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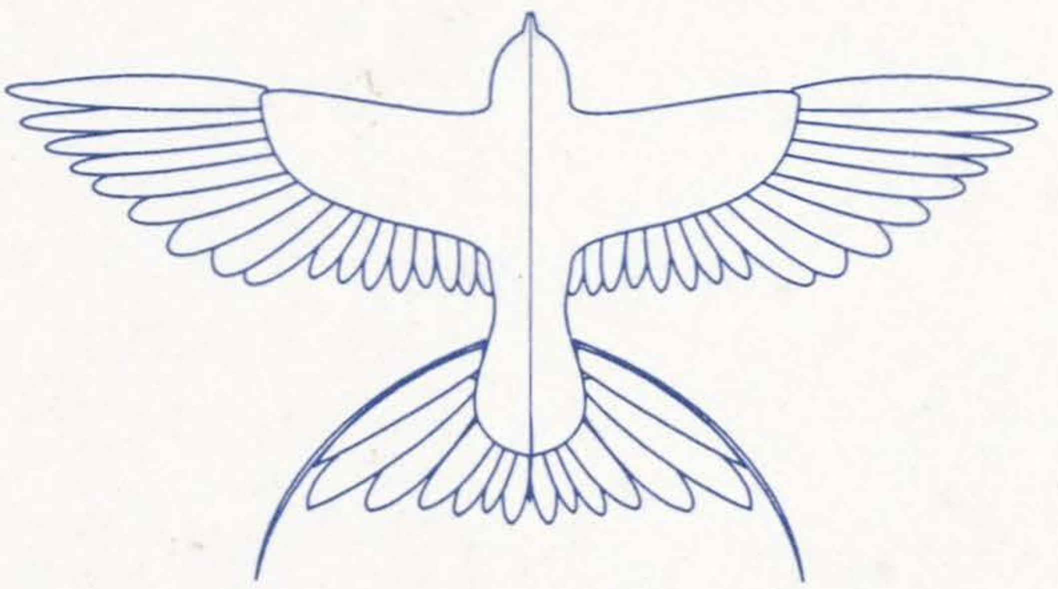
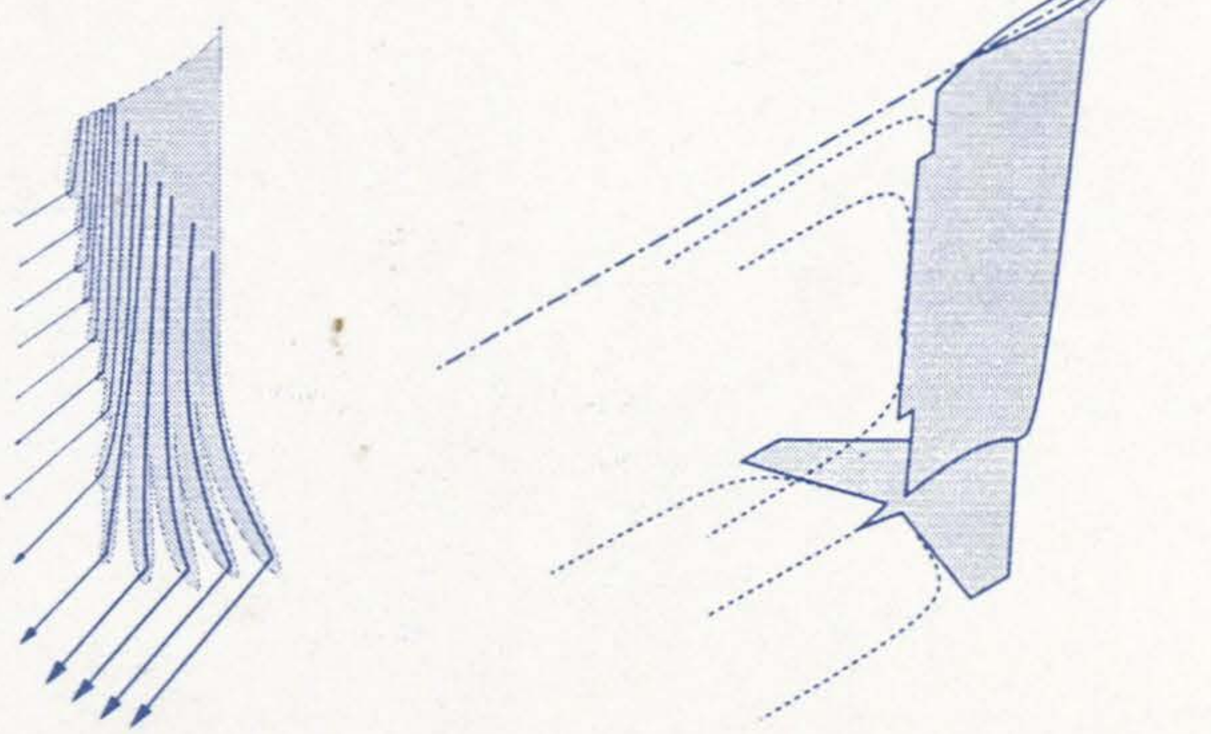
Natural Aerodynamics

by Ian Hannay





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by Ian Hannay

Acknowledgments

With much new material to be researched this publication has been a little longer in production than hoped for. Also a glorious summer sailing over 3,000 miles to Scotland and back did not help the shedule.

I have been greatly assisted by the many technical discussions with people from the aerodynamic world, including members of the RAeS, RINA & SUTR Joint Aero/Marine Group. Special mention must be made of Tony Marchaj and Dr Darrol Stinton who's encouragement helped these particular lines of thought to (hopefully) a coherent and presentable form. Also to Kate Taylor for her helpful advice and work with the initial CFD modelling.

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Ian Hannay *Fleet, October 1995*

1 INTRODUCTION

This is nature's aerodynamics in the sense that it has been used by birds and other creatures of nature for millions of years. It has been developed through the survival of the fitest over many generations. It explains some of the subtleties that nature has developed with the flight of birds and explains how this experience can be used to enable boats to sail more efficiently.

There has always been a noticeable differences between what the serious racing sailor finds makes a sailing boat go faster and what theoretical aerodynamicists say should be the most efficient. Natural aerodynamics goes some way to explain this differences between sailing practice and aerodynamic theory, it covers an area that has been virtually ignored by the writings on aircraft aerodynamics.

Using the principles of natural aerodynamics potentially improves efficiency, but one must be careful when applying these or any other new principles, that the previously achieved levels of efficiency are not lost. The optimum performance is always a balance between many separate factors and is very rarely the optimum for any particular part.

The 'westernisation' of the traditional Polynesian 'Crab Claw and the Chinese 'junk' rigs amongst others has caused the loss of much of the original subtleties. Just as a modern farmer would have difficulty trying to plough with a team of horses, so the modern sailor and sailing theoretician miss much that has gone into the rigs over the past centuries and have virtually ignored what nature has developed. Modern rigs are relatively efficient, but can be made even better by understanding some of the reasons why various options were selected in the past and understanding why nature has chosen particular paths of development.

The reason for choosing birds, rather than fish as the main support for efficiency is that birds expend considerable energy and effort to remain in the air, in some cases for months at a time – this can only be achieved by the use of minimal energy and therefore these birds must have good efficiency. However fast the sea creatures are they can always slow down or rest and as a percentage of their weight, their total propulsive effort is considerably less than that of aero active birds such as the swallow.

All the elements of bird flight which are referred to cover many species that are predominantly aero active and therefore it may be assumed that these features have been developed because of the benefits they bestow to flight.

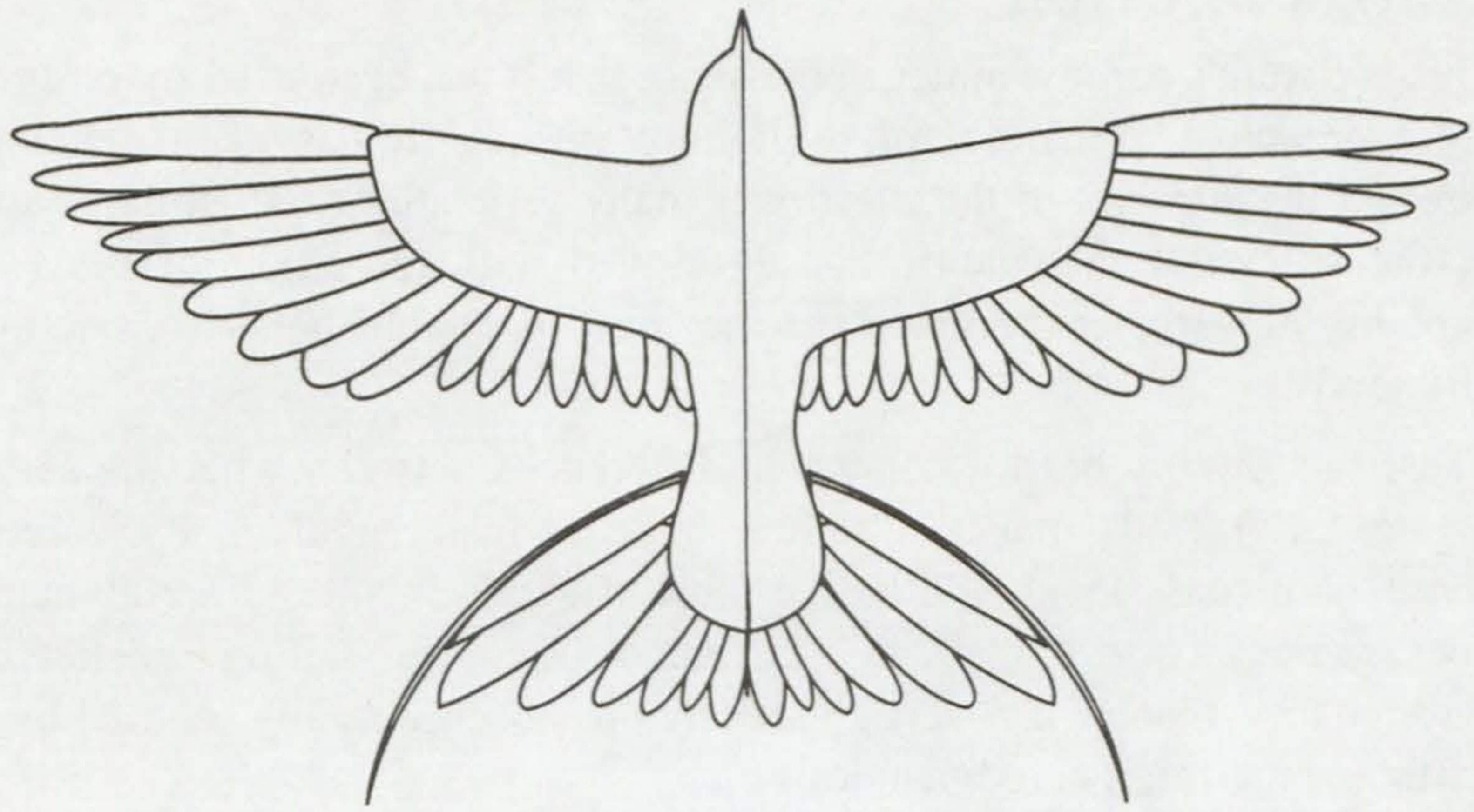

Figure1-1a The plan view of a swallow in mid stroke during manoeuvring flight, with the tail out stretched[6]. Note the ragged trailing edge of both the wing and the tail. This appears to be beneficial to flight.

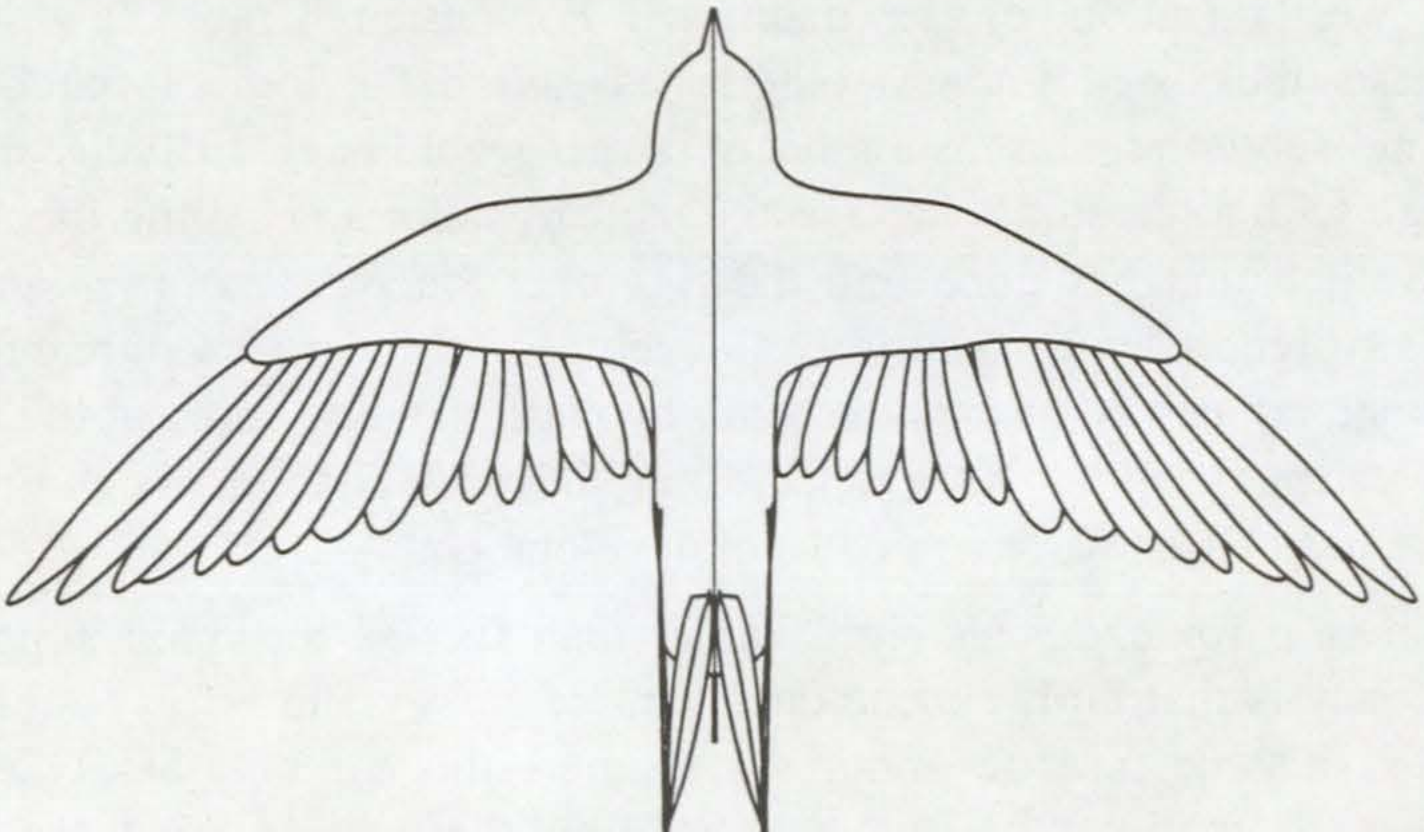

Figure1-1b The plan view of a swallow in mid stroke during forward flight, with the wings swept back and the tail trailing in the minimum drag position.
Note the still prominent ragged edge of the wing. similarly this appears to be beneficial to flight.

2 SOME FUNDAMENTAL PRINCIPLES

A useful feature of nature is that it tends to take the easy way out and works towards minimum energy loss. Just as we would walk round a hill to get to the other side with a load, rather than go over it, so nature tries not to expend unnecessary effort to achieve an objective.

There are several features which are common to most aerodynamically active birds. These include a relatively small tail that can be folded away in flight and the configuration of the wing is significantly different from the classically shaped elliptical 'Spitfire' wing. Few can have failed to notice that the trailing edge of almost all bird's wings are ragged, yet the outline of an aircraft's wing is smooth (except when the flaps are extended). This ragged outline applies particularly to large birds and those which spend much of their life flying.

One of these aero active birds is the swallow shown in figure 1-1a. This species has to be very efficient as it spends most of its life on the wing and flies vast distances. The point in question is, does this type of pointed wing with its ragged trailing edge have any aerodynamic advantage or is it just a part of the natural selection in birds which has little to with survival or efficiency and all to do with fashion and sexual attraction ?

The view in figure 1-1a is in manoeuvring flight with high lift and the wings swept forward. In this situation the tail is supplying positive lift and acting as a flap to the main wing. With the wings swept back in normal flight the ragged trailing edge is still very prominent as can be seen in figure 1-1b, but the tail is now stowed and its form helps to stabilise the flow around the body and minimises its drag.

Birds have what might be termed semi gothic shaped wings rather than the aerodynamicist's elliptical wing. Even birds such as the frigate and albatross with their large span and high aspect ratio wings have tips that are very similar in outline to that of the swallow. The conventional reasoning for these pointed tips is that they reduces bending (or heeling) moment, but is there more to it ?

If we look at the wing in figures 1-1a & 1b it would appear that the tip of each feather is prominent enough for there to be a separate vortex coming off each one. Could there be any advantage in this arrangement, or is the classic Spitfire wing with its single pair of trailing vortices the only way to minimise induced drag ?

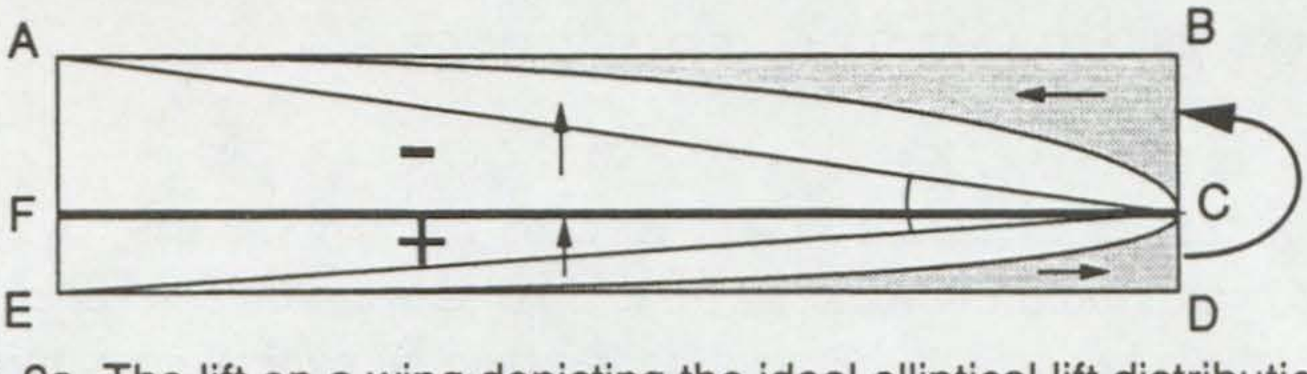

Figure 1-2a The lift on a wing depicting the ideal elliptical lift distribution with the low pressure area on the top and the higher pressure below. The constant downwash consists of the downwash due to the lift and the horizontal flow due to the leakage around the end that causes the induced drag.

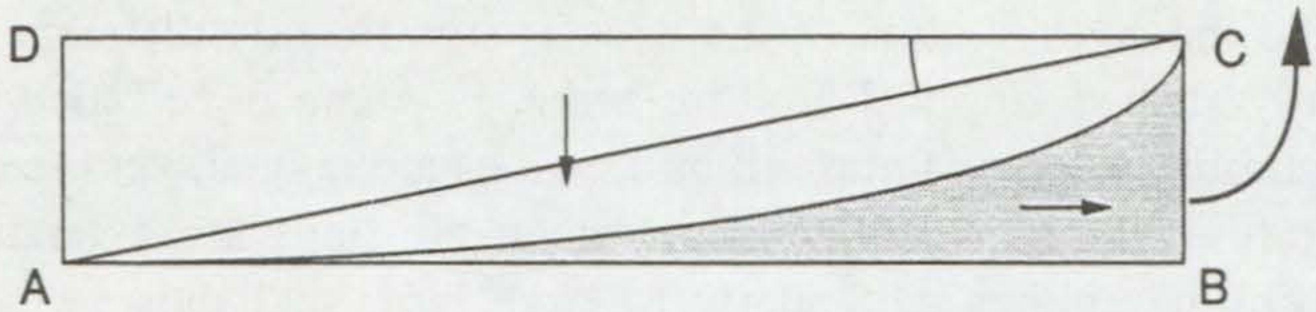

Figure 1-2b This represents the downwash of the wing in figure 1-4. The white section represents the downwash due to the lift and the grey area the potential flow around the tip that creates the induced drag.

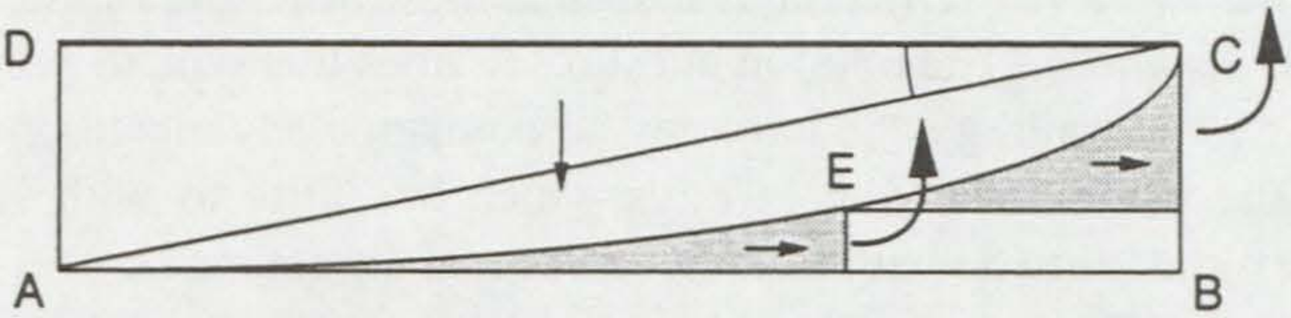

Figure 1-2c If the cross flow is bled off at point E the induced flow is reduced by the area EB and there are now two vortices, starting at points E & C.

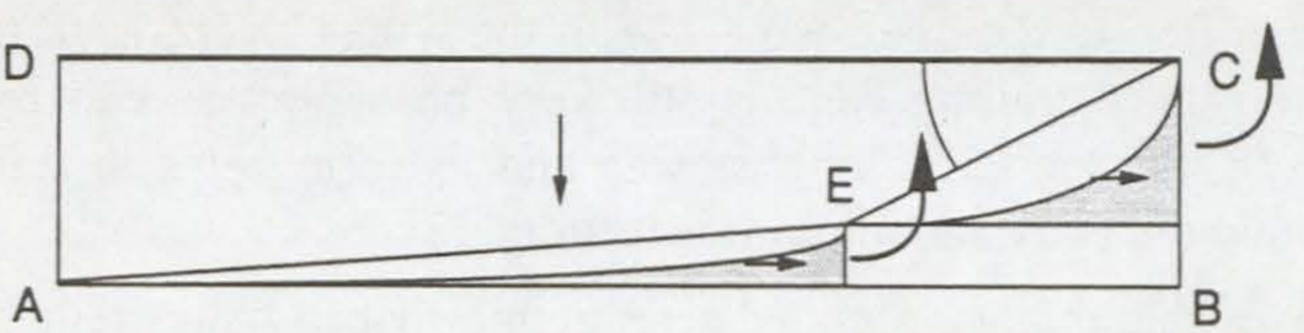

Figure1-2d The reduction of the cross flow causes the lift in each segment to increase and approximate to an elliptical distribution, with a consequential reduction in induced flow

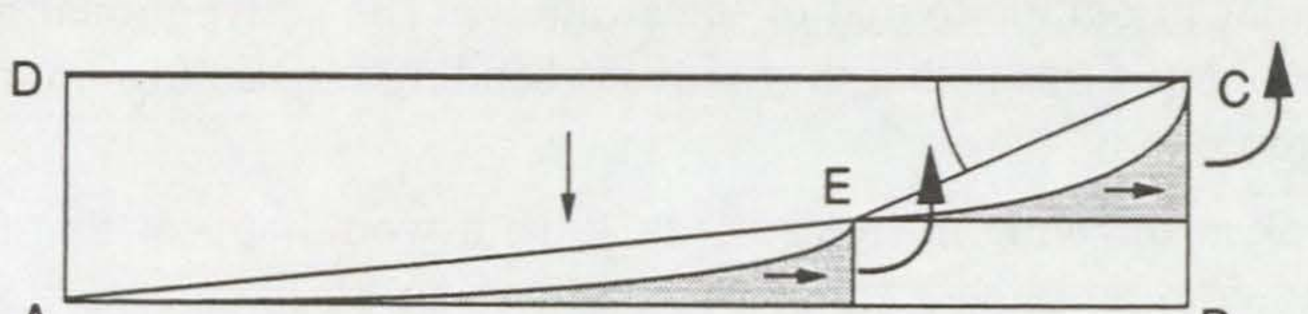

Figure 1-2e With more cross flow removed at point E the vortex at the tip C is reduced. As compared with the wing in figure 1-5 the lift is increased and the induced drag reduced.

In traditional aerodynamics as formulated by Prandtl, Munk and others in the early part of this century it was established that the minimum induced drag occurs with an elliptical lift distribution and a constant downwash across the entire span. This downwash is made up of two components, the direct reaction to the lifting force, which is directly downwards and a cross flow due to the leakage of air around the end of the finite wing due to the difference in pressure on the top and bottom surfaces. This leakage of air both reduces the lift available and creates additional drag.

Figure1- 2a shows the pressure above and below the wing. The enclosed white area represents the lift and the shaded area the cross flow that causes the induced drag. This is simplified in figure 1-2b with the constant downwash represented by the rectangle ABCD, with the reaction to the lift the white area and the induced cross flow the shaded area.

According to basic aerodynamic theory if the induced drag is reduced the lift will increase (at the same angle of attack). There is less cross flow and more vertical lift is created as a result (the effective span of the wing is increased). The conventional way to reduce induced drag is to restrict the induced flow across the wing by use of winglets or fences at the tip. This increases the effective span and therefore reduces the span loading. Induced drag being proportional to (span loading)^2 – double the loading and the induced drag will be increased four fold.

What would happen if instead of allowing all the induced flow to go around the tip, part was bled off further inboard? If for instance the cross flow was stopped at point E in figure 1-2c the cross flow and therefore induced drag should in theory be reduced by the area of rectangle EB.

With the induced flow reduced, the lift would be expected to increase and the lift distribution in each segment would naturally tend to become more elliptical, therefore the lift and drag distribution would be expected to be more like figure 1-2d. With the lift distribution elliptical in each segment the lift is increased and the induced drag reduced in line with the expected predictions. The grey area is greatly reduced, but the angle DCE is increased so the actual tip vortex velocity would increase, but with much less mass of air. The slope EA is much less, so this vortex will be weaker. The overall effect of this bleeding off of the cross flow appears to be to increase lift and reduce drag.

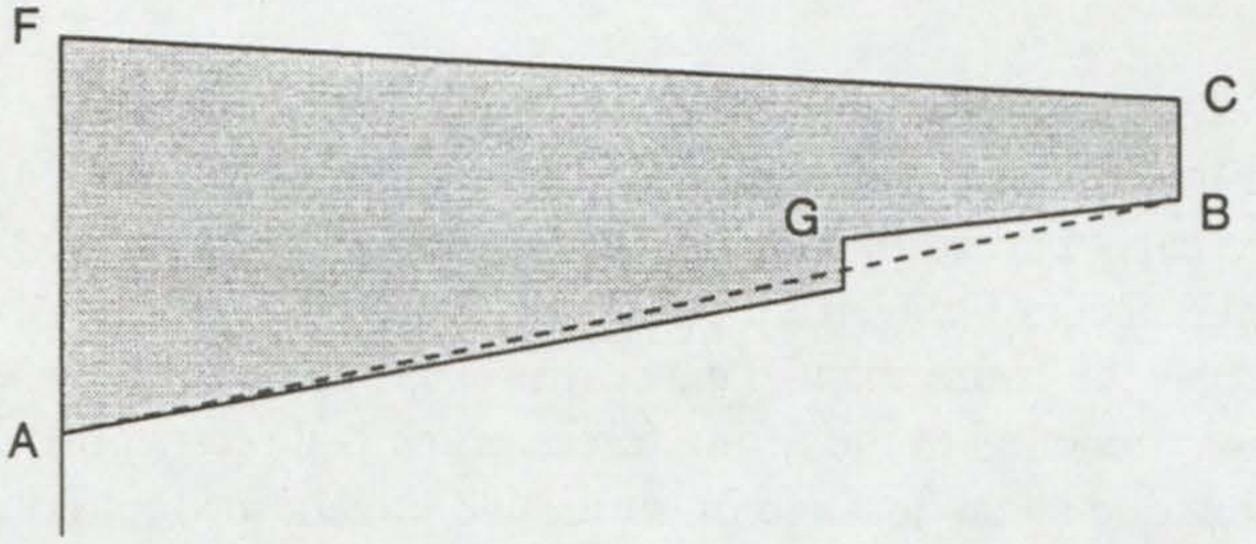

Figure 1-3a A standard wing (dotted outline) and one with a single cut out in the trailing edge at 70%.

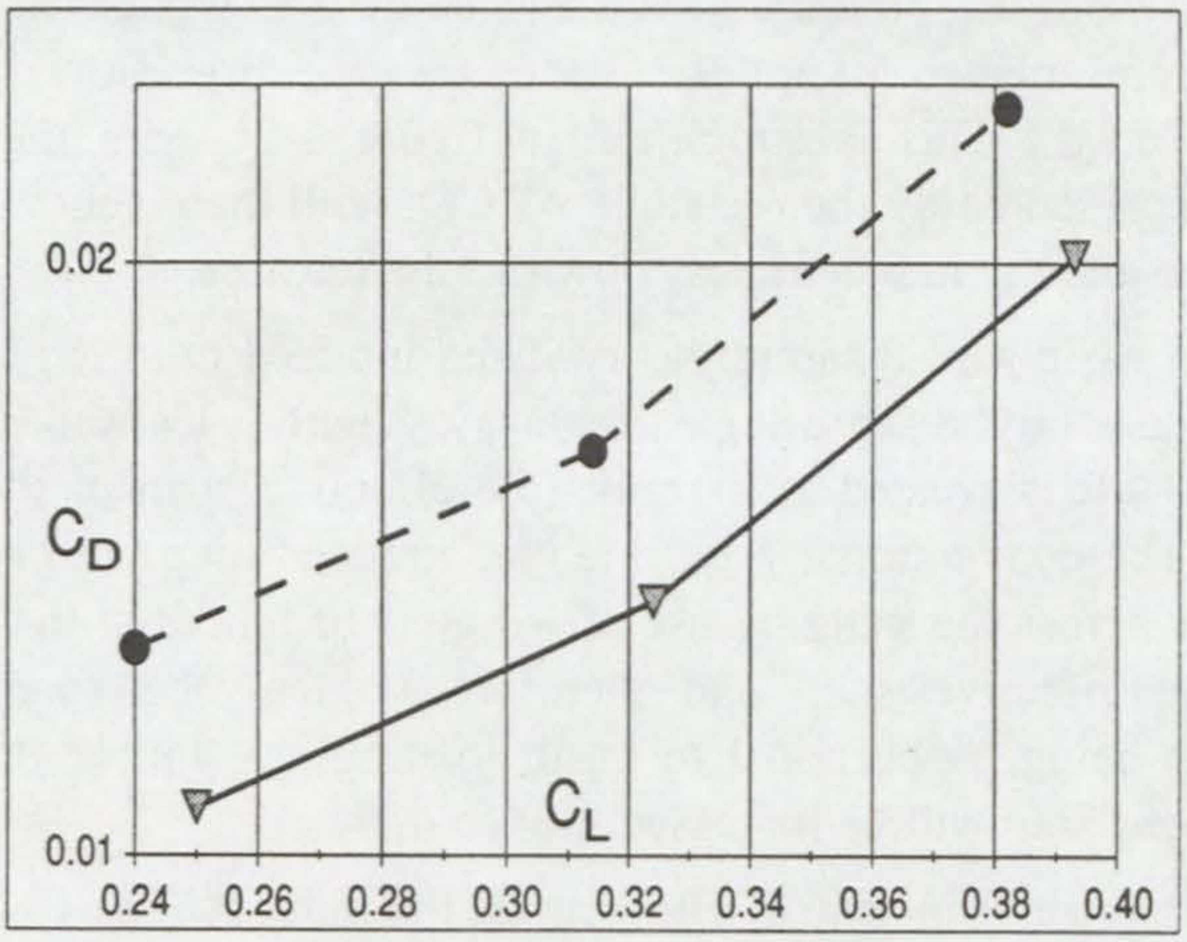

Figure 1-3b This shows the result of the Phoenics CFD code calculations on the plain and notched (at 70% span) wing shown in figure 1-9. The two wings are of equal area and calculations were made at angles of attack of 2°, 3° & 4°. The notched wing (solid line) has a greater lift and reduced overall drag as compared to the plain wing (dotted line).

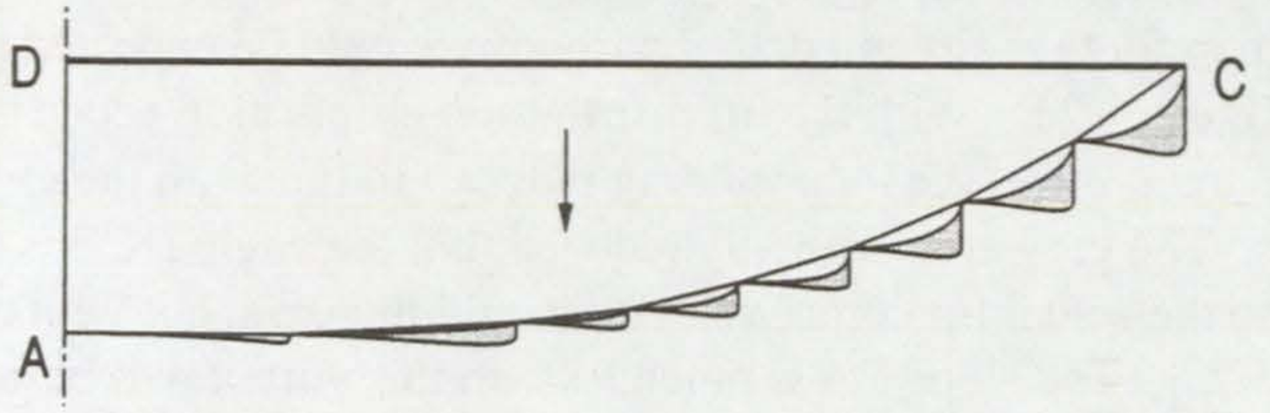

Figure 1-3c This is similar to the swallow wing in figure1- 1a which would be expected to have the same reduction in induced drag.

To reduce the steepness of the slope CE it would help if more air was removed at point E. The effect of this is seen in figure 1-2e, where the area EB has been increased. Although the lift is less than in figure 2d it is more than the basic wing in figures1- 2a & 2b, with noticeably less induced drag.

In order to verify the above hypothesis the two wing shapes in figure 1-3a were checked with a computer using the PHOENICS CFD code. The basic wing was made up using the NACA 230 mean line with a taper ratio of 4. The wings were in effect cambered plates with no thickness. The second wing had a notch at 70% span and the same total area. The results of calculations at 2°, 3° & 4° are recorded in figure 1-3b. At each angle of attack the notched wing (solid line) has greater lift and less drag when compared to the basic wing.

The bleeding off of the cross flow short of the tip appears to offer a way of reducing the additional drag induced by lift.

The results of these calculations are in line with the predictions and follow the indications from the bird world, although it must be remembered that computer comparisons are not all that reliable when delving into unproven areas. The importance here is the difference in lift and drag rather than the absolute values.

If this level of reduction in drag is possible with a single bleed off point what would be the situation with several cut outs in the trailing edge? In figure 1-3c it will be seen that the effect of many separate trailing vortices is to considerably reduce the cross flow area and results in a great reduction in the area of induced drag. In practice there will be some interference between each trailing vortex and so the reduction will not be as great as if each one could be totally isolated.

Swallows and other birds would appear to use this aerodynamic system to reduce significantly the energy required for flight. The owl gives us another view of the same problem. Although they do not fly far they are renowned for their very quiet flight and it is well known that drag creates noise. The owl's wing with its predominant and regular trailing edge feathers would appear to help minimise the noise from the wing vortices.

It might be expected that the owls would achieve laminar flow at their low operating speeds. The indications are that they use turbulators in the form of fine down to create turbulent flow so as to increase the maximum lift available – typically turbulent flow achieves about 50% more lift.

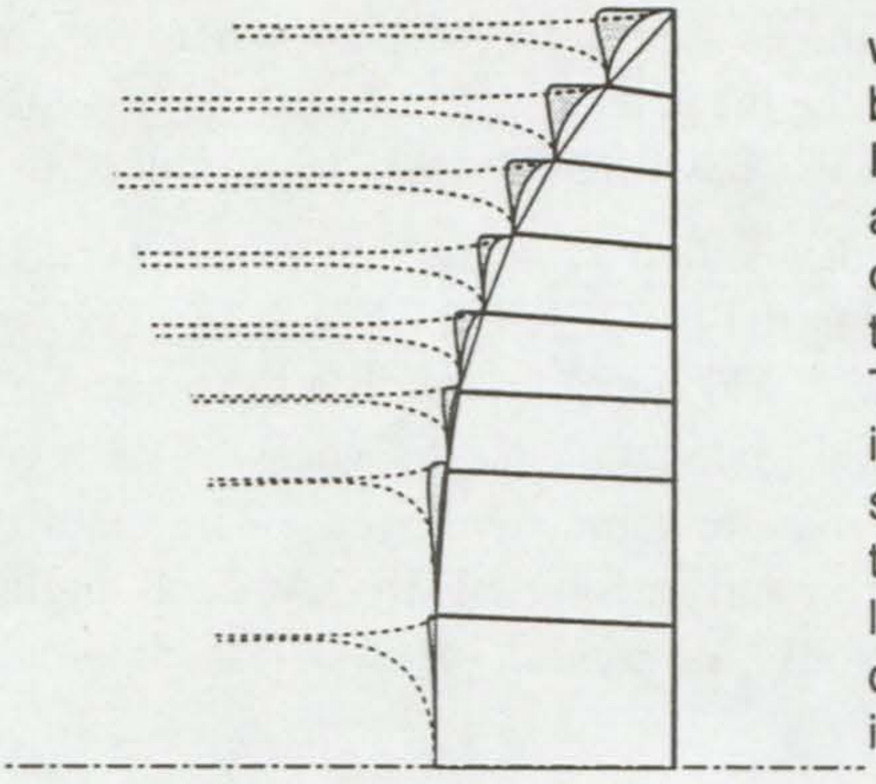

Figure 1-4a This is how the 'swallow wing' flow might occur on a fully battened soft wing sail.
It is important that each vortex is of approximately the same magnitude, otherwise the bigger ones will devour the lesser.
The vortices will still tend to combine into one single vortex further downstream in accordance with conventional aerodynamic theory, but the longer this amalgamation can be delayed the greater is the saving in induced drag.

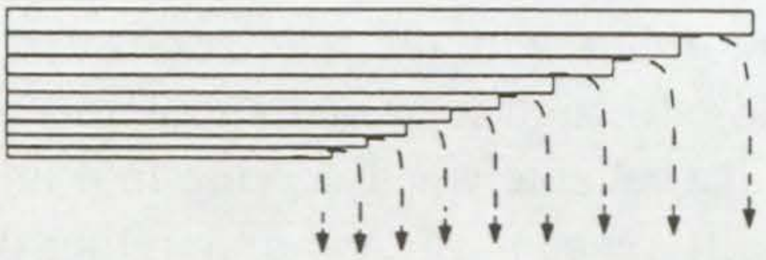

Figure 1-4b The effect of many separate vortices is to have a system that is similar to having many separate wings, fixed one behind the other.

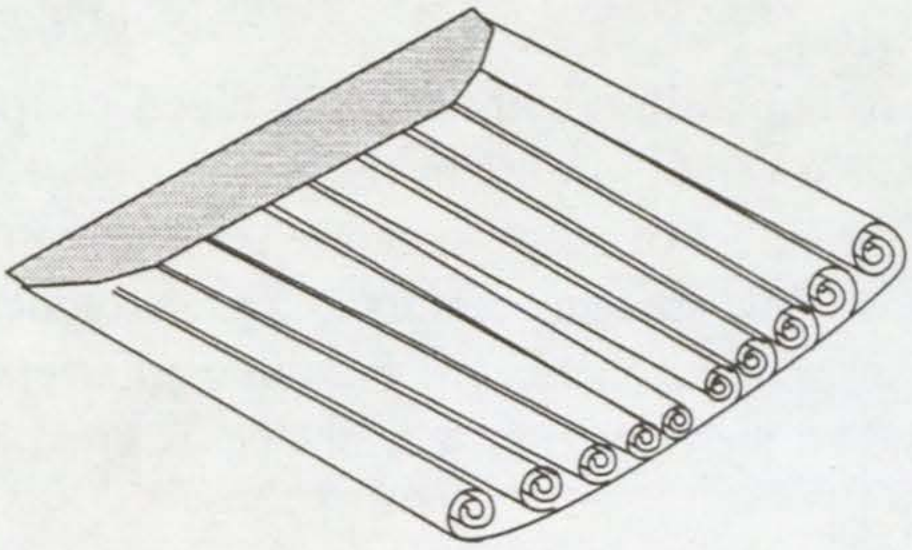

Figure 1-4c The multiple pairs of vortices remain separated downstream of the foil as depicted on the left.

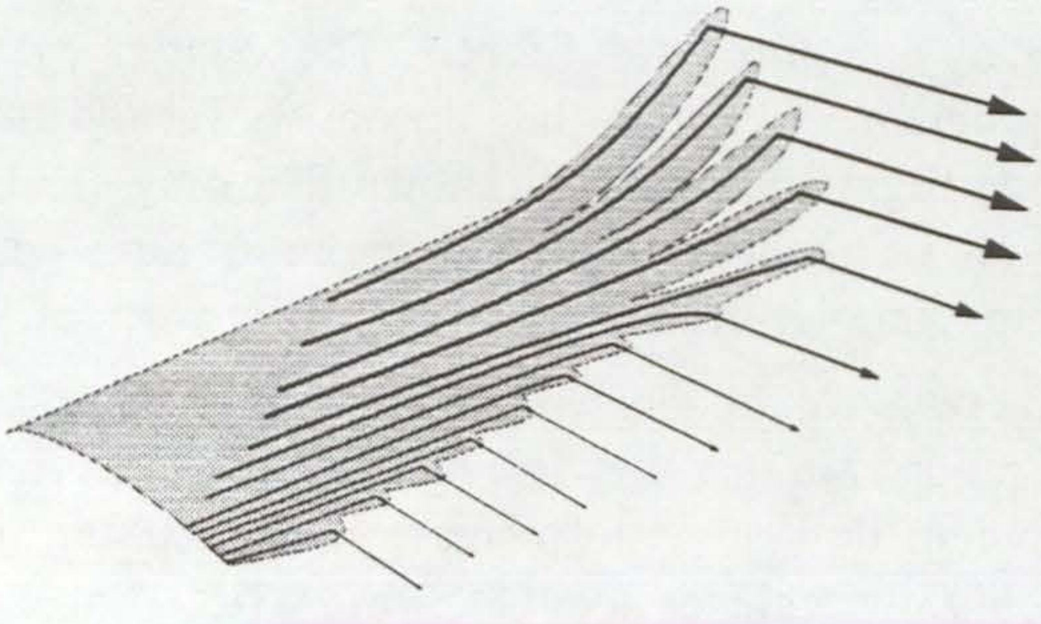

Figure 1-4d The flexing of a birds feathers ensures that the tip vortices remain separated and each feather along the trailing edge also has its own separate vortex. This bleeds off the cross flow into many small vortices rather than a single strong vortex as is achieved on a standard aircraft wing.

The wing shown in figure 1-3c is very similar to a mainsail with a separate vortex trailing off each batten (1-4a). Provided that each vortex is of approximately the same strength the stronger will not devour the weaker.

According to the principles discussed above separating the induced drag trailing vortex into several separate ones should produce less drag than a wing or sail with a single horseshoe shaped vortex system.

The most efficient system would be if each segment were to extend to near maximum span, but this would then require that the tips are kept apart, as is the case with the wings of the eagle or buzzard.

If the span is not limited it is structurally easier to spread the segments along the span, but still keeping them as long as possible. This gives us the semi-gothic wing shape of the swallow and many other aerodynamically efficient birds, with their ragged trailing edge. The albatross with its long wings has a smooth trailing edge, except for three distinctive feathers at near the tip.

The system of using a ragged trailing edge appears to have been used by nature since the times of the pterodactyl but it is not part of established aerodynamics, so it has not been used on wings, wingsails or foils so far and is presently the subject of international patent applications.

There is little relevant experimental data on the details of this type of flow, so working out what is happening has so far be dependant upon computer simulations and observations. In conventional aerodynamics the flow off the trailing edge is assumed to combine downstream into a single strong vortex off each tip. The indications from natural aerodynamics are that although the flow still combines, it is further down stream and of greatly reduced intensity. Thus the passage of a foil through the surrounding fluid causes less disturbance, resulting in less overall drag for the lift produced.

The whole setup can be considered as a series of smaller foils and to optimise the set up it would pay to have most of the foils going to full span as is seen on large birds. To keep the vortices separated the tips are spread across the flow. This is normally achieved by the flexibility of the tip feathers and although this is in theory possible to use on rudders, centreboards and keels they would probably be too prone to damage to be of any practical use in the real sailing world.

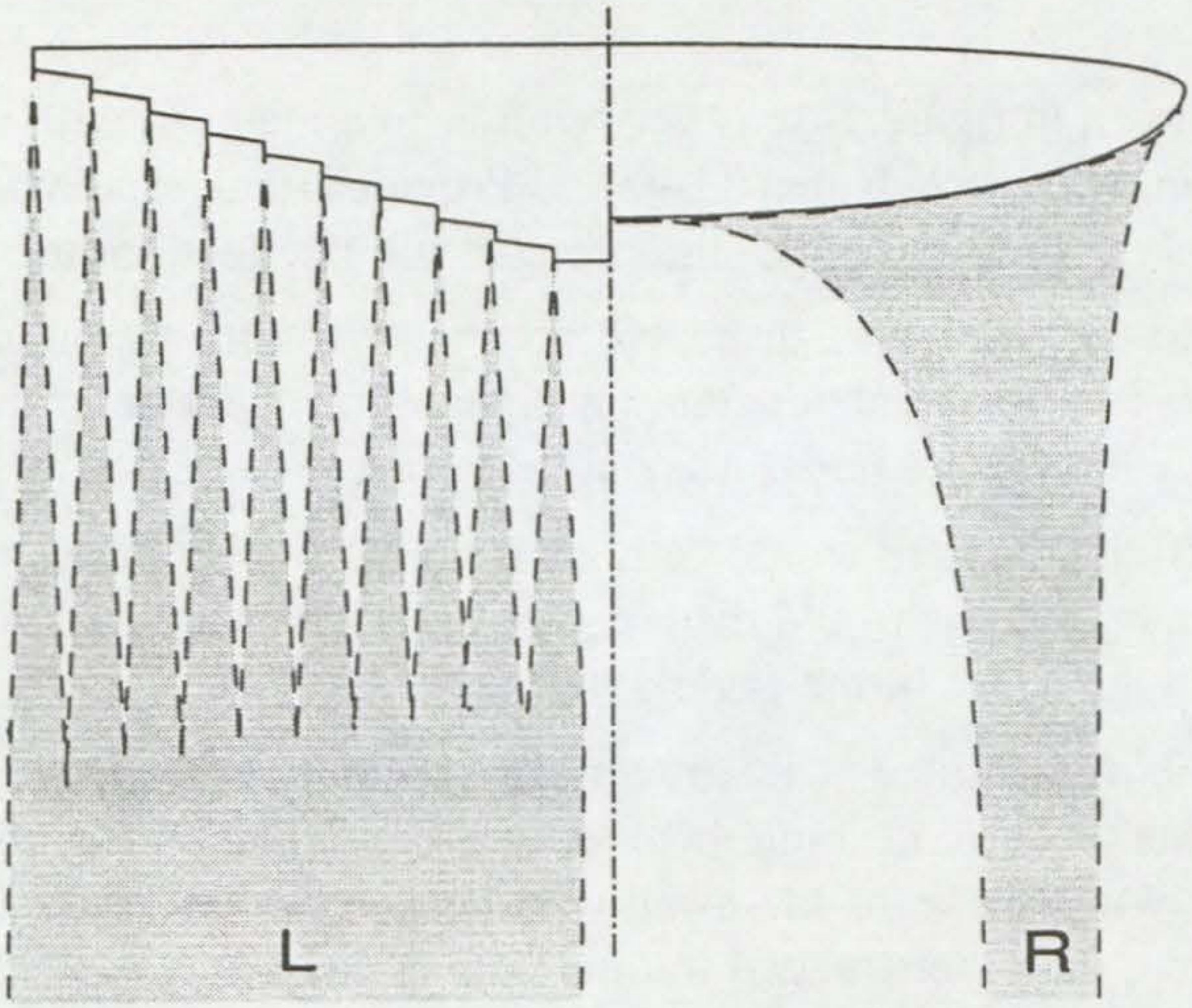

Figure 1-5a The left section shows a wing with a series of fixed trailing vortices which combine down stream into a large but weak trailing vortex.
The right half shows the conventional single horseshoe trailing vortex produced by an elliptical wing. In practice the tip vortices are much stronger and dominates the flow downstream.

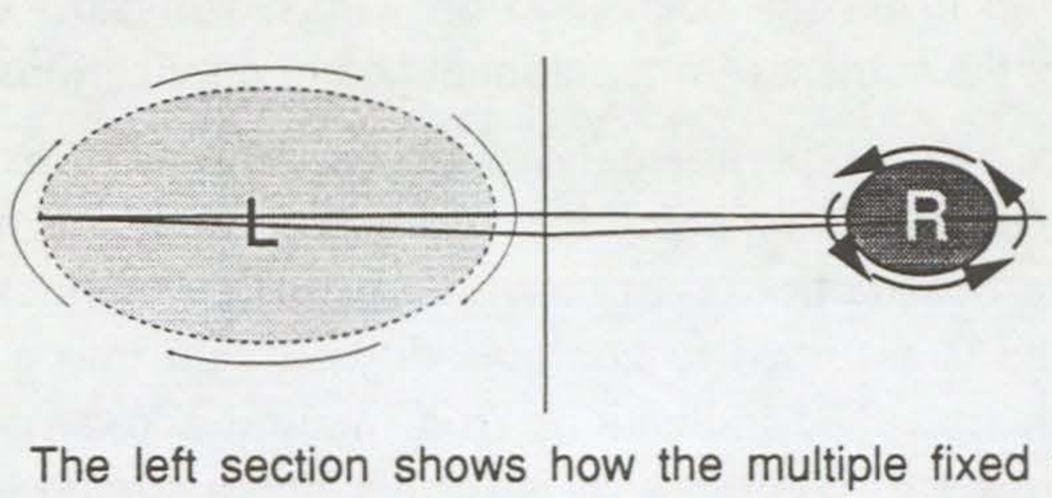

Figure 2-5b. The left section shows how the multiple fixed trailing vortices combine downstream into a large but very weak elliptical trailing vortex.
The right half shows the conventional single intense horseshoe trailing vortex core produced by an elliptical wing.

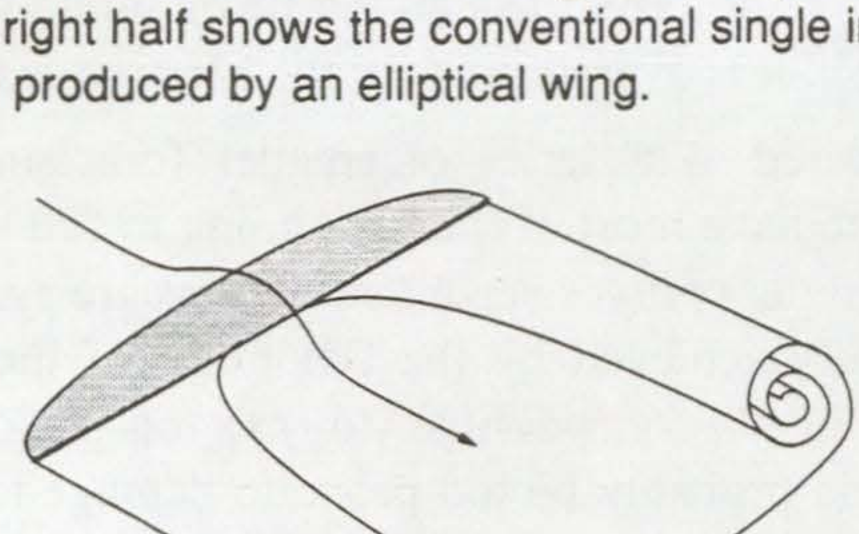

Figure 1-5c The conventional approach to a wing with a single pair of vortices rolled up into a horseshoe wake.

Over the years there has been an anomaly as aerodynamic advice has been in conflict with what has been found to work best by the top racing yachtsmen. Aerodynamicists have been telling sailors that they need to have such things as elliptically shaped sails for minimum induced drag and maximum efficiency. Yet sails which are nearly triangular with only a small amount of roach are surprisingly efficient. The apparent increase in the power of the larger elliptical roached sail does not appear to be caused by anything more than the extra sail area, and when the wind blows these sails appear to be at a disadvantage. Is this just a handling and rigging problem or might it be that these elliptical sails are basically less efficient ?

In strong winds when the stability is limited the triangular sail has the advantage of a lower heeling moment for the same induced drag[91] because the centre of effort is lower for a given mast height. Even in light winds a sail with a small roach and significant twist appears to be close to the optimum. The twist is in the order of 15° and is considerably more than the effect that wind gradient alone would require. This effect appears in bird's wings and hang gliders as well.

With this area of natural aerodynamics there is a shortage of scientific verification due to it being ignored by classic aircraft aerodynamicists. There is plenty of evidence to support the phenomena and amongst other things it may help to explain why birds have an odd number of feathers on their wingtips – even numbers pair off too easily, so reducing the number of vortices and thus increasing the drag.

The conventional aerodynamic approach is to consider the rig as a vertical foil with the sea surface acting as an endplate so that there is in effect a mirror image and the effective aspect ratio is in theory doubled. With this arrangement the trailing vortices combine into a single pair at 78% of height (span) as is shown in figure 1-6a. Recent studies[111] have shown that this is an idealistic approach and unachievable in practice since the relative roughness of the sea's surface and the wind gradient prevents any form of useful endplate ever being formed. The main effect of the sea and hull is to modify the tip vortex and thus the characteristics of the flow around the sail. This 'choked' flow can be adapted to minimise the induced losses. The problem is that there is little information available on how this should be controlled for best effect. The shape of the hull and deck has a significant influence and requires further study.

The aspect ratio can be a confusing figure as there are so many ways of measuring it. The basic rule is *height*^{2} */ area*, this can be for individual

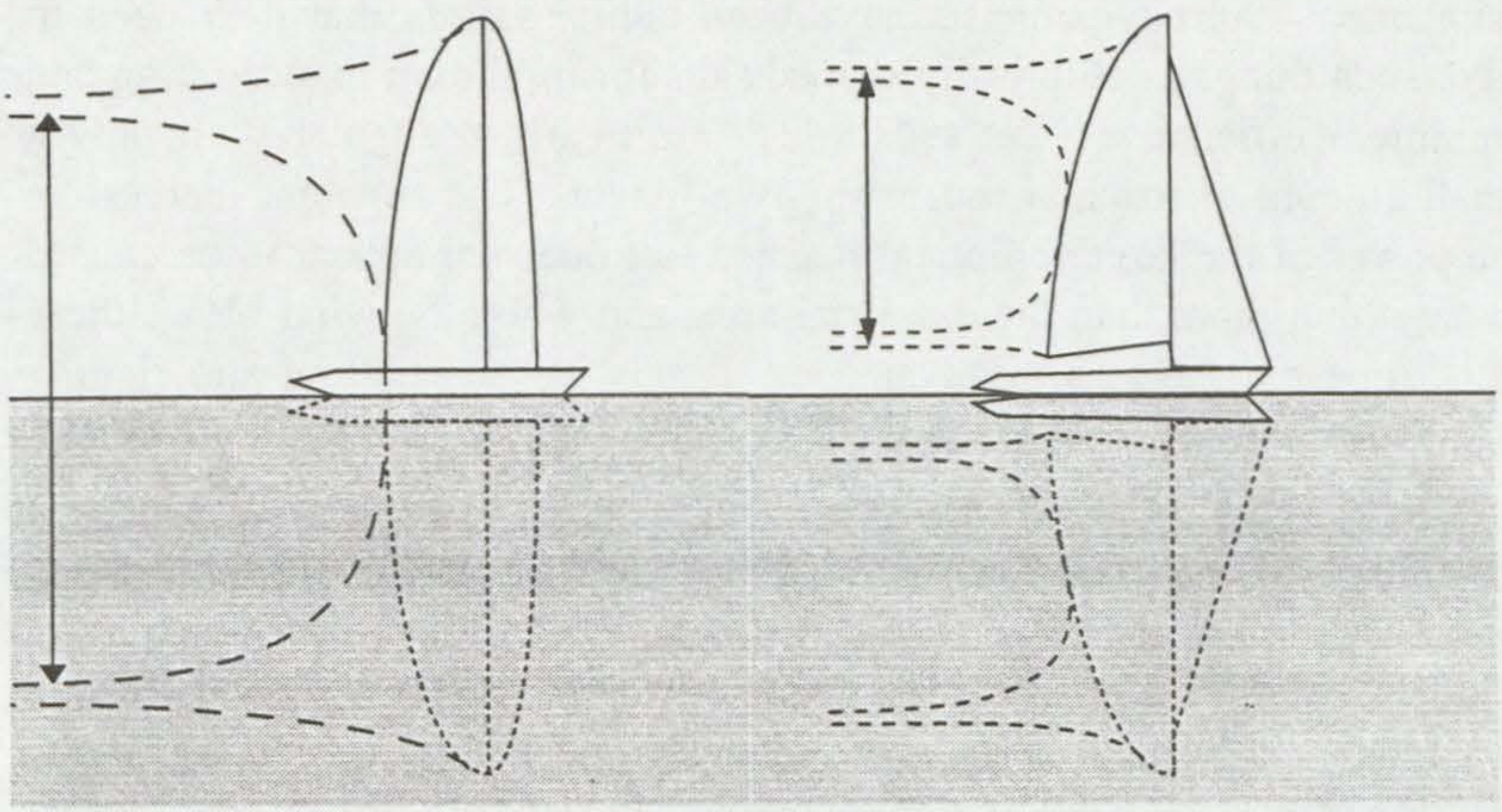

Figure 1-6a The aerodynamicists conventional approach to the induced drag of a sailing boat. The sea's surface creates a reflective surface such that there is a mirrored rig and flow below the surface. This has the effect of doubling the effective aspect ratio of the rig and theoretically halving the induced drag. Experimental results(111) show this to be very optimistic and that the predicted reduction of drag is not achieved in practice.

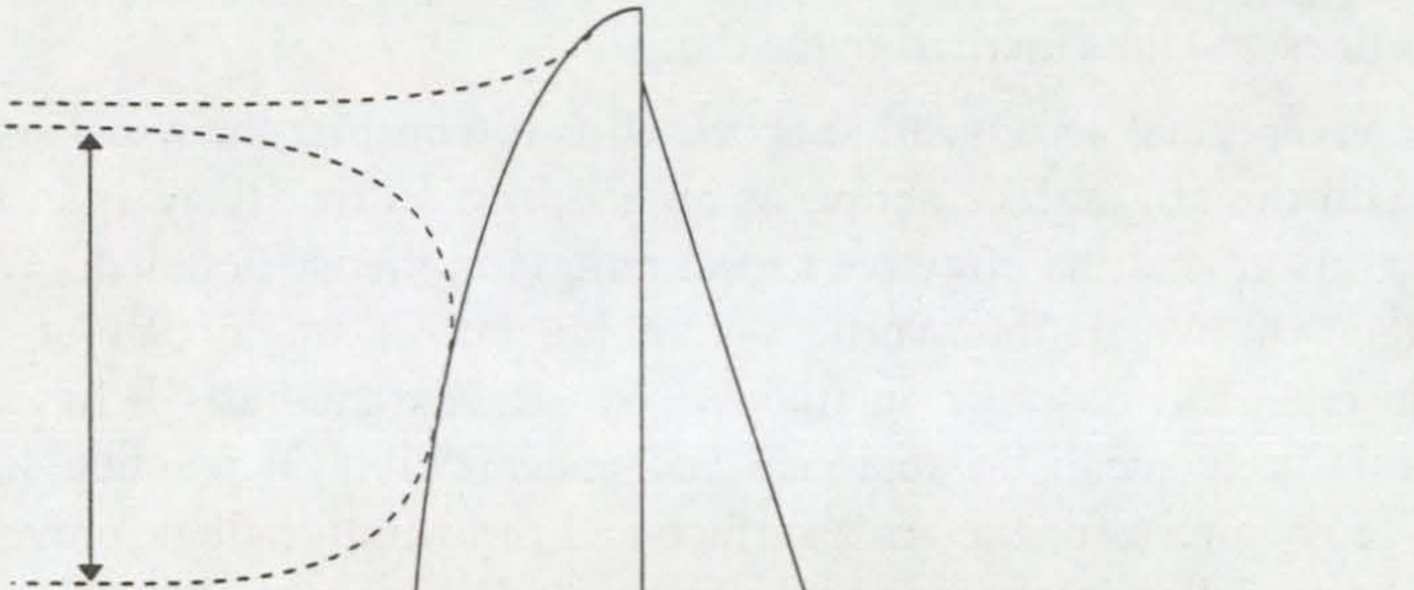

Figure 1-6b The flow over a conventional rig is more like the above with trailing vortices from both the top and bottom of the rig. The hull in effect acts as a boundary layer bleed and keeps the sails isolated from the turbulent layers near the sea, although the hull itself also has its own boundary layer and increased turbulence in its wake.

sails or the rig as a whole. The height is the effective distance between the two tip vortex systems. In figure 1-6a the aerodynamic world would double the aspect ratio of the rig on the left due to the mirror image effect of the sea surface.

For sailing it is probably more realistic to use an aspect ratio that is close to the geometric one for the whole rig *($height^2/area$)* as shown in figure1-6b and not the more traditional use of the aspect ratio of individual sails. There will be some form of vortex system at both the top and bottom of the sails. This leakage around the ends causes induced drag and may be reduced by either moving the tip vortices further apart or reducing their intensity, or both. The normal way of doing this is to reduce what is known as the span loading because in conventional terms the induced drag is directly proportional to *($span\ loading)^2$*. In sailing there is a practical limit to increasing mast height (span) due to either stability or class rules[(113)]. With a given stability, as the sail height is increased so the allowable sail force reduces. The result is that increasing the height of a rig decreases the maximum force which can be used. There is in practice a basic rule for the maximum power from a rig:–

Only increase the height of a rig when the sail area is limited.

At all other times spread it as long and low as is practical. This is explained in more detail in AYRS 113, but basically a 'normal' sail area is about *$Length^2$* and the optimum aspect ratio is in the range 1 – 2. The most powerful rigs have bowsprits and bumpkins like the yachts of a hundred years ago. Developments since then have improved the power from a given sail area, but the restricted areas applied by the racing rules has reduced the overall power output available and therefore reduced the overall performance of contemporary yachts. This is particularly noticeable in lighter wind conditions where cruising yachts use the auxiliary engine to overcome any short comings of the rig.

When designing a rig it is important to understand the differing effects in the limiting factors. They may be class rules, area, spar lengths, technology available or simply bank balance. Each of these limitations will produce different optimum rigs and any real rig is usually a combination of these and many other factors.

Trying to produce something non-standard inevitably cost more in terms of both time and money, with the initial efficiency rarely coming up to expectations. Without change we will never get any new developments and development is what the AYRS is all about.

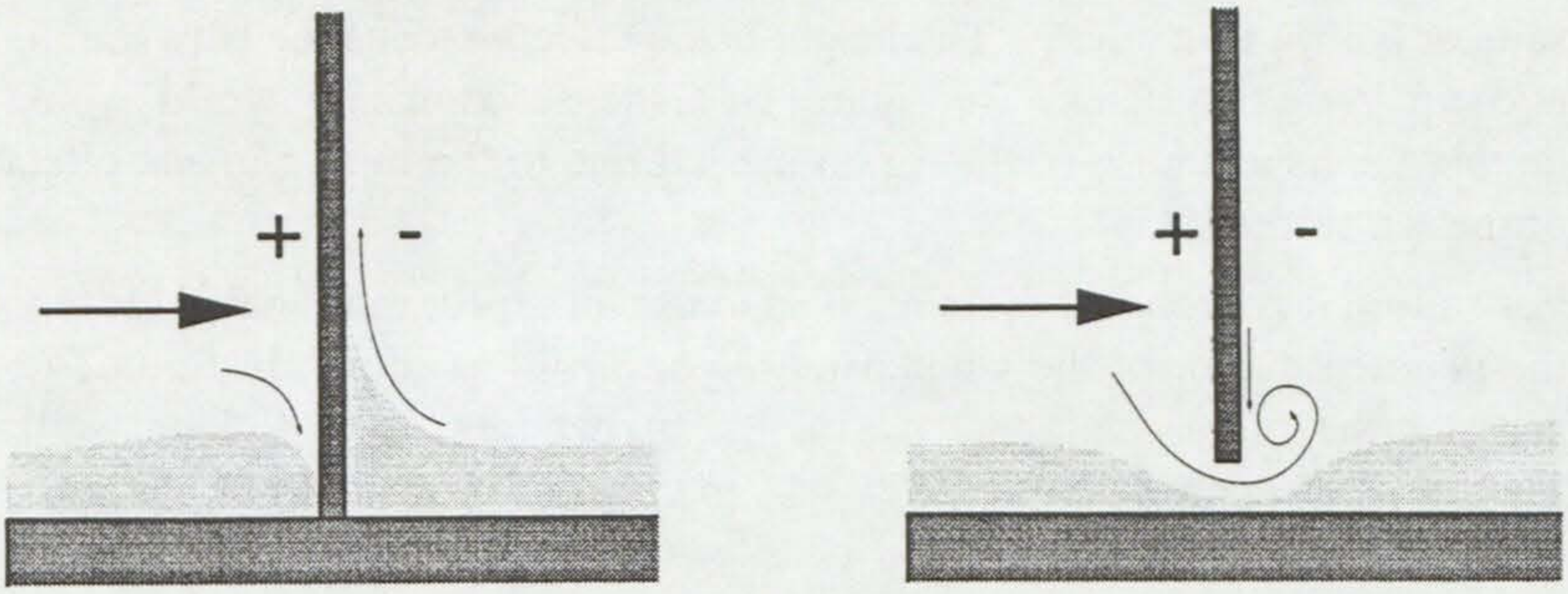

Figure 1-7a The effect of bringing the sail down into the boundary layer is to drag the turbulent air up into the low pressure side. This both increases the drag and reduces the power available.
A small gap as shown on the right produces a vortex which keeps clearer air flowing around the sail and improves performance.

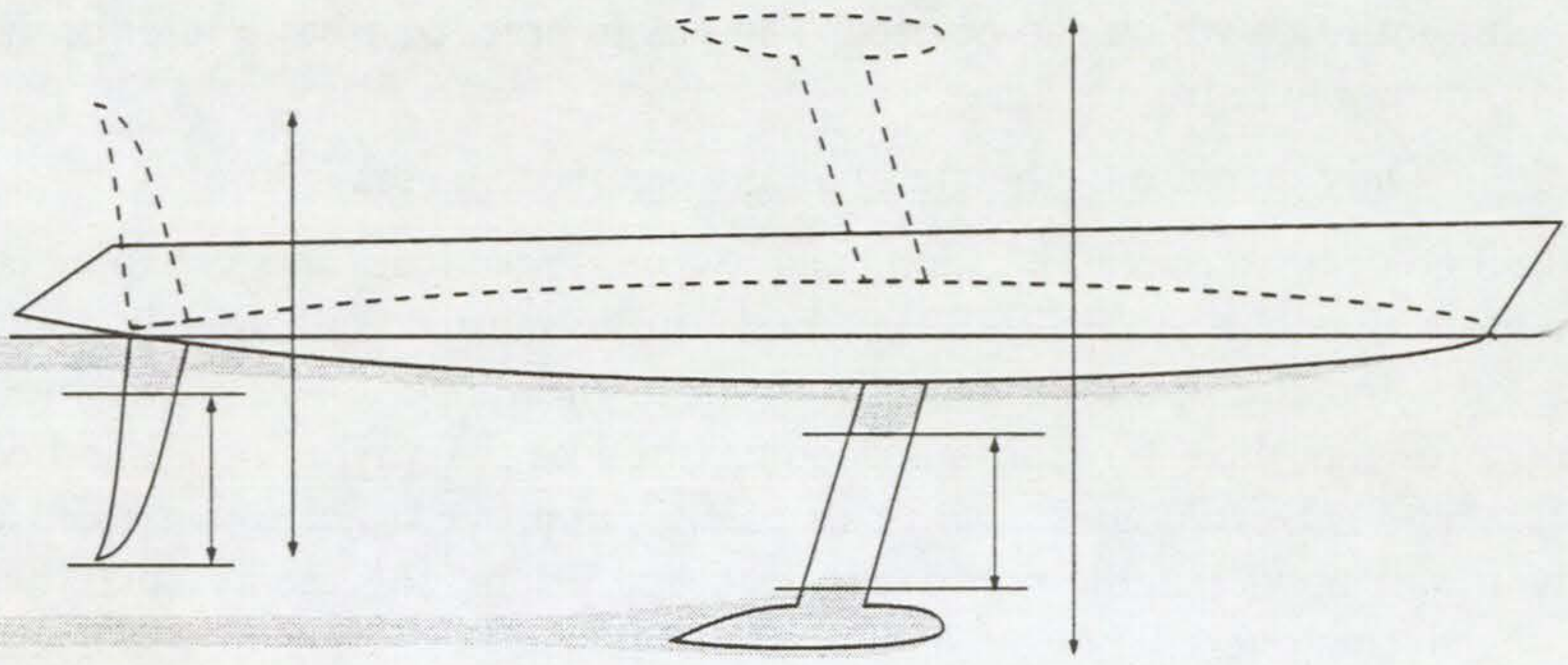

Figure 1-7b The same principle applies to the top of the keel and rudder where the boundary layer of the hull reduces the efficiency of the top of the foil. This has the additional effect of lowering the centre of pressure and increasing the heeling moment.
The flow over the bulb also has an adverse effect on the efficiency at the lower end of the fin.
The conventional approach assumes some mirror image effect and a near doubling of the effective aspect ratio as depicted by the dotted lines above. In practice the situation is more like the shaded area, where the boundary layers and mutual interference reduce the overall effective span.
There is still a great deal to learn about optimising the interface between the fin and ballast bulb. The indications are that the conventional approach, with a simple bulb attached to the base of the fin is amongst the least efficient layouts.

3 *SAILS*

With sails having been developed almost entirely along empirical lines it is not surprising that many of the features developed in nature have also appeared in sails.

The previous section showed how the conventional aerodynamic approach with its mirror image as shown on the left of figure 1–6a is not borne out in practice and the real situation is more like the drawings next to it.

If there is not a single trailing vortex at the tip but a series down the leech and no mirror image there must be a lower trailing vortex system of some sort. The intensity of the lower vortex system depends upon the gap between the bottom of the sail and the surface (water or deck), but except in certain circumstances the gap should never be closed completely.

With the conventional slope to the leech of a mainsail there is a tendency for the flow off the leech to flow down the sail as indicated by the arrow in figure 2-1a. This brings the two legs of the trailing vortex system closer together, reducing the effective span and increasing the induced drag. As the rig heels so the apparent geometry changes and the effect is reduced.

If the sail is fitted with battens which protrude slightly beyond the edge of the sail vortices can be induced to leave the leech in the manner indicated and this is why there is no performance to be gained by trimming off the short exposed ends of battens.

The main lower vortex comes off the boom but a secondary one may also be induced off the lower battens in light winds. The effect of the boom vortex is vital for stabilising the flow over the lower part of the mainsail. If the sail touches the surface then the flow is disturbed and the low pressure on the lee side is reduced, as shown in figure 1-7a.

At the head of the sail several separate vortices may be induced from the mast, headboard and battens. The more there are the less will be the drag, but care must be taken that there is not one dominant vortex which devours the lesser ones and looses the advantage.

If the leech is straight or even slightly hollowed and the top bent back there is a tendency for the flow to move towards the head and clew, thus separating the end vortices and reducing induced drag This phenomena has been reported in wind tunnel tests.(111) It would appear to be that since the vortices at the extremities leave the sail slightly later than those further in they tend to draw the main vortex cores apart, increasing the effective aspect ratio and reduce the induced drag slightly.

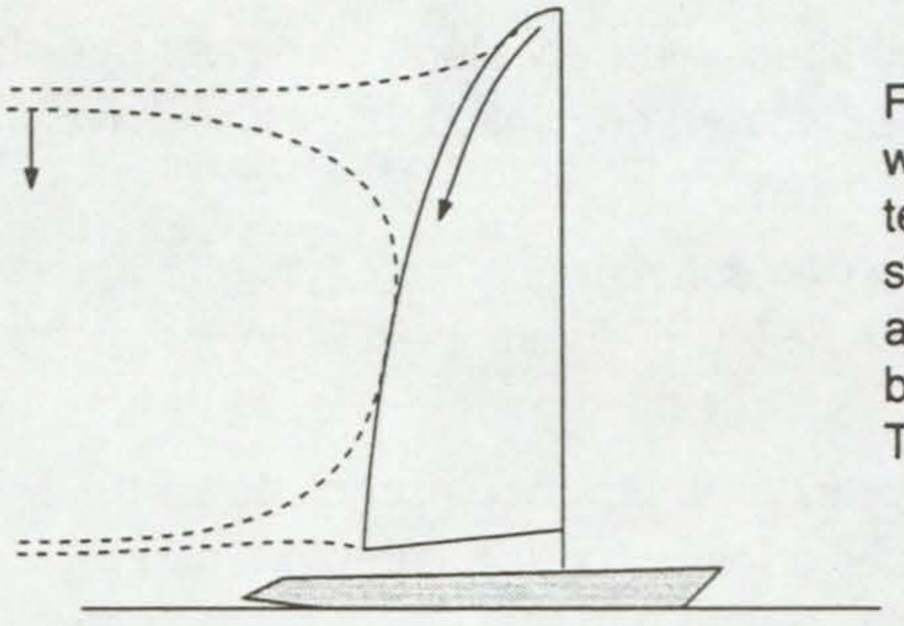

Figure 2-1a On conventional sails with convex leeches there is a tendency for the trailing vortex to slide down (as indicated by the arrow) and reduce the separation between it and the boom vortex. Thus increases the induced drag.

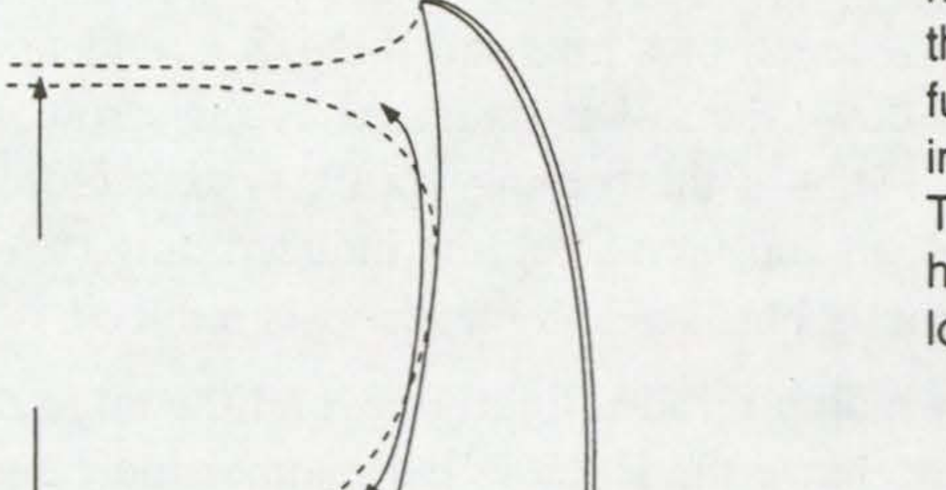

Figure 2-1b If the leech is hollowed there is a tendency for the trailing vortex system to move further apart and reducing the induced drag.
The stronger vortex at the boom has the effect of dragging the lower one down.

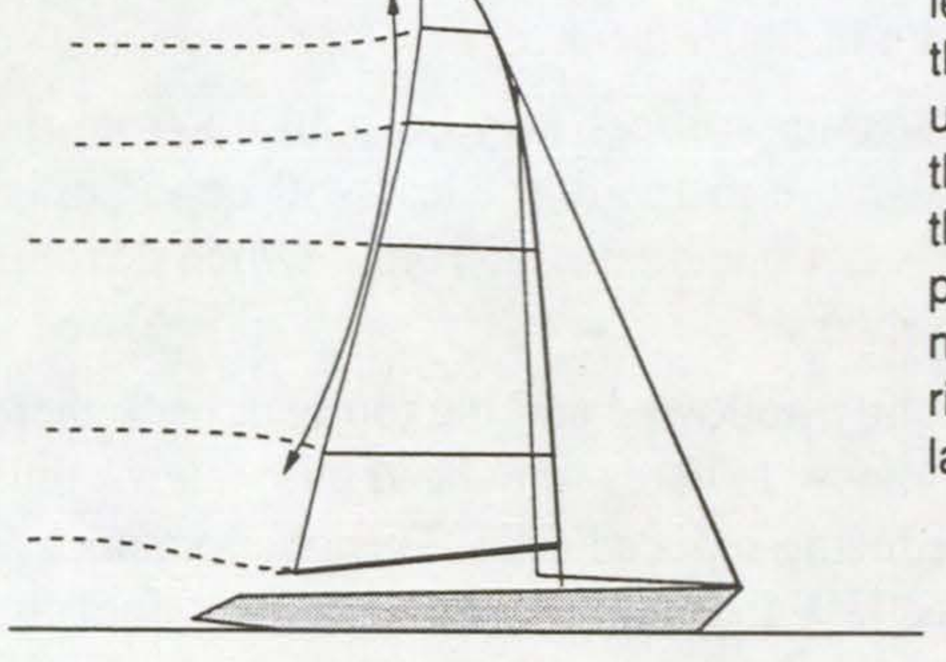

Figure 2-1c In strong winds it usually pays to rake the rig back and bend the mast so that the leech is hollow. This encourages the trailing vortices to leave as far up or down the leech as possible, thus reducing induced drag. With the angle of rake reducing the power from the sails, this is normally only practical when the rig needs de-powering due to a lack of stability.

In experimental terms it is very difficult to detect differences in a wind tunnel or test tank of less than ±1%. The results of the same tests on different days can easily vary by more than this, making it difficult to detect small variations and making it very easy to misinterpret the results.

The well known effect of raking a rig back to de-power it has the advantage of reducing the drag by pulling the trailing vortices apart in the same manner as a hollow leech. The effect of both sweep back and reduction of the apparent angle of attack of the sails which reduces pointing ability, but conversely the reduction in drag allows a higher pointing angle. This process is therefore of most use in fresh winds and open seas where driving power rather than pure pointing ability are more important.

The head of the sail and masthead have an important influence on the overall aerodynamic efficiency of a mainsail. Figure 2-2a, b & c show how the flow can be persuaded to leave at the batten ends and even the headboard and masthead crane have an influence on this. The mast above the top of the sail is often ignored, but it is an important part of the overall aerodynamics of the mainsail. Cutting away the masthead and raising the top batten too high can have an adverse effect on the vortex flow as is shown in figure 2-2c.

One area frequently overlooked is the vortex off the boom. This has a dominant effect on the power of the lower part of the mainsail and influences the flow over the after part of the hull. The boom is in effect part of the sail area (and why it normally pays to go for the maximum allowed depth). It helps if the after end in particular is kept clean and clear of fittings. Certainly any weight saving cut outs should be covered with plastic film, and a simple central mainsheet system helps. The wire strops used in some classes are also helpful and if you reef the sail it should be neatly bundled, particularly towards the after end.

The habit of leaving the reef fold hanging below the boom is only effective if it can be prevented from flapping (by putting some sort of sheet on it). Similarly the traditional cluster of blocks and fittings at the end of the boom are not helpful to the vortex dynamics. The boom end should also be drooped if possible as it helps spread the lower the trailing vortices and reduces the aerodynamic wake (drag) of the hull.

The traditional philosophy is that it is the length of luff that matters for windward sailing efficiency. It is in reality the effective length of leech that has far more effect on pointing ability by moving the vortex systems apart and reducing the level of induced drag.

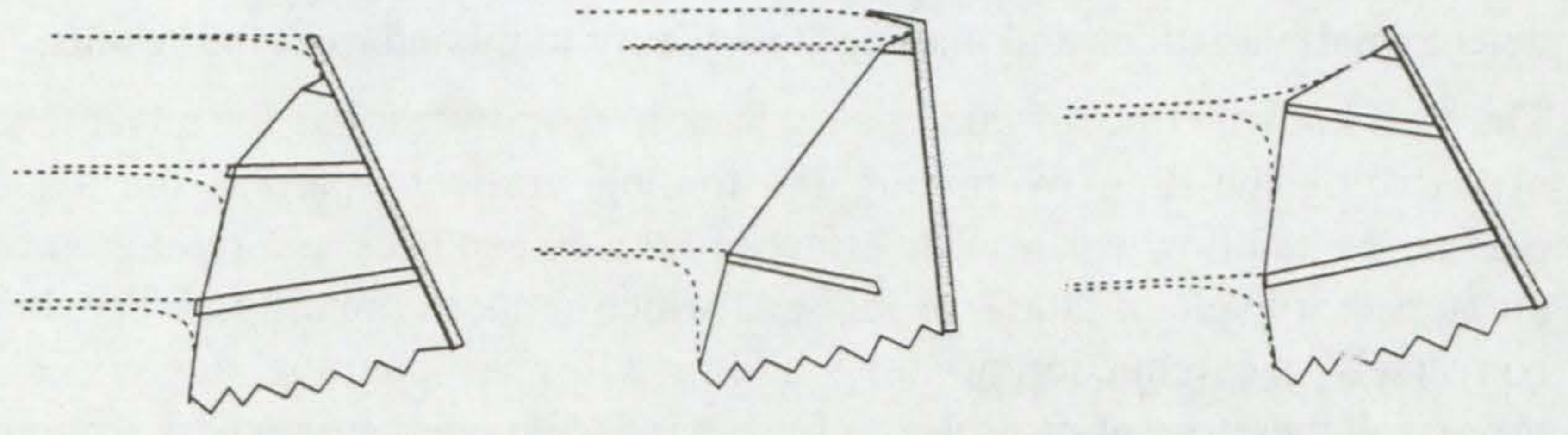

Figure 2-2 a,b,c

Different types of mast head. (a) shows three separate streamers from the mast head and the top two battens. (b) shows how it is possible to have separate flows off the headboard and masthead crane, These need careful design to either encourage one or two separate mast head streamers. (c) has a very short masthead and the top batten raised so as to bring the top masthead streamer down and potentially increases the drag. The mast above the top of the sail is a part of the overall aerodynamics and should not be ignored.

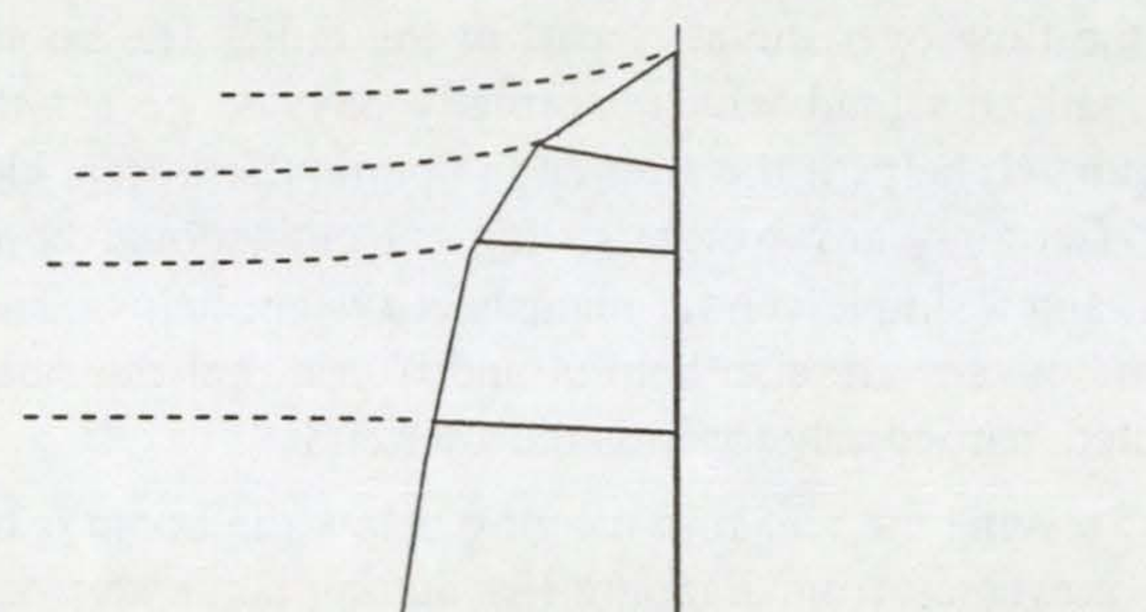

Figure 2-2d A sail fitted with a series of battens which protrude from the leech such that they allow a separate series of trailing vortices to develop.

As stated earlier there is little relevant experimental data on the detail of this type of flow, so working out what is happening has so far had to depend very much upon observation and interpretation, but at the time of writing (1995) there are a series of studies and experiments being undertaken which will hopefully shed some more light on the situation.

One such study is investigating the effect of the sea's boundary layer on the performance of various sails, both with and without a hull present. There is also a comparison being undertaken between bermudan, chinese junk and the polynesian crab claw rigs. One of the main advantage of the older style rigs is that they appear to achieve considerably more power off the wind, without very much compromise in windward performance. The problem has been that the westernisation of these rigs has lost much of the subtleties developed over many centuries.

A recent series of wind tunnel tests on a variable geometry wing appears to show some strong indications of the effects of natural aerodynamics in that a wing with about 10° of twist is noticeably more efficient than one without. This is contra to conventional thinking and surprised the experimenters at the time, but this is in accordance with the effect reported here. These results are now being re- analyzed in light of natural aerodynamics and its polyfoil hypothesis (as explained in these pages).

Once the results of these investigations are available it is planned to produce another AYRS booklet based on the findings.

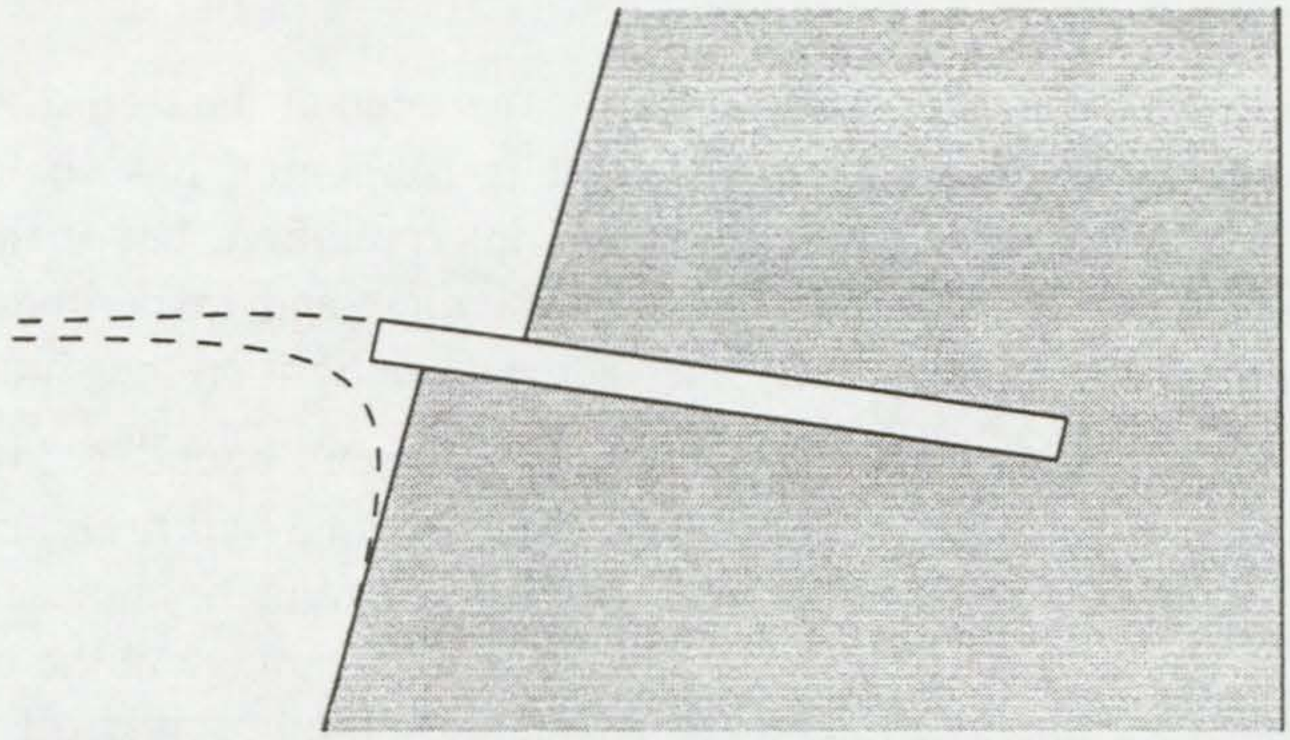

Figure 2-3a The vortex off the batten endings reduce the tip vortex and thereby reduce the overall drag of the rig.
It would appear beneficial to cut the sail away as shown despite the small loss in sail area.
Extending the battens beyond the leech of the sail further encourages the induced drag vortex to be shed from the sail

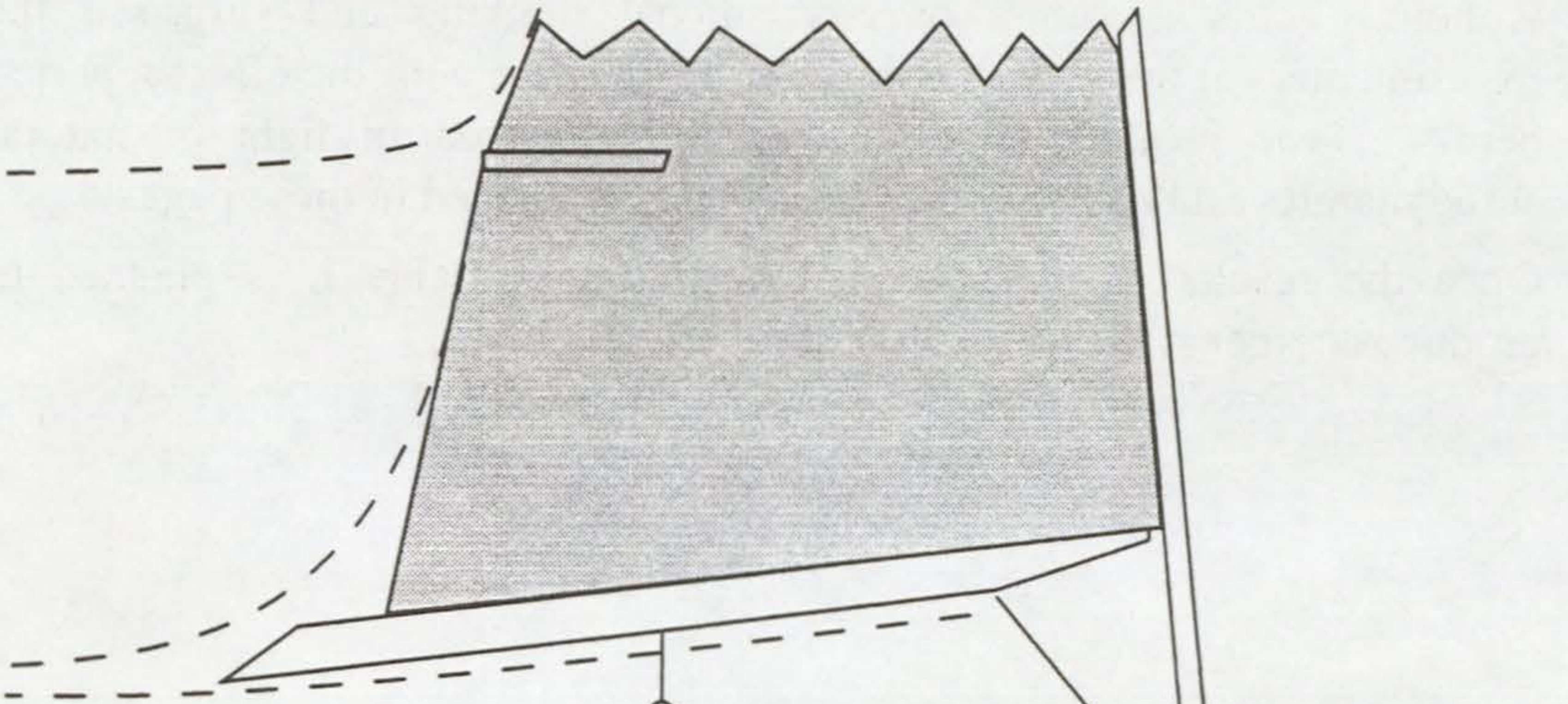

Figure 2-3b The vortex off the boom is an important part of the power of a mainsail. It is just as important that the boom is smooth as it is with the mast and sails. All fittings and holes should be faired in and blocks and fittings should be avoided at the aft end. The lower batten may also help the vortex control.

4 KEELS & FOILS

The foils in the water are there to produce a side force which opposes the sail force and to control direction. The more efficient they are the more of the sail force remains available to propel the craft.

When a boat heels due to sail force the side load is directly proportional to the angle of heel. This side force is resisted by the hull and foils. On a keel there is leakage around the bottom and at the top there is a difference in pressure on either side of the hull. There is little reduction in drag due to any endplate effect from either the hull or the water surface. At the top of the keel the water cannot flow over due to the presence of the hull, but there is higher pressure to leeward and lower to windward which must meet in the wake. This vortex causes part of the added resistance due to heel.

The leakage around the bottom may be reduced by using a winged keel. This basically adds an endplate to the fin and often more importantly allows the centre of gravity to be lowered. The reduction in drag comes from achieving separate vortices off the trailing tips; for this reason the most efficient winged keels appear to have concave trailing edges which encourage the vortices to be shed nearer the tips – see figure 3-2a &b.

In theory if a third vortex could be formed off the centre bulb the induced drag would be reduced further and it is also likely that the flow around the central bulb would also be improved. It will take some time to come up with optimum arrangements as the details of this type of flow have not been studied in any great depth and there are many unknowns still to be resolved. Trying to resolve this type of complex flow by computer simulation alone is all but impossible as the result is so dependant upon the assumptions made in the first place. A simple series of wind tunnel tests should give a guide as to the way to go.

The resistance of a winged keel could be further reduced by having separate vortices off the trailing edge of the fin and in particular the top, where the interference with the hull causes a noticeable increase in drag. This interference is caused by the complex flow formed by the junction between the fin and hull meeting, as well as the top of the fin entering the hull boundary layer which has the same effect as dropping the bottom of a sail into the dirty boundary layer of the deck – it reduces efficiency.

In principle the smaller the section at the joint between the hull and the keel the better, but unfortunately this causes serious structural problems. It is the thickness/chord ratio that appears to be the more critical, therefore this

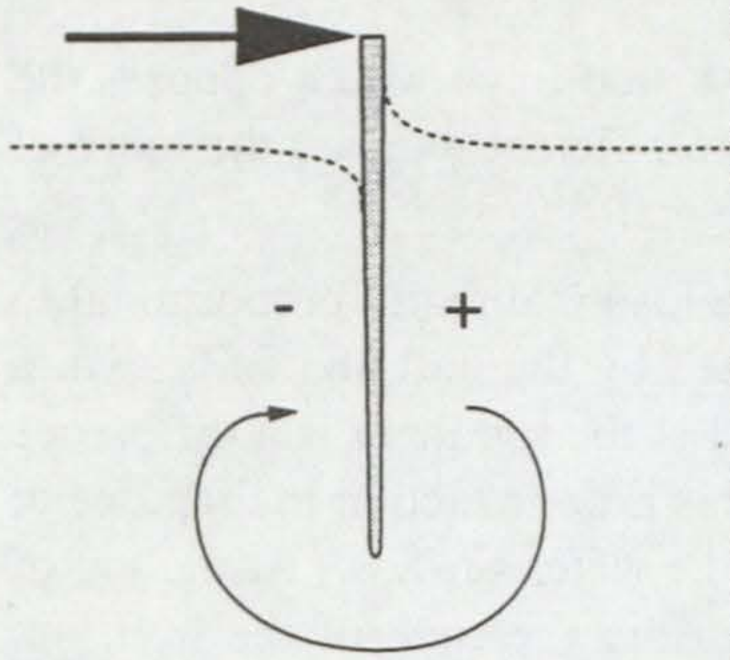

Figure 3-1a When the side force from the sails is applied to a keel or centreboard there is an increase in pressure to leeward and a reduction on the windward side.
This causes a leakage around the tip at the bottom and a difference in the water level at the surface, this later is normally hidden within the wave system of the hull.
The effect of the surface is the same as fitting an endplate – no cross flow can commence until leaving the foil – the vortex then developed is similar to a simple tip with no end plate.

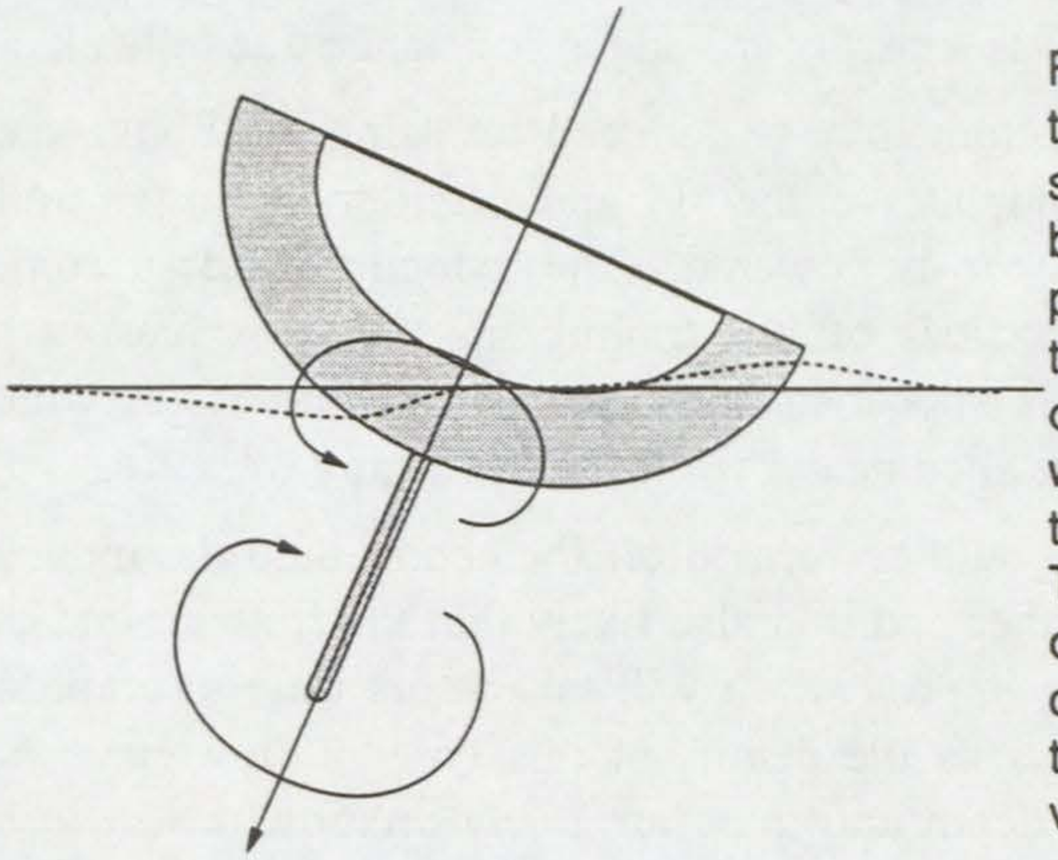

Figure 3-1b The conventional keel produces a single vortex around the bottom edge and the pressure difference at the top produces a depression of the hull wave to windward and an increase to leeward.
The hull also provides part of the side force and this cross flow is combined with the keel flow into a trailing vortex in the wake.

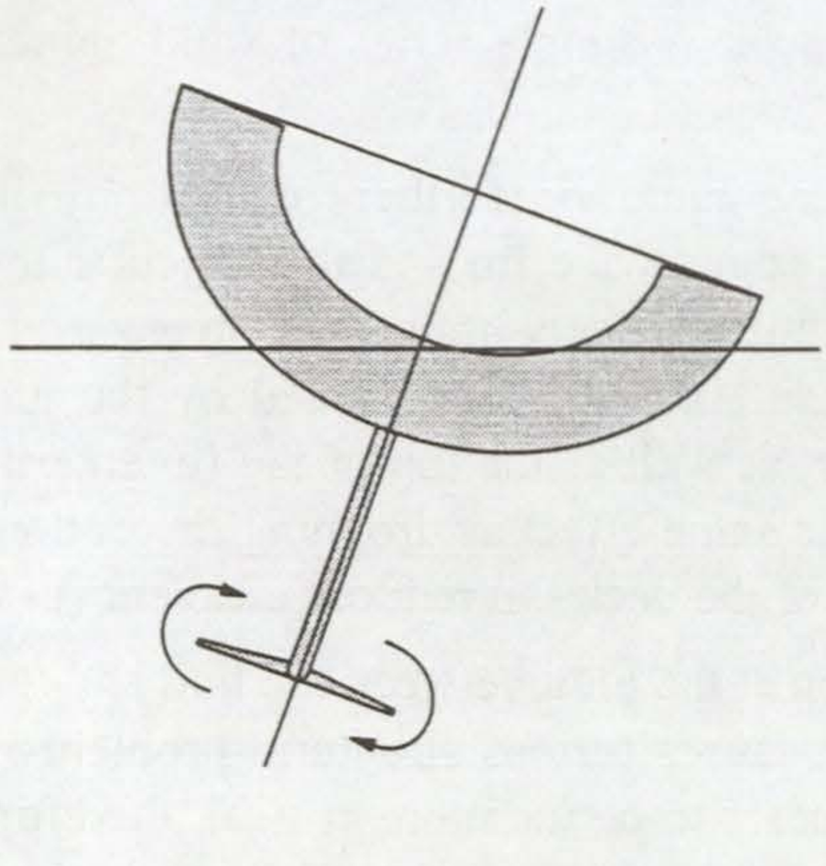

Figure 3-1c The winged keel has two advantages. The increased volume low down lowers the centre of gravity and if the wings are correctly shaped it is possible to have two separate trailing vortices, reducing the total intensity of the induced drag. Note that in this case the tip vortices rotate in the same direction.
With little side force the extra wetted area of the winged tip will always create additional drag.

may be reduced by increasing the length of the top of the keel as shown in figure 3-2b. This strake, as used on many fighter aircraft, has the advantage of keeping the flow attached at high angles of attack and therefore helps the acceleration out of a tack or other sharp manoeuvre.

Where a winged keel is undesirable or banned altogether the keel may have a series of cutouts in the trailing edge as shown in figure 3-2b. This initial study produces a very similar outline to the MME (Mickey Mouse Ear) style of keel as used in the eighties. The aim is to reduce both the interference at the top of the keel and the tip loading at the bottom. This achieves a near elliptical loading for minimum induced drag as predicted by conventional aerodynamics. The effect of the plain MME keel is that it tends to drag the top and bottom trailing vortices closer together, causing extra drag whereas the stepped trailing edge reduces it.

By having several separate trailing vortices as indicated by the modified keel the induced drag will be less than that of a more conventional keel. Another advantage of this system is that the CLR (Centre of Lateral Resistance) is raised, for the same level of induced drag, so reducing the heeling moment.

We are only at the beginning of the learning curve for this new system and initial studies show that it is very like early winged keels – the wrong shape can do much more harm than good.

From all the foregoing it can be appreciated how difficult it is to rate (or handicap) the real efficiency of a keel or rudder by taking a few measurements. The same applies to rigs. We are all aware that a very small adjustment to a sheet or the halyard tension can transform the performance. The same principle applies to keels and rudders, so there can never be a simple way of measuring their true performance potential.

All class rules should have some form of penalty for narrow tops to fin keels in the interests of practical engineering and safety. It was after the loss of several keels in the Rater classes in the 1890s that the girth measurement was introduced for the 12, 8, 6 etc Metre classes and fin keels were effectively banned for fifty years. The Star class is one of the few survivors from the previous fin keel era.

The traditional style of keel bolt and attachment which failed the fin keels a hundred years ago is still in general use today ! The problem is that it is relatively easy to calculate the static loads on a keel, but it is almost impossible to estimate with any degree of accuracy what the maximum dynamic loads are likely to be. So-called *safety* factors are in reality more

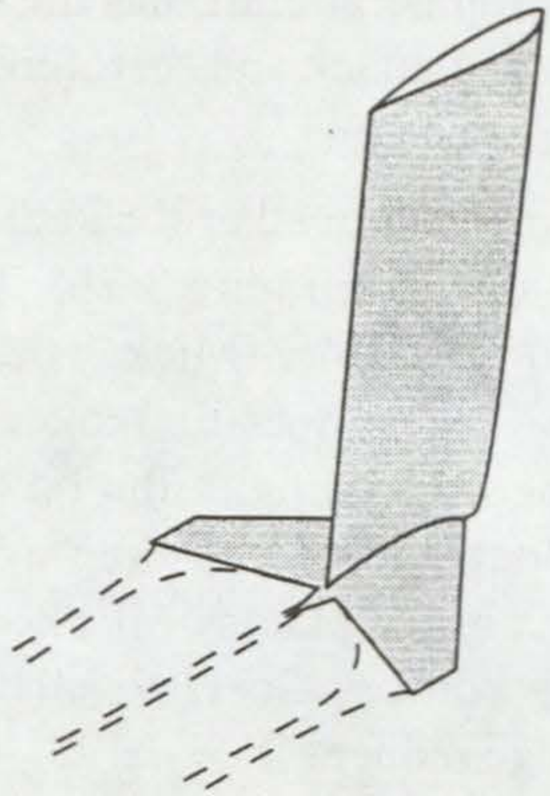

Figure 3-2a On a winged keel there should be a pair of vortices, one off each tip, and it may be possibly with good design to have one off the centre bulb as well.
For this to work each vortex needs to be of approximately the same strength, otherwise the stronger swallows the weaker and the advantage of the reduced drag is lost.

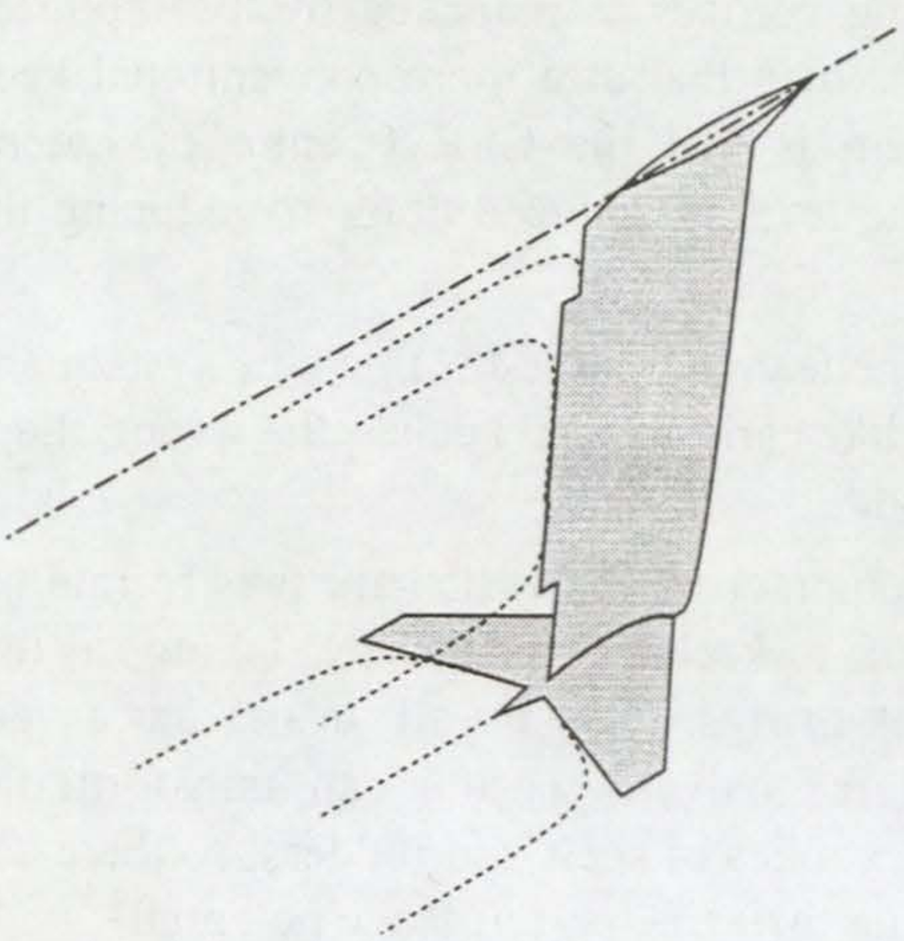

Figure 3-2b By applying the principles of natural aerodynamics to a winged keel the design could turn out to be something like this.
There can be separate trailing vortices off the winged section and the bottom of the fin.
At the top there are vortices off the cut-out at the top and a cut-out lower down.
The leading edge strake at the top helps to reduce the interference drag and helps keep the flow attached during manoeuvres.

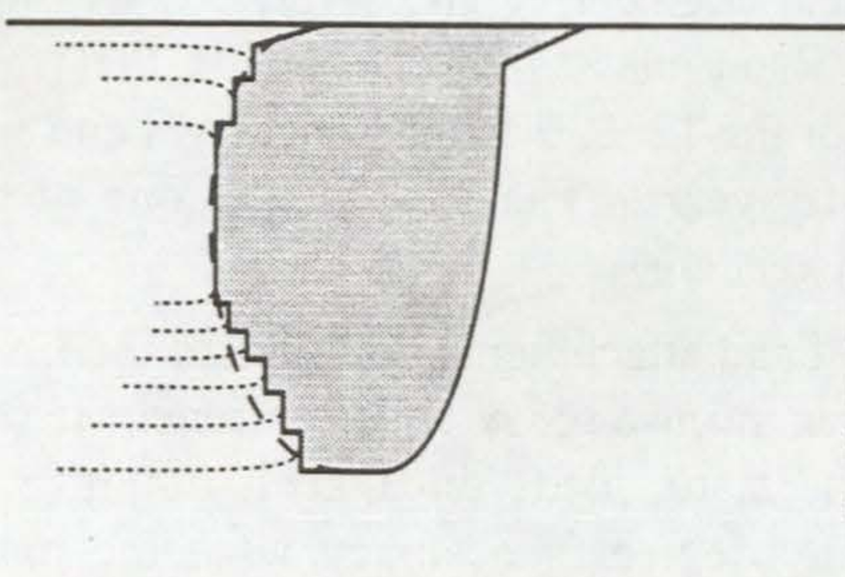

Figure 3-2c This shows how the new style of keel might appear as compared with the MME (Mickey Mouse Ear) style used in the eighties. The interference between the hull and the keel is reduced by making the top of the keel thinner, but this can causes severe structural problems.

of *don't know* or *guess* factors. They do not so much represent safety as an admission of the lack of real knowledge of the likely maximum loads.

The modern yacht with its separate hull and fin keel is much more fragile than the more traditional style of integrated hull and keel. With the older raked style to the bottom to the keel, running aground was usually a fairly gentle affair with no serious consequences. Now groundings or even just touching the bottom can lead to rapid sinkings. The modern racing yacht and the many production cruisers which copy their style are very much more vulnerable than their predecessors. Current assumptions about keels and their continued attachment to yachts needs serious revision otherwise there are going to be more and more yachts that make work for the rescue services and increasing insurance premiums, not to mention the risk to life.

Whereas cars are being made safer without compromising their comfort or performance, modern yacht (and ferry) designs are becoming less and less able to cope with accidents or damage. Unlike the car world, safety never appears to be mentioned in naval architect's work. By far the biggest contribution to yacht safety is the statistic from France that the average boat spends less than four hours per year at sea. The vast majority are in effect marine caravans and are fortunately never put to the test.

The few sailors who put their boats through their paces are the real test pilots of yachting. Going around the World, particularly against the wind, really finds the weak points. Even events such as Speed Week represent a test of ideas in the real world and frequently demonstrates how difficult it is to estimate accurately the many forces involved. This also applies to the strengths and rigidity of structures.

Nigel Irens places the ratio of art to technology in design on a scale of 1 - 10, with 10 being fully scientific and 1 pure art and gut feeling. Even the most technical yachts hardly reach 2 on this scale, but on the other hand the aerospace industry, despite its large budgets and powerful computers probably represents no more than 4 or 5. There is still plenty of guesswork and hunches in optimising any real design, whether it be for, Speed Week or outer space; both are venturing into the unknown where experience and empirical rules may only be of very limited value.

There will never be such thing as an ideal design. Each optimisation will bring different factors to the fore and even then these factors may be combined in many different ways to produce a suitable end product. The only thing to remember is that the finish article should be a significant improvement on what went before, not just a redesign or copy.

5 RUDDERS & CONTROL

Rudders provide two separate functions; one is to provide directional control and the other is to produce part of the lateral force which resists the side force of the sails. The current practice is to extend the separate spade rudder to almost the depth of the keel to achieve a reduction in induced drag by using the biplane effect. These deep rudders are shaped like centre-boards and have followed the classical 'Spitfire' elliptical outline which is said to give the minimum induced drag. This comes directly from the aerodynamic theories developed by Prandtl and Munk.

Although it is desirable to have minimal drag from the rudder, the drag may also be reduced by having a smaller rudder since the real requirement is maximum lift or side force for minimum drag when running.

One of the conventional approaches is to look for a laminar flow section. This can be misleading. With laminar flow the maximum lift which can be achieved is (C_l) 0.8 to 1.0. With turbulent flow this is increased to more like 1.4 Thus a laminar flow rudder would have to be considerably larger than a turbulent one to achieve the same side force. Since it takes time for the flow to change from one state to the other it would not be practical to try and make the flow suddenly turbulent when applying a large rudder angle The flow must be turbulent before the angle of attack is increased.

It is interesting that the vast majority of applications of the NACA laminar flow and similar sections(1) are used in non laminar applications – this applies both on air and sailing craft. The main advantage of these sections is not their laminar flow but the fact that the pressure pattern avoids large peaks which can easily cause flow separation when suddenly applying large angles of attack and they tend to have trailing edge separation at the stall, which gives them more docile handling characteristics.

Unfortunately there is virtually no information on the dynamic flow characteristics of aerofoil sections or complete foils for that matter. All the information in the reference books(1) is for static conditions and this has only partial relevance to sailing rudders and other dynamic foils. One of the most noticeable features of this is how it is easy to have a spade rudder that becomes over balanced when large amounts of helm are applied, despite the fact that the hinge line is well forward of the aerodynamic centre (usually around 25% of the mean chord). Rudders normally have to be hinged at nearer 20% to prevent this oversteer effect and this has the effect of increasing the load on the steering when sailing in a straight line.

6 INTEGRATION & EFFICIENCY

It is a fact of life that it is impossible to make one change without it effecting a stream of others. Yacht design is no different; change the rudder and the rig has to be altered to match the change in loadings. Even the top sailboarders find that they have to change their skegs when they change sails. The whole unit has to be finally balanced for optimum performance. For this reason many top crews uses relatively few sails in important races because it takes time to tune the boat and crew to the new sails. Older sails are used when the the racing is less important so as to save the good ones for important events.

In the world of one-designs it can take a crew a month or two to get the feel of a new boat despite the fact that it is to all intents and purposes identical to their previous one. From this it can be inferred that it will be very rare for one-off designs to attain the same level of efficiency as is achieved at the top end of a good one-design fleet.

In events such as the America's Cup more is learnt by the teams in terms of fine tuning by testing near identical yachts side by side, than is ever possible on the race course. All the races show is if the techniques you have developed are better or worse than the opposition.

Racing recently in one of the current style of light displacement performance yachts with a broad stern, bowsprit and asymmetrical spinnaker it was found that by moving the crew weight forward to keep the bow in the water the performance increased by over 10%. The owner had failed to invested in a set of performance recording instruments, preferring to spend his time and money on achieving small reductions in the rating.

The best performance optimisation is by sailing near identical boats against each other regularly. With instruments the smallest possible performance difference that it is realistic to record is greater than $^1/_{10}$th of a knot or 10' (3m)/min. With boats sailing side by side differences down to about $^1/_{100}$th of a knot or 1' (0.3m)/min can be detected. This small amount may not appear important, but over the length of a race can amount to a winning margin (60' or 18m/hr).

One of the surprising aspects of one-off designs is that it is very rare for there to be any provision for moving the position of the mast, although this may be partly covered by the current fashion for changing keels at the drop of a hat (or the loss of a race). Where one-designs allow the mast and keel positions to be moved, the optimum position is very rarely where the designer originally put them. In classes where the mast and keel cannot be shifted the mast is usually either raked as much as possible or pulled forward to improve the position of the centre of effort. The cut of the sails may also be changed from the aerodynamic optimum to correct the position of the centre of effort. The effect of tightening the leech is to move the centre of pressure aft and increase the amount of weather helm.

It is not often appreciated that the hull above the water is also an aerofoil in its own right and with the apparent wind well forward of the beam it produces significant forces. They can be useful or just simply drag depending upon the layout used and the position of the crew.

Individually crew will only create drag directly downwind, but huddled together it is possible for them to actually produce some useful thrust ! The function of sitting on the gunwale is not purely to act as movable ballast.

One of the easiest ways to increase the performance of any boat is to carry out a detailed *drag audit*. Even on the most efficient racing yacht it is possible to find items which may be causing unnecessary drag. Individually they may not amount to much but when taken together can add up to something significant. The following section shows how significant this can be.

7 The CREW in DRAG

Great efforts are made to ensure that the hull surface is smooth and fair. The rig also receives close attention, but for some unknown reason windage within about 1.5m (5') of the deck is considered not to be of any serious consequence. It appears to be assumed that there is relatively little or no resistance caused by crew and deck equipment.

Although the wind at deck level is in theory not as strong as that at the centre of effort, the effect of the air being accelerated over the gunwale all but negates this assumption.

Water may have a density of 840 times that of air, but the apparent windspeed is virtually always higher than the water speed, and with the resistance increasing as the square of the velocity the actual difference in relative resistance is considerably less than 840.

With a typical apparent wind of just over four times that of the water speed the difference in relative resistance is reduced from 840 to 50 ($840/(V_{air}/V_{water})^2$). When going to windward the added wind resistance of a member of the crew would be the same as dragging a 20cm (8") doll through the water in the same relative attitude. Even a 25cm (10") winch on the cabin top is the same as dragging a 4cm (1.5") version in the water These obviously create much more resistance than a barnacle or two on the bottom. It does not take many pieces of exposed deck equipment to equate to the drag of the propeller and shaft. There may be a rating allowance for propeller drag, but there is none for deck equipment or crew.

In light conditions when the apparent wind is only twice the boat speed then the difference in resistance is about 200 and the windage of an individual crew member is the same as dragging a 4" (10 cm) doll through the water.

The drag at 29 knots in air is the same as 1 knot in water (1 knot ≈ 30m or 100'/min ≈ 0.5m/sec). Try sitting up to your head in the water in a current of 1 knot and you will appreciate the additional resistance that you are creating in 30 knots of wind.

Not everything about the air flow around the hull and deck is bad news; much of it is helpful. With a correctly shaped deck, the siting of equipment and judicious use of where and how the crew are positioned, it is theoretically possible to achieve what might be call negative drag.

Length ft	20	30	40	50	60	80
Length m	6	9	12	15	18	24
Approx run. res. kgs	30	100	250	500	850	2000
Single crew @16kts	2.2	2.2	2.2	2.2	2.2	2.2
% of run. res.	7.4	2.2	0.8	0.4	0.2	0.1
% performance loss	3.3	0.9	0.4	0.2	0.1	0.0
Dist lost m. / nm.	61	18	74	3.7	2.2	0.9
Boat lengths lost/nm.	10	2	0.6	0.2	0.1	0.0
Typical crew no	3	6	9	12	16	24
Total crew res kgs	6.6	13.3	20	27	35	53
% of run. res.	22.2	13.3	8.0	5.3	4.2	2.7
% performance loss	11	6.6	4.0	2.7	2.1	1.3
Dist lost m. / nm.	274	144	90	62	48	31
'Rough' lengths/nm.	15	5.3	2.5	1.4	0.9	0.4

Figure 5-1

The effect of crew windage on the performance for several sizes of sailing craft.

The approximate penalty for having a *Rough Dressed* Crew is shown in the bottom line in terms of boats lengths lost per mile sailed. This is particularly severe on the smaller sized boats and is probably why they have already started smoothing both their clothing and image.

The crew huddled close together on the weather rail can create in effect a low aspect ratio aerofoil which at large angles of attack can produce a total force which will not be directly downwind but approximately at right angles to the chord line (gunwale in this case). Any gaps in the line and shaggy hairdos are bad news. The helmsman using a tiller extension in the lee of the rest of the crew is creating much less drag than the macho *'hi-drag'* stance at the wheel.

Cyclist operate with apparent winds of about 30 knots, they learnt a long time ago that windage has a dramatic effect on performance and they will do anything to mitigate its effects. Athletes are also beginning to take note and modify their dress and hair styles. Surprisingly a sprinter is running at only twice the speed of a marathon runner. The sprinters are now using tight fitting clothes, but the long distance runner expends about 200 times more energy on windage and needs to devise low drag garments which give adequate ventilation. Cooling not being a problem for sprinters.

Dinghy sailors are moving towards wearing smooth suits and equally important close fitting headgear, but keel boat crews still like to go around in loose fitting high windage macho style garments, not to mention beards and long hair. In windage terms they might be termed ***square riggers.***

It is very simple: if you can feel the wind on your face and around your body when going to windward you are creating additional resistance and reducing the performance of the boat.

Drag has a direct effect on windward performance. If the drag angle is increased by 1° then the VMG is reduced and the tacking angle is increased by 2°. Since it is possible to calculate the approximate reduction in windward performance from an increase in drag let us take a look at what sort of reduction is involved.

The exposed area of a typical crew member can be taken as about $0.5m^2$. In 16 knots of apparent wind the added resistance would be about 2.2kg (5lbs). With a 'smooth' crew sitting down and wearing close fitting clothing this could possibly be brought down to something like 1 kg (2lbs).

What does this represent in performance terms ? Conveniently the running resistance of hulls of the same length when going to windward is fairly constant regardless of the displacement. By running resistance is meant the water resistance of the hull without the induced drag from the rudder, keel etc. For a multihull the resistance is about 10% of weight, for a racing yacht about 2% and a heavy cruiser 1% – this gives the net force which the rig and keel (the wind-engine) have to produce to propel the hull to windward as approximately;

Hull resistance = Length $m^3/7$ kgs. or (L $ft^3/112$ lbs).

This resistance equates to nearly half the apparent wind angle (β) and represents the net thrust from the sail-keel 'wind engine'. The actual forward component from the sails is more than twice this figure and the actual sail force is very much higher(113).

For a 12m (40') boat the running resistance works out as about 250kgs (550lbs), that is that a pull of 250kgs will pull the hull (without foils or rig at just under 7 kts. Thus the windage of a single crew member is near 1% of the net thrust. This does not mean that if ten crew stand up the boat will go 10% slower, but it has to sail further off the wind to increase the driving power to compensate for the extra drag and this inevitably reduces VMG

For a 5m (16') dinghy the added resistance of the two crew close together can be reduced to below a quarter of the running resistance, but they need to be out on the trapeze for stability. Like all crews they need to provide the maximum stability for the minimum additional drag.

On a sailboard at a record breaking 45 knots the added resistance of the crew is about 15kgs and approaches the total resistance of the planing board on the water.

From the course theorem[113] the running resistance when close hauled represents half the apparent wind angle (β). In simple terms this means that if the crew drag is 10% of the resistance the tacking angle is increased by 10% and this represents more than 5% extra distance to sail. All in all the performance can be effected by the positioning and dress of the crew.

All these added drag calculations are equally applicable to the deck layouts and fittings. The airflow around the hull and between the hull and rig is an important part of the total windage calculation, but so far very little hard information has been published.

These calculations are only a very general approximation and in reality the figures could easily be ± 50%. It is a guide to the level of improvements that can be expected and even if the possible gain is only a small fraction of the above it is still significant in terms of winning races.

Once the significance of crew and deck aerodynamic drag is appreciated by the top racing crews all serious racing crews will be dressed much more like racing cyclists. This will not only improve performance but will almost certainly become the established image for all *go fast* crews. The current rugged macho style with oversized loose fitting garments will be for offshore cruising only. On an America's Cup yacht the difference between a 'smooth' crew and a 'rough' one could in theory be as much as $^1/_3$ boat's length per mile sailed ! Even if the wind at the deck were only 70% that at the centre of effort the crew resistance could still be the equivalent of $^1/_6$ length per mile.

From the principles given above it is quite simple to make your own calculations and see what a significant effect windage has on windward performance. The important thing is to appreciate the difference between useful and effective sail area, against adverse windage. A row of crew sitting close together along the weather rail can become in effect useful sail area, but one person sitting on their own represents pure drag.

<u>The design of the deck area is seriously in need of an aerodynamic input.</u>

8 *MAXIMUM LIFT*

When considering the maximum force which can be developed by any foil it is usual to consider only the shape of the foil system. No consideration is normally given to the fact that there must be a maximum force that can be extracted from the flow on a continuous basis and no amount of cunning will make it possible to exceed this figure. The only way of exceeding the maximum lift is to add energy to the flow in the form of jet flaps, boundary layer control, etcetera.

From disc actuator theory it has been shown that there is a maximum amount of energy which can be extracted by a negative actuator (windmill). If the disc absorbed all the energy the flow would cease and the only energy would be in the form of drag (stagnation pressure). At some point less than this the maximum rotational (or lift) force is obtained. This turns out to be just under one third of the total energy flowing through the area of the disc[91].

The same sort of limitation would appear to apply to any aerofoil system in a uniform, steady flow. According to theory if all the circulation were converted into lift the maximum $C_{Lmax} = 4 \times \pi$ or 12.6 and if $^1/_3$ of the energy only can be absorbed by the foil system C_{Lmax} will always be less than $4 \times \pi /_3$ (< 4.2).

The maximum coefficient of lift (C_{Lmax}) which can be achieved from a simple aerofoil or sail without camber is in the region of 1.0, with camber this can be increased to over 1.5[1]. On aircraft this can be further increased to something like 2.5 by the addition of various arrangements of both leading and trailing edge flaps (in this case this relates to the total projected area and not just that of the basic wing alone). With sophisticated wings and flaps figures of over 3.0 have been reported.

It is possible to obtain higher figures when energy is added to the flow. This is usually by means of some kind of boundary layer suction, jet flaps, or a combination of both, but still the total energy which can be extracted from the free flow would still be expected to be limited.

Both lift and drag extract energy from the flow, therefore the maximum lift comes from the available flow which is not causing drag. The total energy which can be extracted is the sum of both the lift and drag. For any foil system in a free uniform flow:-

$$C_L + C_D < 4 \times \pi/3$$

Where C_L & C_D are based on the total projected area.

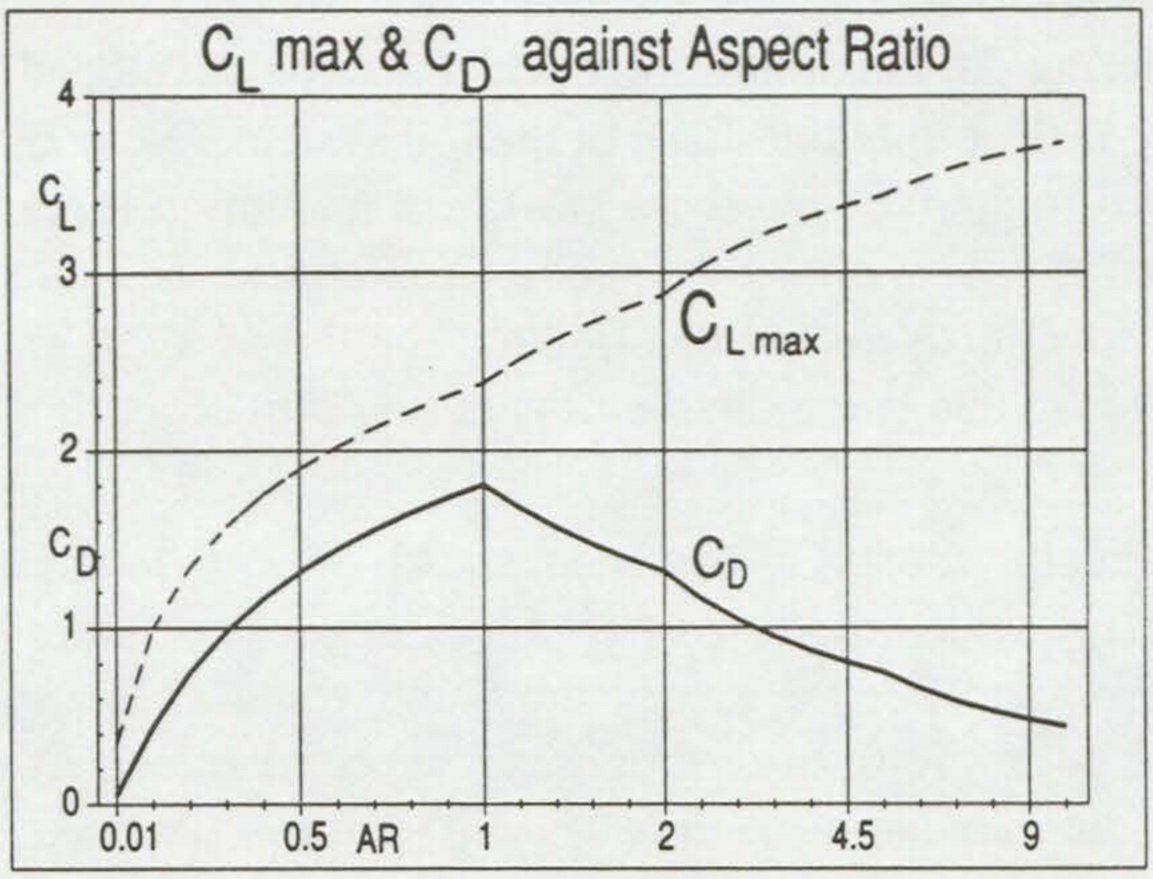

Figure 6-1a This represents the ranges of aspect ratio likely to be used in sailing. Even the most efficient wing sail will have a maximum lift of just over 3. (Note the change of scale along the bottom of the graphs.)

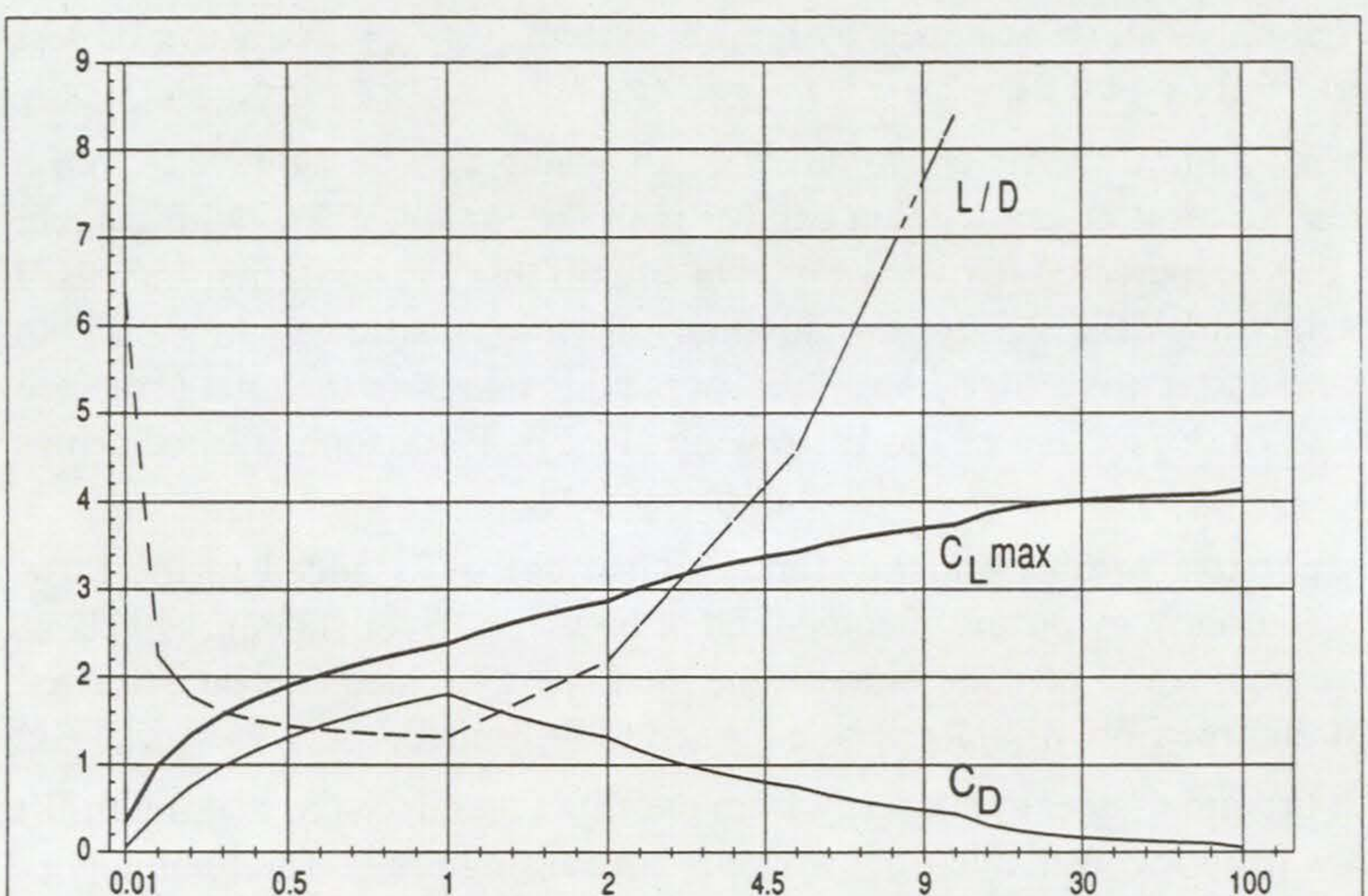

Figure 6-1b At high Aspect Ratios the maximum lift levels off at just over 4 and the Lift(max)/Drag ratios exceeds 10. Also at very low aspect ratios the L/D improves. The lowest Lift/Drag ratio at maximum Lift is with an AR of 1.

With induced drag being a large proportion of the drag at high lifts and the induced drag $C_{Di} = C_L^2 / (AR . \pi)$ *for a near elliptical lift distribution* we can solve the quadratic equation and write:-

$$C_{Lmax} < AR \times \pi /2 \times (\sqrt{(1+16/3 /AR)}-1)$$

When discussing C_L it is important that the same reference area is used. In aircraft design it is usual to take the basic wing area only without taking into account any extra projected area created by the flaps or leading edge devices, but including the wing area hidden in the fuselage. In all the cases considered here the area represents the whole projected area including all flaps and leading edge devices, or in nautical terms the total projected sail area including spars.

The most important factor from the above principle is that drag reduces the maximum sustainable lift and therefore it helps if drag is minimised. When trying to maximise lift the consequential drag is usually given little consideration.

As the lift is increased just beyond the maximum sustainable figure the local airflow will be reduced and the lift will decrease to somewhere below the maximum figure, so that at or near the maximum achievable lift there are likely to be oscillations in the lift figure produced. It is only by going below the maximum lift that a steady flow will be maintained. This is seen at the stall of any aerofoil section where the flow becomes unsteady

Trying to extract too much energy from the local flow has an effect on the commencement of the stall; for maximum lift it is important to avoid pressure peaks. For this the 'roof top' or supercritical sections are more appropriate than the popular NACA 00 sections (0012 etc) as they limit the peaks in the pressure distribution. It appears that although the C_l is well below the theoretical maximum the local flow is exceeding the sustainable figure and cannot obtain sufficient energy from the surrounding air. The maximum lift can be expected from aerofoil shapes which avoid both peaks in the pressure distribution and flow separation.

Lift above the sustainable figure (or superlift) can be achieved for short periods before the flow collapses. Birds can be seen using this hysteresis phenomena to good effect on landing. They give one last beat of the wings which causes a short but substantial increase in lift just as they touch down after which the flow collapses and the bird remains firmly on the ground where the wings may then be folded relatively slowly, with there being little fear of being blown back into the air.

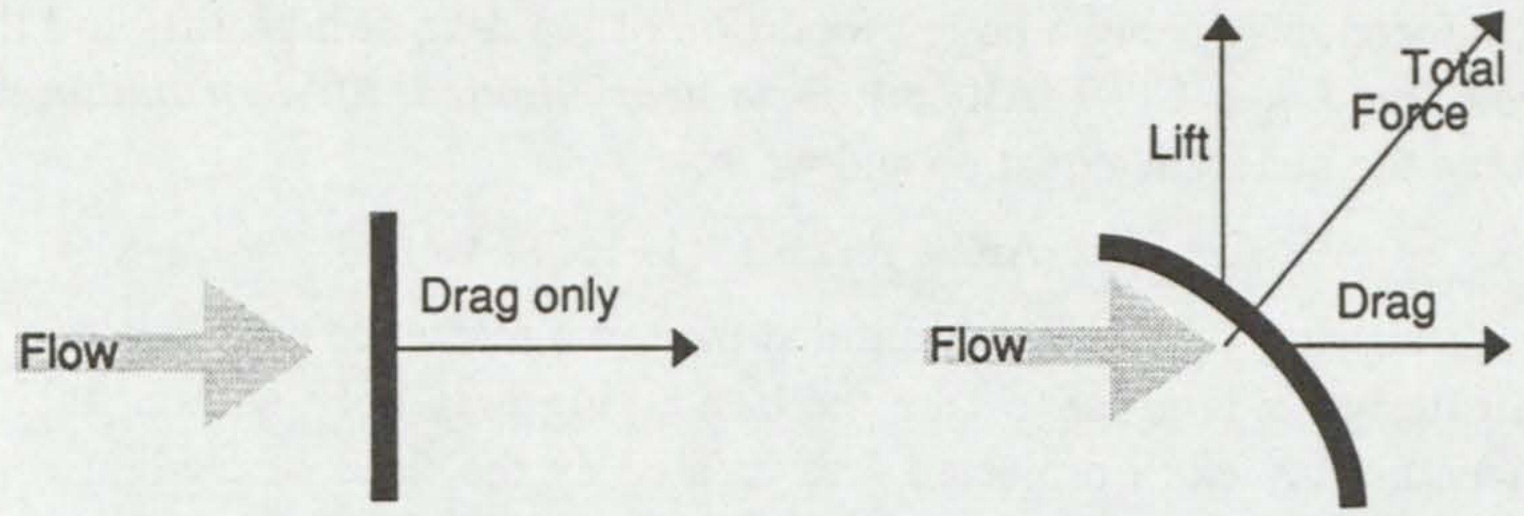

Figure6-2a A flat plate perpendicular to the flow will only experience drag, with the maximum the stagnation pressure when C_D= 2. With a curved plate and circulation a total force can be created that is greater than the drag.

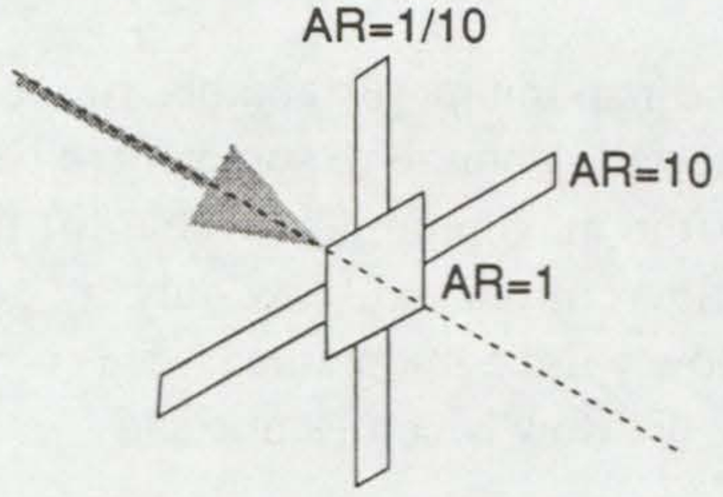

Figure 6-2b For drag in the line of the flow an aspect ratio of 10 or 1/10 appears exactly the same and will therefore have the same basic drag, but for the lift component they will be completely different. An aspect ratio of 1 will appear the same to both the lift and drag forces.

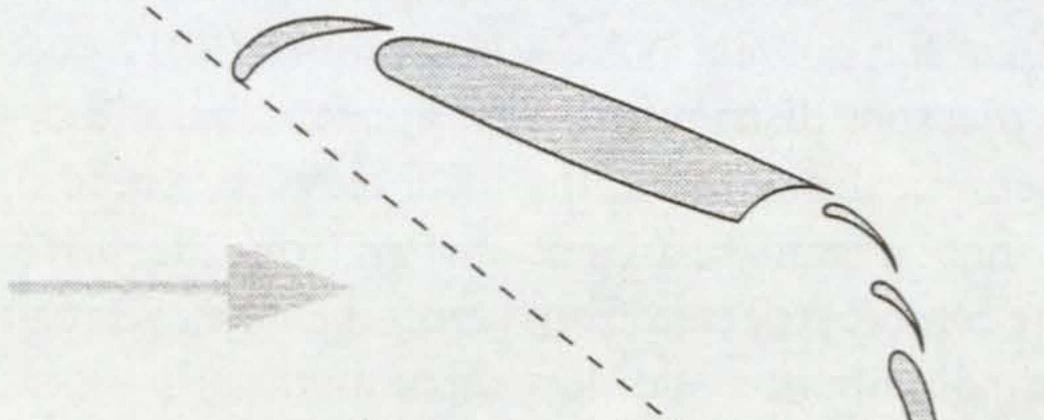

Figure 6-2c A typical airliner high lift wing section, with flaps extended at maximum lift. Note the angle of attack is close to 40° and the trailing edge is near vertical (compiled from several sources). For a sail the trailing edge should be close to fore and aft for of much of the sail as possible.

Most practical aircraft systems appear to produce a maximum lift in the range C_L 2.0 - 2.5, Even with large aspect ratios, wings do not appear to achieve more than 3.0.

It has not been possible to find any trustworthy evidence of any aerofoil systems with a $C_L + C_D > \pi/_4$. The experiments reported by Handley-Page in the early twenties showed a maximum lift of 3.9 and a relatively high drag, with a multi slotted foil, but these are unreliable as the problems of windtunnel blockage were not fully appreciated at the time. The lift of 3.9 is about as expected, but the drag reported is much too high, this is typical of very many tests and calculations. In practice an accurate drag figure is always very difficult to come by, drag difference between different tests is usually more reliable.

The wind tunnel tests carried out by C A Marchaj[111] to verify the performance of low aspect ratio sails showed a C_{Lmax} of 2.13 for a foil of aspect ratio of just over 1 (This was a cambered piece of square cloth) and represents an efficiency of about 90%. At higher aspect ratios the maximum lift was reduced in these tests, to $C_{Lmax} = 1.67$ at AR 1.9 or 60% efficiency. In these cases the lift is dominated by vortex lift and pulling the vortices further apart with the increase in span does not increase their power and so the lift per unit area reduces.

Hoener[2] reports the tests on a javelin of aspect ratio of $^1/_{100}$ to give a C_L of 0.31 and again this represents an efficiency of 90%, but the drag is much lower than that expected from the basic calculations. The calculated drag figures fit well when AR>1, but under this they are significantly lower than that produced by the above hypothesis and appear always to be less than the maximum lift. This is where we have to go to athletics where it is demonstrated that a javelin travels further than a round flat discus. In fact in order that the discuss can absorb more energy it is made heavier; if it were the same weight as the javelin it could not be thrown as far. Even the lighter Frisby disc cannot be thrown (flown) as far as the javelin. This demonstrates that very long thin spears are more efficient aerodynamically than round flat shapes. This fact has been known to hunters since prehistoric times. The maximum drag therefore appears to reduce below an aspect ratio of 1. The maximum C_D would always be expected to be < 2.0 (the stagnation pressure) and in practice nearer 1.2 The drag force is along the line of flow and in this case an aspect ratio of 10 looks the same to the drag flow as $^1/_{10}$. it is just rotated 90°, thus below an AR of 1 the induced drag reduces.

The situation at very low speeds is complicated by the change in the pattern of the flow when a very much larger area is affected by the presence of the foil, therefore this simplified explanation is not valid in very light winds.

The static pressure of the flow hitting a flat plate is represented by the change in momentum:-

$A.\rho.v^2$ where A= area, ρ= density and v= velocity

From aerodynamic principles: Drag = $^1/_2.A.\rho.C_D.v^2$.

With all the flow stopped $A.\rho.v^2 = {}^1/_2.A.\rho.C_D.v^2$:thus $C_D = 2$

This basically means that the maximum drag force that can be applied in the direction of the flow is when $C_D = 2$ and then no lift force is developed across the flow (in practice this is not possible as the flow has to move out of the way somehow).

If on the other hand we take a plate and place this at an angle to the flow, the total force can be over 4. From this it would appear that for any reduction in drag over twice the saving can be converted into lift and the greater the total force the greater is its angle from the free stream flow.

Again from aerodynamic principles we have an ideal foil of infinite span will increase its lift with increasing angle of attack at a rate of 2π/radians and if we have a maximum achievable lift of $4.\pi/3$. This maximum lift will be achieved at an angle of attack of :-

$$(4.\ \pi/3)/(2.\pi) = 2/3 \text{ radians} = 38.2^\circ$$

Putting this into simpler terms it means that the maximum lift from any foil will be achieved at an angle of attack of just under 40°. Even low aspect ratio foils will achieve their maximum lift at this angle, just the figure achieved will be less.

From some very imprecise observations it appears that javelins and discusses float down to the ground from the top of their trajectory at an angle of attack near to 40°. The typical high lift wing in figure **** also achieves its maximum lift at an angle of attack of near 40°.

There is a maximum amount of energy which can be extracted from a free stream without the use of additional energy being added and is the sum of both the drag and the lift produced.

There is not much to be gained from high lift devices on low aspect ratio foils when they are already achieving nearly the maximum lift force available.

The lift may be maximised by reducing the drag to the minimum practical and the total force = $\sqrt{(\text{Drag}^2 + \text{Lift}^2)}$. An efficiency of about 90% appears possible, with the additional drag being in effect the profile drag. This is inline with the performance of contemporary aircraft propellers.

Traditionally too much attention has been placed on trying to increase the lift coefficients without realising that this may be helped significantly by reducing all forms of drag.

This maximum lift theorem and its consequences is again an area that has yet to be full investigated by the aerodynamic world and some systematic research will be required before more precis figures can be applied, but the basic principle of there being a limited amount of energy that can be extracted is no doubt true.

For maximum power when sailing do not set your sails at a greater angle than 40°. A stalled sail, whether it is a mainsail, jib or spinnaker will produce considerably less total power than one with flow across it and is for this reason the fastest course to leeward is achieved by tacking downwind.

The older style of sail such as gaff, junk or crab claw have much higher stalling angles than the current style of tall bermudan rig and produce a better off wind performance. The reason for this is that at high angles of attack they produce powerful vortices which are not present on the contemporary style of sail.

Understanding how and why the maximum lift can be achieved on a foil reduces the amount of trial and error required to come to a useful answer and enables us to create more effective sails and wings.

CONCLUDING REMARKS

We can learn a great deal by looking at what nature and our forebears have developed in the past. It is presumptuous of us to assume we have all the answers and that little could have been learned by man or nature over the last few million years simply because they could not communicate, write or use computers. We have a great deal to learn and are at present only scratching the surface of natures offerings.

Over recent years the sailboard has developed into a practical and very efficient sailing machine and all this has been done by simple trial and error and in a way very similar to the Darwinian principle of the survival of the fitest. This is what happens when thousands of people are free to spend years developing a new tool free from rules and institutional regulations.

Even with the most complicated technical design, the experience of nature should not be ignored. Nature after all is very much more complicated and subtle than anything that humans can ever hope to produce (without the help of nature).

Follow the flight of birds and it will enable you to sail more efficiently and effectively.

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Natural Aerodynamics

Some fundamental principles

Application to sails & keels,

rudders & other foils

Integration & overall efficiency

The crew as windage and drag

Maximum lift from a foil system