is a need for some form of standard performance measurement to asses the handling and safety of all designs.

Moderate Conditions

These are the design conditions where, with full sail, the heeling force balances the righting moment at the optimum angle of heel. Designing for these conditions is the simplest part of the whole exercise.

Having gone through all the reasons behind the design of rigs (and maybe weighed down with so much theory) it is a relief to find that the actual design of a rig for one particular set of conditions can be expressed quite easily. Not entirely unexpectedly the traditional empirical methods are not far off the mark. The restrictions over the last sixty or seventy years has severely limited our knowledge of any real alternative styles to the current bermudan rig.

In any conditions too much sail will reduce performance just as much as too little sail will. Near the optimum the exact area is not critical and a variation of ± 10% in area will have little effect on the actual performance. This can be seen most easily in strong winds when relatively large differences in sail set has little effect on the actual performance.

For a conventional craft, find the sail area required to give not more than 25° of heel in the chosen conditions (or optimum angle of heel if less). For all round performance within the allowable stability go for sail area rather than height of rig. Off the wind use long bowsprits or spinnaker booms with asymmetrical spinnakers and the like.

The current racing rigs tend to be short in sail area as the rating rule makers naturally perceive this as an item that controls speed in light and moderate conditions. The designers and sailmakers then try their utmost to squeeze the maximum power out of it. If you are not tied to the same arbitrary measurement rules then be careful that you are not sucked into copying the racing fraternity for entirely the wrong reasons.

Pressure is now building up in the racing world for some changes and it is likely that over the next ten years or so we will see a greater variety of rig designs, hopefully amongst them will be some that are both easier to handle and give an all round improvement in performance. ✔

Modifications to Current Rigs

From the various points that have been discussed it is possible to summarise the modifications that can be made to existing rigs to improve performance. The situation is somewhat different under class racing rules as it depends on how the sail area is controlled and measured.

For any rig the cut and trim of the sails can always be improved and it is possible to increase the driving force in many cases by as much as 50% without resorting to a major rig rebuild.

Windward performance is particularly sensitive to any small reductions in drag. This includes the correct sail shape in section and twist, but outline shape is not as critical as it is off the wind.

A masthead jib will increase the power available but will also increase the induced drag over that of an 85% foretriangle. This type will be able to foot faster rather than point. Similarly increasing the headsail overlap will reduce pointing ability, but increase the total power available. These modifications are best in light conditions where the boat is sailing at relatively low speeds or for heavy undercanvassed craft.

Mainsail efficiency is increased by increasing the 3/4 height girth to about 50% of the foot (a parabolic outline). Increasing beyond this tends to be counterproductive, unless additional heeling moment is required to lift the weather hull of a multihull out of the water. Extending the leech by drooping the boom is also advantageous, but do not drop the tack to less than about 25% of beam to ensure it remains in clean air.

Off the wind the additional sail area may be kept low down and an asymmetrical spinnaker on a long pole is more efficient, safer and easier to handle than a conventional symmetrical spinnaker with its short pole.

Over the last forty years the hull design of racing yachts has changed out of all recognition, from heavy displacement and long keels to light weight, fin keeled skimming dishes. Yet the design of rigs has basically changed very little since the thirties, despite the use of fundamentally different materials.

The reason is simple. It is much easier to measure and control rigs than it is hull forms and rule makers apparently like to introduce restriction where they can.

In the days of old it was easier to measure the spars rather than the sails, so there were the black band measurement limits on the spars and the batten length was limited to avoid gaining free area with a large roach.

For headsails they used the area of the fore triangle rather than the sail itself and limited them to the standard three cornered shape to avoid any extra unmeasured area.

Symmetrical spinnakers came into general use with the adoption of the bermudan rig to restore its relatively poor off the wind performance. In order to limit the spinnaker's use to running and reaching they were made symmetrical and the mid girth controlled to ensure a particularly inefficient sail with a poor L/D ratio.

Rotating masts and permanently bent masts were banned due to the limitation of wooden masts, cotton sails and glues available at the time. The advent of the aluminium spar reinforced the desire for straight spars.

Due to the effective blanket ban on any alternative rig designs over the last sixty years or so we simply do no know if any other arrangement might prove more efficient.

The only performance rig to be developed free from artificial restrictions in recent years has been on sailboards, but this is partially limited by what is practical for board sailors.

There is now a more general acceptance of fully battened mainsails and asymmetric spinnakers, but there is a misunderstanding about the use of sail area. It is like money – it is not so much how much you have but how it is invested that is important. Both too much or too little can make the whole project less viable.

If the development of yacht rig design is not to remain frozen in the *art deco* style of the thirties we need new methods for governing the use of sail on racing yachts.

In strong winds it is fairly obvious that too much sail can reduce performance. This demonstrates a basic truth that applies in any wind – **Too much sail will reduce performance just as much as too little.**

The fundamental rule is that there is a maximum power that can be applied by the sails to a hull and this is limited by the stability available.

It is not always realised that if the height of the rig is limited there is also a maximum useful sail area that can be set for going to windward. This applies off the wind as well but practical considerations usually apply well before this state can be achieved.

The basic performance of a sailing boat is limited by weight and stability, with windward performance dominated by rig height and keel depth, because the induced drag angles of the rig and keel are critical for minimum β and optimum VMG. Extra sail force without extra height increases the induced drag and above an ideal figure reduces the speed made good to windward.

If sail area is unlimited (as with cruisers) the best arrangement is to have as much sail as practical set low down. Overlapping sails help, provided they are set correctly and pointing ability is not important.

When sail area is limited it pays to have a tall rig without overlapping sails.

Rating and class rules are dictated by the whim of the authorities that govern them and it usually pays to take any free area that is allowed. The exception is with spinnakers where the undersized ones are often more efficient when the apparent wind is near abeam. ✔

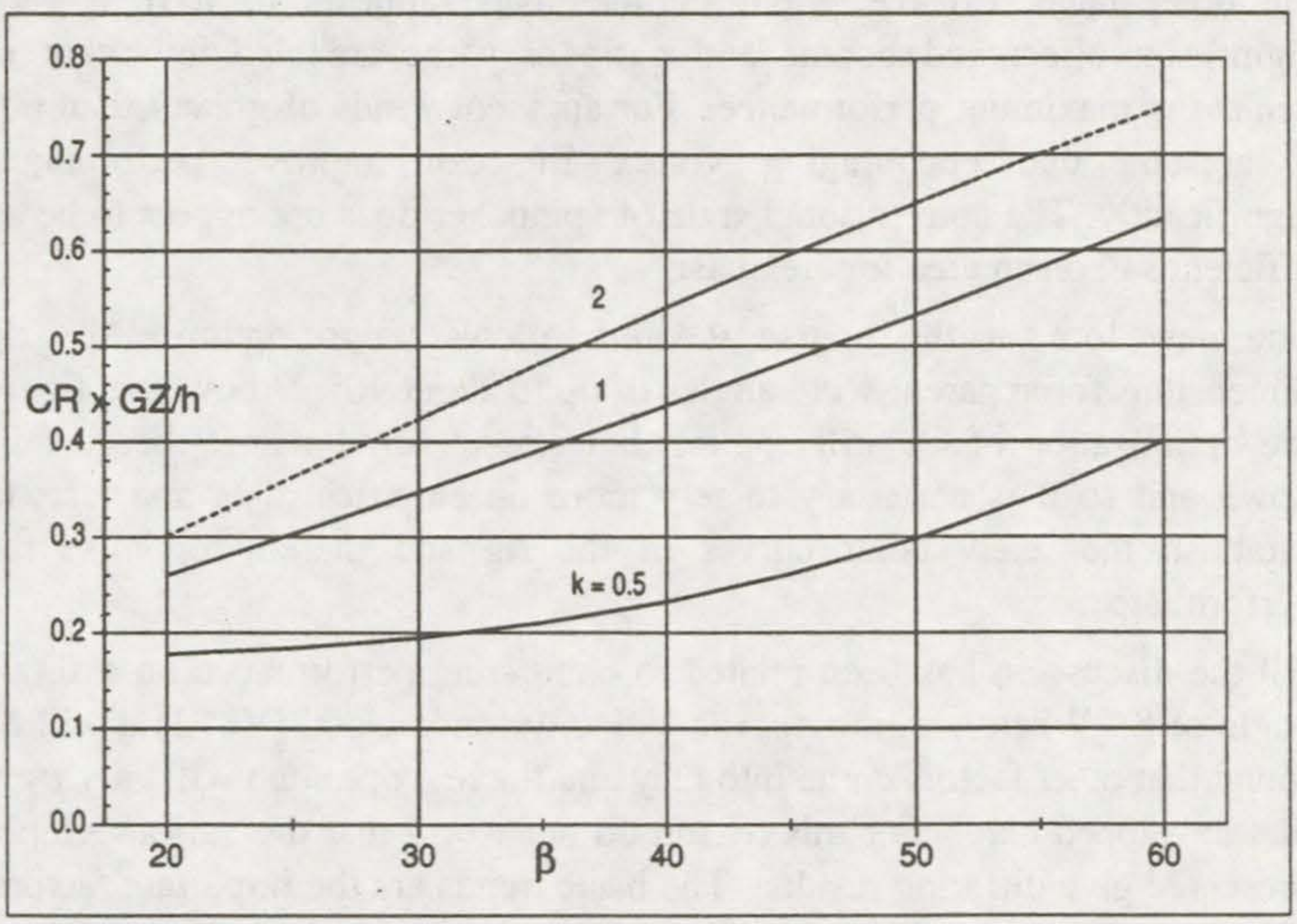


Figure 26 Maximum thrust from a sailing rig as defined by the Course Theorem for k values of 0.5, 1 & 2. In practice the k value converge as β increases, due to reduced effect from windage and reduced efficiency as the sheets are eased. Therefore k will not be such a large effect as shown above.

For a performance multihull with a GZ/h ratio of 1/3, k = 1 and β = 25° the maximum possible C_R with an ideal rig would be 0.1 Δ (displacement). A very efficient monohull, with k = 2 and GZ/h = 1/10 should be able to achieve a C_R of 3% with the apparent wind at 20°. A boat with high windage, k = 0.5, has to bear well of before there is any reasonable thrust available.

Conclusion

The line for k = 2 in the graph of figure 26 represents the maximum theoretical force that a rig can develop to effectively propel a boat. It is therefore possible to compare this with the actual performance and give an efficiency factor for the rig. Since this always assumes a single sail stability limited performance it is quite likely that it is possible to come up with various rigs that have a relative efficiency factor of over 100%.

Most of this publication has been about sailing closehauled or nearly so. This has been quite deliberate as this is the area where aerodynamic theory can be applied most directly and it relies much less on the physical type of testing as reported on in AYRS 111. These tests showed that the outline shape was far less important when closehauled than the cut and trim of the sails (although for final refinement outline and loading are significant). On the other hand, off the wind, outline shape appears to have a very significant effect and booms and gaffs or yards are also important in achieving maximum performance. For apparent winds of greater than 60° it appears that encouraging vortex lift can improve performance significantly. The conventional style of spinnaker does not appear to be an efficient sail on an area for area basis.

The new look at the course theorem allows us to optimise the rig dimensions for apparent wind angles of up to about 40°. Above this figure the optimisation of C_R still applies, but classic aerodynamic theory falls down and so it is necessary to rely more on empirical data and tests to establish the likely polar curves of the rig and thereby optimise the performance.

All the discussion has been related to comparing performance on a single angle of β. When working out the Velocity Made Good (VMG) it will be found that other factors come into play and the real optimum will vary from that developed here. For this reason do not worry that the various graphs presented give differing results. The basic trends are the important factors. The fine tuning comes at the detailed design stage when all the factors involved can be taken into account.

Sailing performance is limited by only three factors, stability. height and sail area. In strong winds stability will always be the controlling factor. With the limit on the actual force available in any condition given by the modified Course Theorem. ✔

Sail, Sheet & Halyard Loadings

When fitting out a sailing boat with new ropes and fittings it can often be difficult to decide how strong these need to be. This particularly applies to many AYRS projects that do not fit into any standard category of boats. The following may help you decide.

The wind pressure is proportional to the apparent wind velocity^2 (V_a^2) kts.

In standard conditions: Temp. 15°C (59°F) & Press. 1013hpa (29.9"Hg) and with the wind velocity in knots.

Air load	(kg/m^2)	$= V_a^2 \times CL \div 60$	**[10m]**
	(lbs/ft^2)	$= V_a^2 \times CL \div 295$	**[10i]**

For real sails the force per unit area may be taken as:-

Load	(kg/m^2)	$= V_a^2 \div 50$	(for C_L=1.21)	**[11m]**
	(lbs/ft^2)	$= V_a^2 \div 250$	(for C_L=1.18)	**[11i]**

(This assumes a maximum coefficient of lift (C_L) noted above).

To calculate the loads on a sail the total load may be considered to act at the centre of pressure and the load is carried by a combination of lines as shown on the left. From simple geometry it can be shown that if a weight is hung from a horizontal line with a deflection of 2%, the tension will be 25 times the load. If the load is spread out evenly along the line the maximum deflection is 1%, or ½ that of the single point load. This is the basis of calculating the shape and loadings on a sail, but is dependant upon the stretch of the cloth.

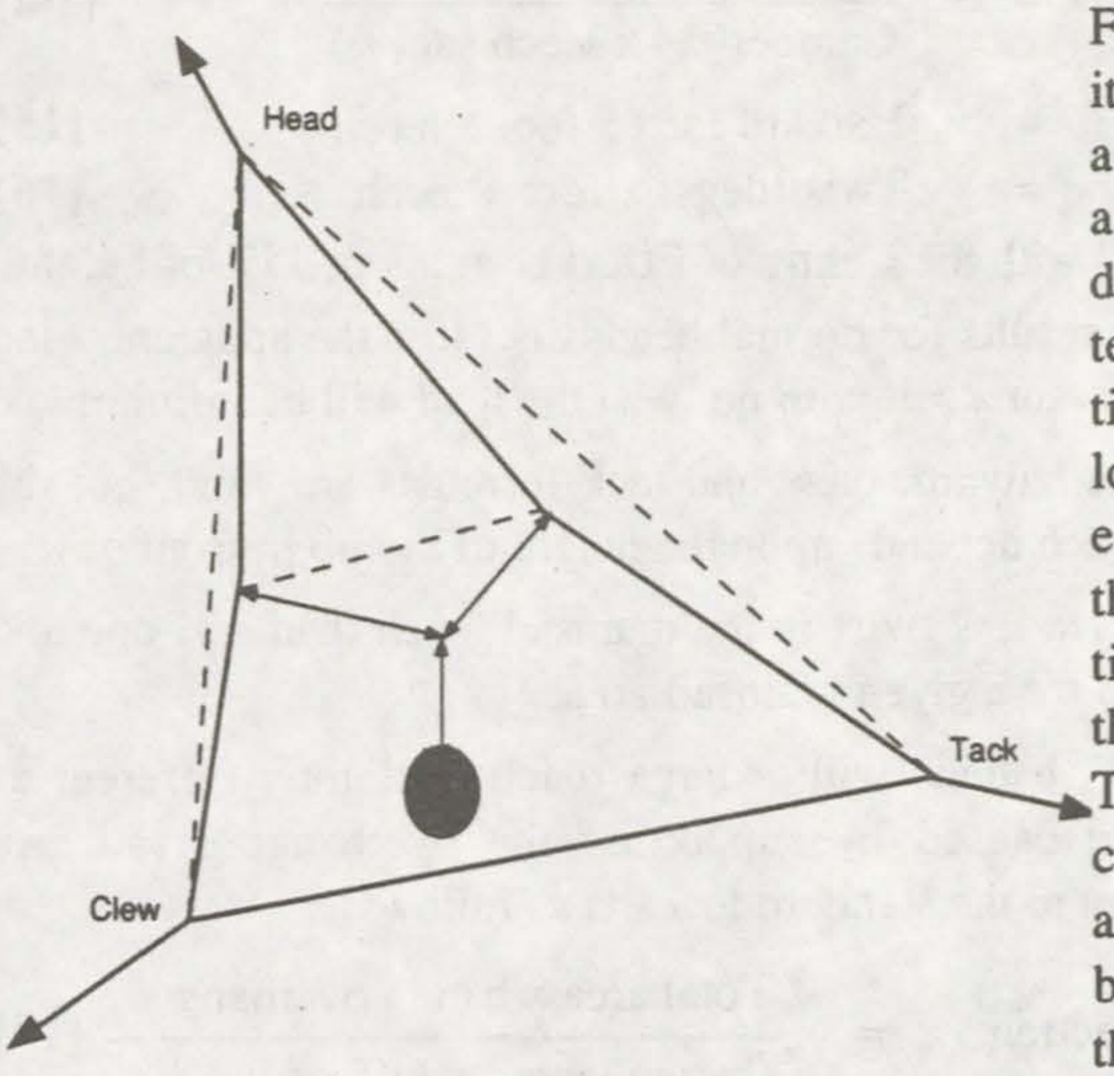


Figure 27 – The total load on the sail is considered to be at the CE and that there are lines transferring this load to the corners, as depicted above.

Combining this principle with the camber in the sail and the sag of the luff and leech it is possible to calculate the forces involved and arrive at the following:

$$\text{Clew load (kgs)} = \frac{\text{Sail area (m}^2\text{) x } V_a^2 \text{ x } 4}{\text{Camber(\%) x Leech sag(\%)}} \quad [12m]$$

$$\text{Clew load (lbs)} = \frac{\text{Sail area (ft}^2\text{) x } V_a^2 \text{ x } 0.8 \text{ (lb}}{\text{Camber(\%) x Leech sag(\%)}} \quad [12i]$$

$$\text{Forestay (kgs)} = \frac{\text{Sail area (m}^2\text{) x } V_a^2 \text{ x } 4}{\text{Camber(\%) x luff sag(\%)}} \quad [13m]$$

$$\text{Forestay (lbs)} = \frac{\text{Sail area (ft}^2\text{) x } V_a^2 \text{ x } 0.8}{\text{Camber(\%) x luff sag(\%)}} \quad [13i]$$

$$\text{Halyard (kgs)} = \frac{\text{Luff (m)}^2 \text{ x } V_a^2}{\text{Camber(\%) x leech sag(\%)}} \quad [14m]$$

$$\text{Halyard (lbs)} = \frac{\text{Luff(ft)}^2 \text{ x } V_a^2 \text{ x } 0.2}{\text{Camber(\%) x leech sag(\%)}} \quad [14i]$$

$$\text{Tack load} = \text{Halyard load x foot} \div \text{leech} \quad [15]$$

$$\text{Leech sag (\%)} = \text{Twist(degs) x foot} \div \text{leech} \quad [16]$$

The twist is taken level with the Centre of Effort or at about 35% of height.

These give reasonable results for normal headsails. It is the apparent wind that is used and if you want a sail with no twist the load will be infinite!

For mainsails the same halyard, clew and tack formulas are valid, but the twist in the mainsail leech depends upon the height of the jib in front of it.

A masthead rig will have less twist in the mainsail leech than a ¾ one and therefore a greater load for a given mainsail area.

The case of full length battens with a large roach is slightly different as there is an extra load caused by supporting the overhanging sail. An approximate adjustment to the standard loads is as follows:-

$$\text{Full length batten correction.} = \frac{\text{Total area x batten overhang x 3}}{\text{(batten length x luff x foot)}} \quad [17]$$

The batten overhang is the distance from the outboard end to a line joining the head and the clew. Use the batten that has the largest overhang/length ratio. All this assumes that the leech tension is not used to control the batten curvature as in this case the load depends upon the stiffness of the battens and is impossible to calculate with any degree of accuracy.

The problem is that we now have to assume some values for camber and sag to get some useful answer. A flat cut headsail might have a 2.5% forestay sag, a 12.5% camber and 6.5% sag in the leech. These formula can therefore be rewritten as follows:

(G)	Clew Load	(kgs)	= Sail area (m^2) x $V_a^2 \div 20$	[18m]
		(lbs)	= Sail area (ft^2) x $V_a^2 \div 100$	[18i]
(H)	Forestay	(kgs)	= Sail area (m^2) x $V_a^2 \div 4$	[19m]
		(lbs)	= Sail area (ft^2) x $V_a^2 \div 20$	[19b]
(I)	Halyard	(kgs)	= Luff2 (m) x $V_a^2 \div 80$	[20m]
		(lbs)	= Luff2 (ft) x $V_a^2 \div 400$	[20i]

In strong winds there is normally a requirement to increase fullness in order to increase drive and increase twist to reduce the heeling moment. The effect of these and any stretch is to reduce the loadings, but any extra fullness will also increase the aerodynamic forces.

For very full sails such as spinnakers with a camber and luff sag of more than 15% the sheet and halyard loads can be taken as equal to the sail load (A). Asymmetrical spinnakers have higher luff loads as they are in the more extreme cases very like genoas. Check on the planned luff sag.

The load on the spinnaker boom, or bowsprit and guys can be calculated from the above loadings, taking into account the geometry of the leads. Similarly with the standing rigging.

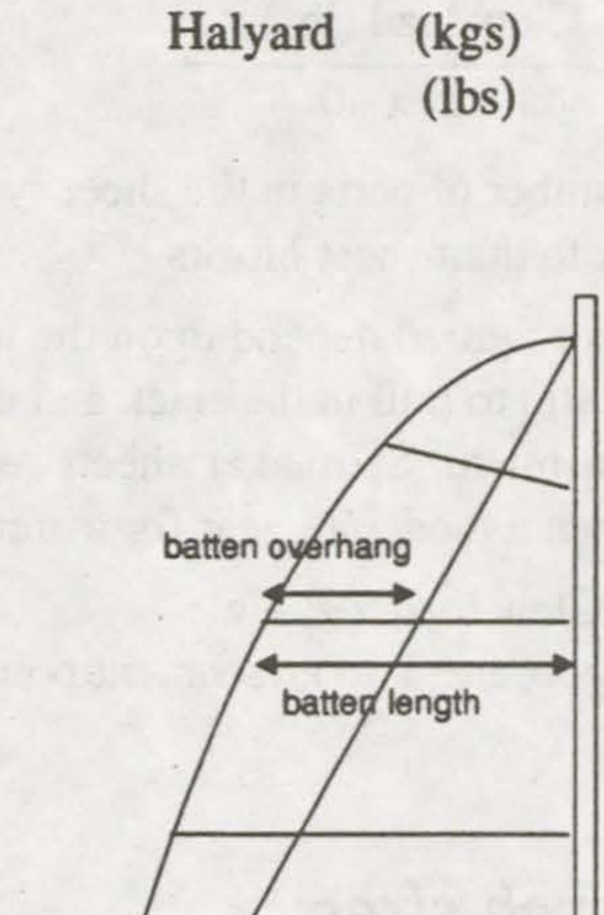


Figure 28 - The sag in the leech is taken along the line, head to clew.

Winch Sizing

The optimum force on a winch handle is about 20kgs with a fit crew and this can be increased to over 30kgs when double handed or with the slower ratchet style of handle, but all are reduced with a less energetic crews:

Sheet winch ratio = Clew load (kgs) ÷ 20 [21m]
= Clew load (lbs) ÷ 44 [21i]

Halyard winch ratio = Halyard load (kgs) ÷30 [22m]
= Halyard load (lbs) ÷ 66 [22i]

$$\text{Mainsheet winch ratio} = \frac{\text{Clew load (kgs)} \times E}{n \times m \times 18} \quad [23m]$$

$$= \frac{\text{Clew load (lbs)} \times E}{n \times m \times 40} \quad [23i]$$

E = foot of sail n = number of parts in the sheet system
m = distance from gooseneck to mainsheet blocks.

With two or three speed winches the ratios required depend upon the use of the winch. For halyards they need a high ratio to pull in the slack and then a low ratio for the final tensioning and adjustment. Spinnaker sheets require rapid overhauling of the slack sheet and then a moderate gear for trimming.

Kicking strap load = Clew load × E ÷ z [24]
z = lesser distance from the gooseneck to attachment point on boom or mast. ✔

A quick check on minimum winch sizes:

(N) Min. Winch Power ratio = Luff² (m) x V_a^2 ÷ 2,000 [25m]
= Luff² (ft) x V_a^2 ÷ 20,000 [25i]

For an apparent wind of 20 knots this simplifies to:

(O) Min. Winch Power ratio = Luff² (m) ÷ 5 [26m]
= Luff² (ft) ÷ 50 [26i]

This is for genoa sheet winches and a handle load of 20 kgs (44lbs).

(P) Min. Winch Power ratio = Luff² (m) x 4 ÷ handle load (kgs)
= Luff² (ft) ÷ handle load (lbs) [27]

For non-overlapping headsails, halyards and spinnaker winch ratios of about $^2/_3$ of these figures should suffice. ✔

Rigging Sizes

The **minimum** safety factor applied to standing rigging is around 2.0 so as to keep the maximum design loads within the elastic range of the material.

End fittings need a minimum factor of 3 in order that any signs of failure will be with the wire first, rather than in the fitting.

For rigging the following are the minimum practical breaking strains (BS):

Min Shroud (BS)	= 2.0 x max shroud load
Min Forestay (BS)	= 2.0 x max forestay load
(the above factors may in some cases be reduced to 1.67)	
Min fitting (BS)	= 3.0 x max rigging load
Min halyard (BS)	= 3.0 x max halyard load
Min sheet (BS)	= 4.0 x max sheet load

From these the following sizes can be calculated.

Forestay dia (mm)	=	forestay load (kgs) ÷ 30 for 1x19 wire
dia (1/16")	=	forestay load (lbs) ÷ 80)
Min halyard dia (mm)	=	halyard load (kgs) ÷ 15 for 7 x 19 wire
dia(1/16")	=	halyard load (lbs) ÷ 40
Terylene rope tail dia	=	wire dia x 2
Min sheet dia(mm)	=	clew load (kgs) ÷ 5 Terylene (polyester)
dia(1/16")	=	clew load (lbs) ÷ 30

For Polypropylene increase load by 20% before calculating required size.

Tests have shown that in the open sea the upper shrouds in particular carry extra loads due to the inertia of the rig and an allowance need to be made for this. The loading on the fore and aft stays can be increased considerably by the inertia forces created by the weight of the rig and buoyancy in the ends of the hull. A heavy rig and full ends will cause increased loadings when beating into a head sea. This can bring about the ideal conditions for fatigue failures, where repeated reversal of the loadings causes failure at well below normal stress limits and stainless steel is particularly susceptible to fatigue. Care needs to be exercised in the design of fittings

If slackness develops in any rigging, the cause should be investigated as it is an indication that an excessive load has been applied and the elastic limit of the material has been exceeded at some point. During the bedding down of a new rig a certain amount of initial movement can be expected.

When any rigging or fitting fails it is important that the true reason is established as it is often an unfair or side load and not the design load that causes the problem. The reason for any unfair loads or damage should be rectified or allowed for in any replacement. If the failure is due to the design load being exceeded then the fitting should be replaced by one that is at least 50% stronger in order to provide a minimal safety margin.

The running rigging requires greater safety factors due to the loss of strength when working around sheaves and winches. The sheaves should be as large as is practical and the grove must match the rope size and type. Too small a sheave or the wrong shaped grove can easily reduce the ultimate strength by more than half.

All the above figures and calculations are based on information from several manufacturers and are passed on for information only. Before working on any real rigging please check with your manufacturers for their recommendations as to the actual loadings and safety factors that should be used in your particular case. ✔

Foil Calculations

The lift from a sail or foil system is fairly simple to calculate. The bigger problem is finding out the total drag to anywhere near the same degree of accuracy. Even the aviation world get it wrong, despite the use of wind tunnels, powerful computers and full sized prototypes.

Lift in water (kgs) $= S\,(m^2) \times C_L \times V^2\,(kts) \times 14$ **[27m]**

(lbs) $= S\,(ft^2) \times C_L \times V^2\,(kts) \times 2.85$ **[27i]**

Lift in air (kgs) $= S\,(m^2) \times C_L \times V^2\,(kts) \div 60$ **[28m]**

(lbs) $= S\,(ft^2) \times C_L \times V^2\,(kts) \times 295$ **[28i]**

Drag for foils in water C_L range 0 - 0.6 AR range 1 - 10

$$C_D = C_L \times 0.01 + C_L^2\,(0.01 + 1/(AR \times \pi))$$ **[29]**

Drag for sails in air C_L range 0.8 - 1.5 AR range 1 - 5

$$C_D = C_L \times 0.1 + C_L^3 / (AR \times \pi))$$ **[30]**

For drag replace C_L with C_D in formulas 27 & 28 above. These figures should give reasonable results for a first approximations. Do not forget to include the drag of the hull and rigging as well as the interference drag. Once the initial figures have been calculated seek more accurate data.

Human beings are by nature optimistic and the real drag figures are very rarely less than the estimated ones and often a great deal more. As a rule of thumb for any new project check that it will still work successfully if the drag is double that estimated ! ✔

APPENDIX :

Units:- Where formulas are given these are for metric and imperial units and will give approximately the same result. Exact equivalents have been avoided as this complicates the figures and assumes a much higher degree of accuracy than the data can possibly provide.

Where ratios are given these are as far as possible non-dimentional so that it does not matter what system of measurement is used.

The most convenient units are the metric Metre and Kilogram with Knots used for speed as metres per second are less familiar to most yachtsmen.

For those that still think in Imperial units Feet and Pounds are used, but still with Knots for speed (apologies to those who like their feet per second). ✔

References

1 **Theory of Wing Sections,** *Abbot & von Doenhoff,* Dover 1959

2 **AYRS 111, Rig Efficiency,** *C A Marchaj et al,* AYRS 1993

3 **Sailing Theory and Practice,** 2nd Edition 1982, *C A Marchaj,* Adlard Coles Ltd. London. Dodd Mead'& Co New York, USA

4 **Aero Hydrodynamics of Sailing.** 1979, *C A Marchaj,* Adlard Coles Ltd, London. Dodd Mead & Co, New York, USA

5 **The Design of the Aeroplane,** 1983, *Darrol Stinton,* Granada Publishing Ltd, London.

6 **Fundamentals of Aerodynamics,** 1991, *John D Anderson Jr,* McGraw-Hill Inc. New York.

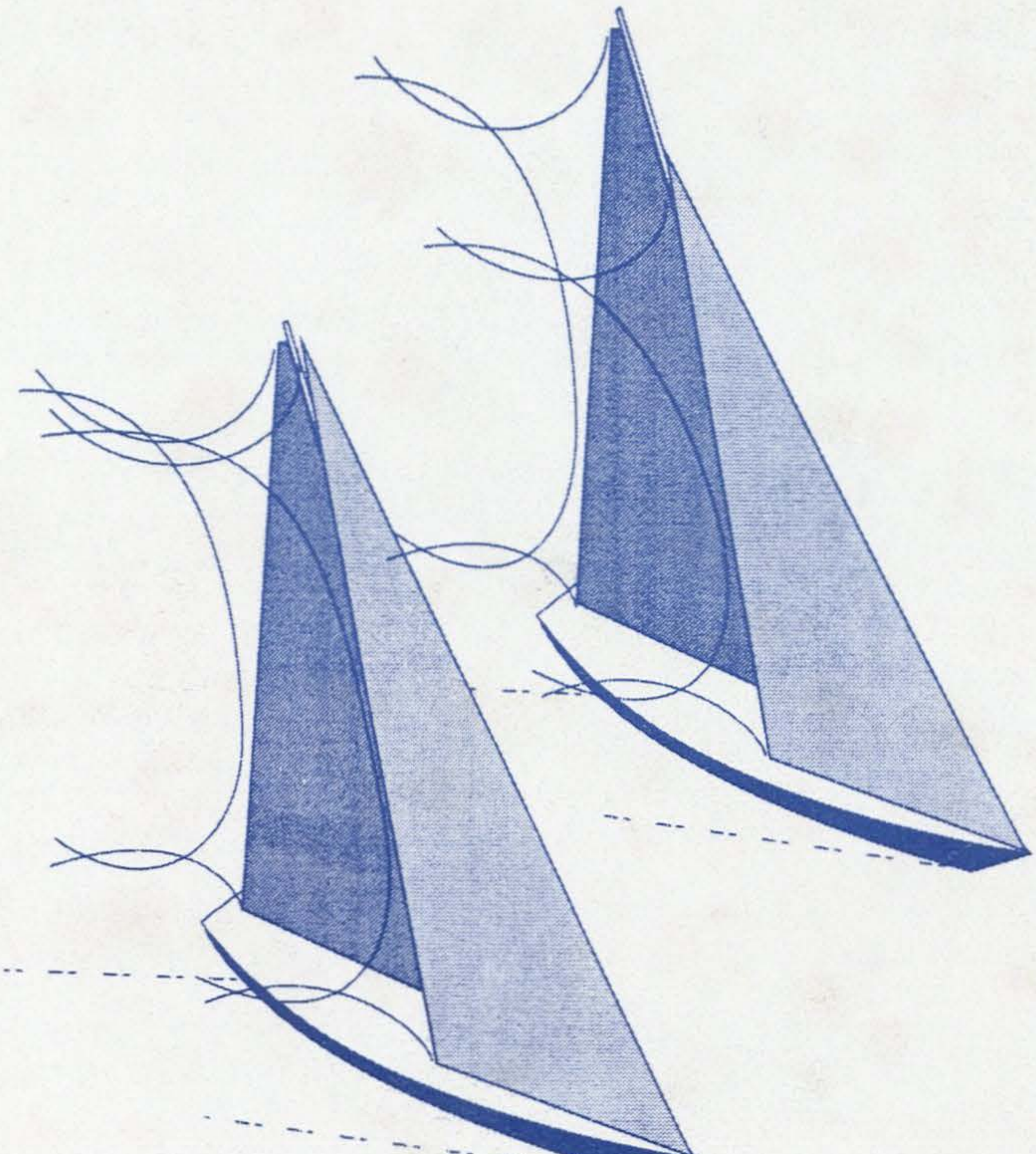
7 **Fundamentals of Flight,** 1989, *Richard S Shevell,* Prentice Hall, New Jersey, USA.

8 **Regional Conference on Sail-Motor Propulsion,** 1985, Asian Development Bank, Manila, Philippines.

9 **Model Aircraft Aerodynamics,** 1978, *Martin Simons,* Model & Allied Publications, Watford, Herts.

Many of the explanations have been kept short, in order to keep this publication to a reasonable length, but it is planned to fill in these gaps with articles in forthcoming newsletters and included them all in any future edition. Let me know the parts that are of interest and require further explanation. IH ✔

Printed by Speedprint, Gladiator Street, Forest Hill, London SE23 1NA



Rig Theory

CONTENTS