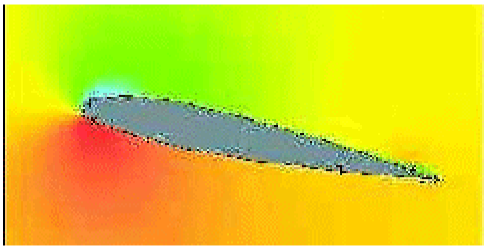
HOW BOARDS AND RUDDERS WORK

Lift theory



By B. Kohler

HOW BOARDS & RUDDERS WORK

Our boats become faster and faster and a better understanding of how a sail, rudder, dagger board works will help you to understand the physical phenomena who acts on a sailing boat, no matter of it concerns a multi hull or mono hull boat. The faster our boats get, the hydro and aero dynamic plays an even bigger role.
This is a transcript from my lecture I was giving on the international multi hull symposium in Monickendam the Netherlands in the year 1988 explaining how sails, rudders and boards are working, with the main emphasis how a section I.e. profile works.

I was asked to tell you a little bit more about how rudders and dagger boards work. These important appendages to our boats make the difference between being a efficient sailing boat or not.
We are here concerned with multi hulls. These have a still a bad name when it comes to windward performance and handling quality in general. I have to admit this is true for some of the designs.
The boats become much better today , but still there is room for improvements. To name a few:

1. Rigs with better lift to drag ratios.
2. More aerodynamic shaped boats to lower parasitic drag.
3. By making the leeway preventers, with other words keels,
dagger boards, center boards and rudders more efficient.

The purpose of the boards is, as everybody knows, to counteract the aerodynamic force acting on sail and hull perpendicular to the centerline of the boat, maintaining an equilibrium at the lowest possible leeway angle.
I hear already people say, that V-and asymmetrical hulls need no boards and sail also to windward. This is true, because every hull acts against this adverse aerodynamic force to some degree. Asymmetrical hulls generate if slightly heeled (about 3 degrees) much hydrodynamic force to point high. By modern standards V-hulls need boards to point high enough.
Lightweight hulls with U - and trapezoid cross sections have a relative small projected side area and depend for there windward ability on some sort of leeway preventers.
To make things more clear and easy to understand, let us consider the underwater area as being a wing standing vertical in the water.

The working principle of a wing section, wings (dagger boards), in water or in air is the same. The difference is in the density of the medium. Water is tenser with a factor of 832 at sea level and a temperature of 20 ° Celsius. Of course the viscosity is different, but for understanding the working of a section in the context of this article it is of no interest.

But first we have to understand how a wing works

Let s have a look how lift is generated (see fig.1). Two theories exist to explain the generation of lift. Both theories are correct, but with the circulation theory developed by Kudda, Joukowski, Prandtl and others more phenomena playing a part in our boats, can

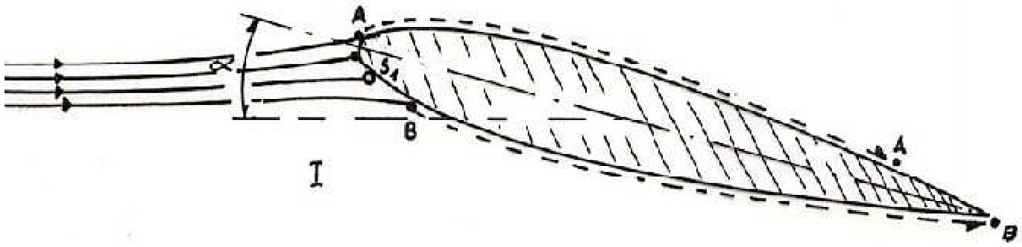


fig. 1

be explained. These theories have been proven by experiments and can also be observed in praxis. In the textbooks on aerodynamics asymmetrical sections are used to explain the generation of lift.

Usually we use symmetrical sections for boards and rudders, so I shall try to explain the generation of lift on a symmetrical section.

A symmetrical profile which passes straight forward through a fluid generates of course no lift at all, because there is no pressure difference between the upper and the lower side. But we can make the profile asymmetric in respect to the flow by setting the profile at an angle to the flow, the so called angle of attack.

We assume that the flow has just started. Two fluid particles A and B above and below the so called stagnation point S1 travel along there surfaces at equal speed. Since the distance for particle A is longer as for particle B, particle B attempts to go round the trailing edge (fig.2).

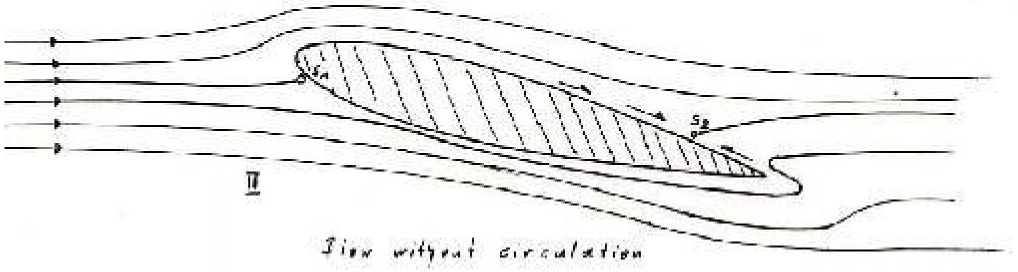


fig. 2 Flow without circulation

Without circulation present around the section, the forward and rear points of zero velocity which we call stagnation points, occur at S1 and S2. Where those points occur depends on the foil section and angle of attack with respect to the flow.

It needs not much imagination to realize that no flow around a sharp edge and against the direction of the general flow would be maintained for long. The air/fluid does not like that, because at the high speed required at the trailing edge and the large viscous and inertia forces which are in action. So the flow breaks away, and the so called starting vortex begins to operate between the trailing edge and stagnation point S2

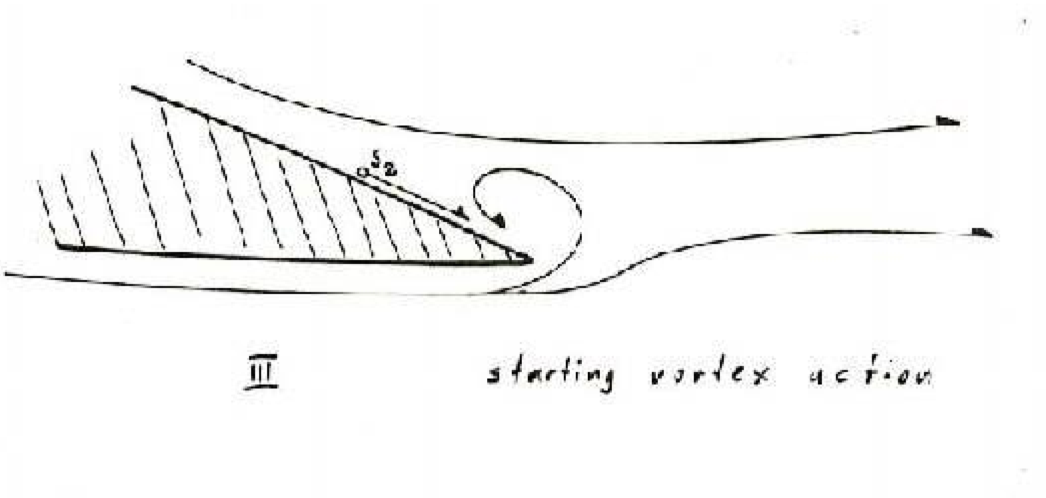


fig. 3 Starting vortex action

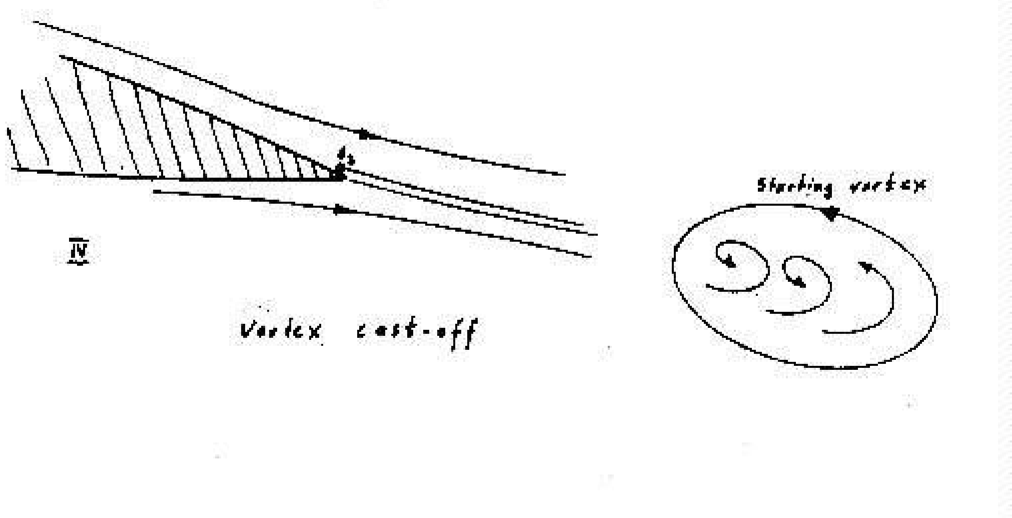


Fig 4 Vortex separation

Logically the starting vortex rotates counter-clockwise (fig.4) and rotation develops around the profile in the opposite direction of the starting vortex. This is caused by the viscous forces involved in the process of regular momentum transfer. This theory is closely related to the fundamental principle of physics that an action (in this case the vortex rotation) creates a reaction.

The starting vortex breaks away and travels downstream. This will occur when the stagnation point S2 moves close to the trailing edge, in which case there is no velocity difference any more between the stream lines leaving the upper and the lower surface. Therefore there is no stimulus any more to support the vortex. The flow around the foil will be now more or less steady and also the lifting force (fig.5).

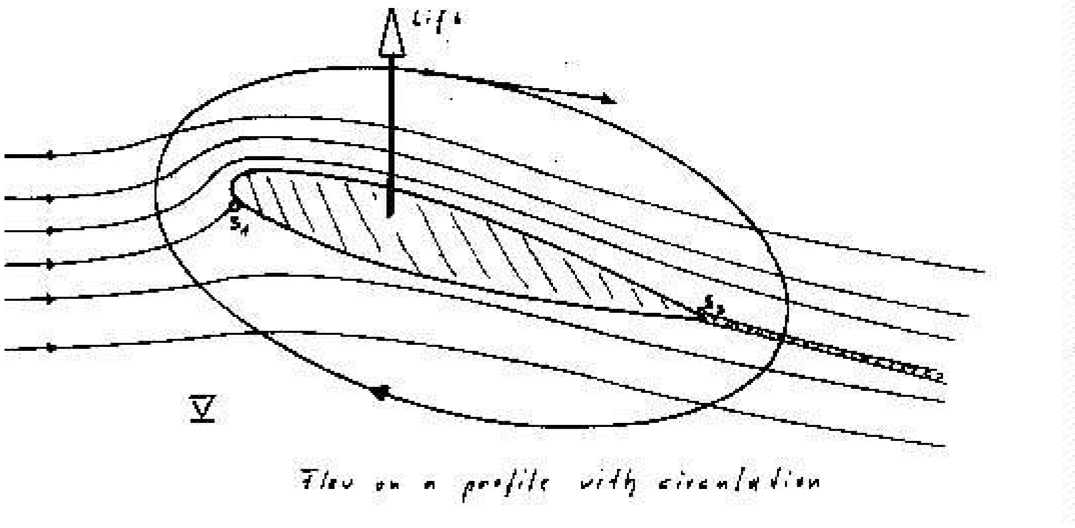


Fig. 5 Flow on a wing section with circulation

This theory is sometimes challenged with the argument a profile produces lift simple by bending the streamlines upwards, giving rise to a lifting force on the profile.
But it does not invalidate the circulation theory of lift generation. Both explain lift generation in general in the same way. The stream-lines indicate the water/air particles have to travel faster over the upper surface as over the lower surface in order to reach the trailing edge in the same time, a physical necessity; only under this condition lift can be generated.
But the circulation theory gives an explanation why it takes some time before lift is generated. By lift generation experiments under unsteady condition, for instance change of the angle of attack, it was found that it takes 6 cord-lengths before the maximum lift is regained (fig.6).This explains why a boat with a low aspect ratio rudder responds slower to a rudder action as a boat with a high aspect ratio rudder. The same is valid for high and low aspect ratio sails.

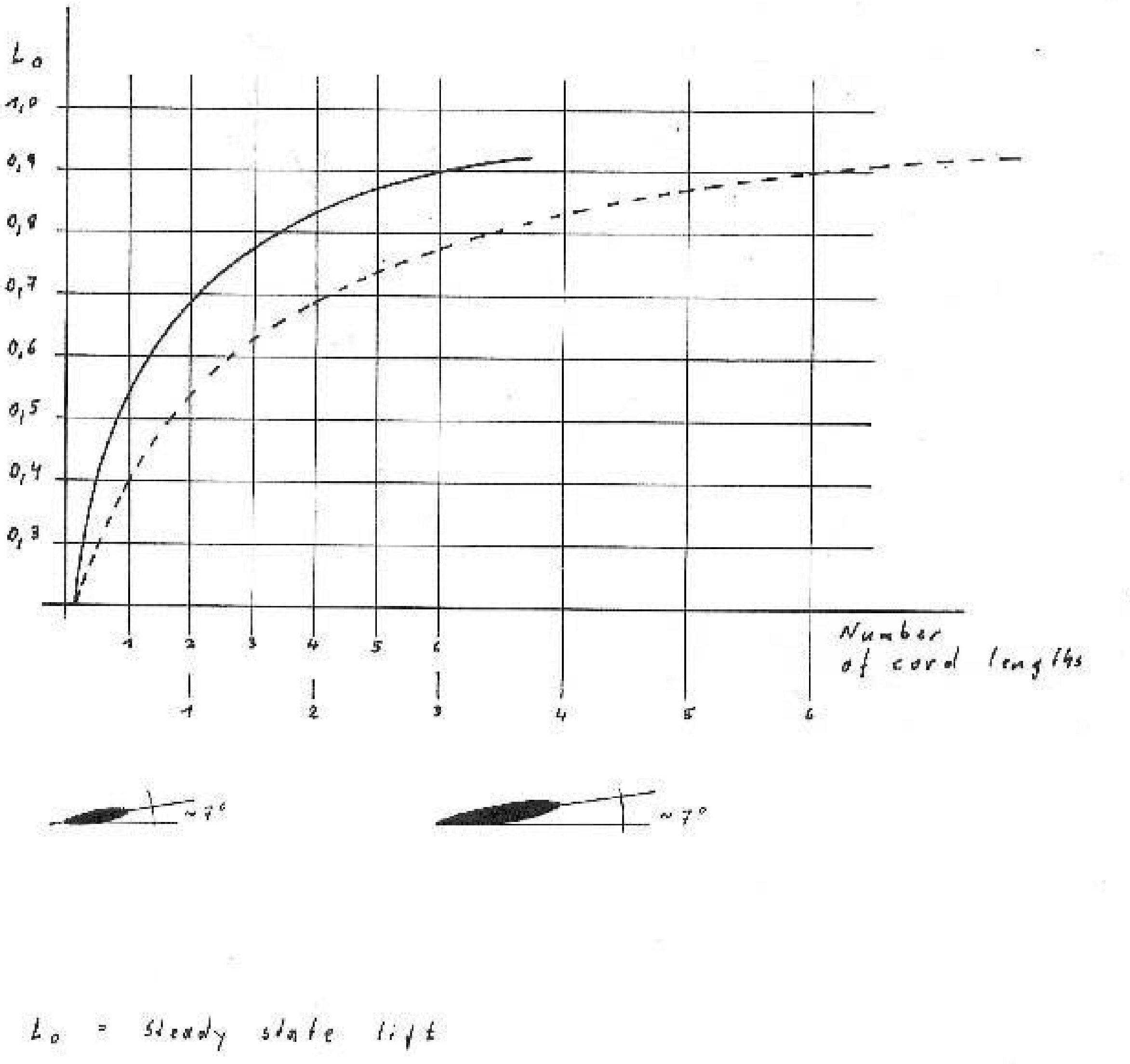


fig. 6

Lo= Steady state lift
N = Number of cord lengths

the reaction of a boat during maneuver.

Drag

Now lets investigate drag. This is rather a complex matter to explain in short but I will try.
Drag can be divided into two basic parts.
a. Form drag.
b. Skin friction.

Form drag is due to vortices formed when a viscous fluid flows past a solid object. The flat plate shown is an extreme example. The resistance or drag is due to the pressure on the plate and the vortexes. Skin friction is negligible. (fig.7)

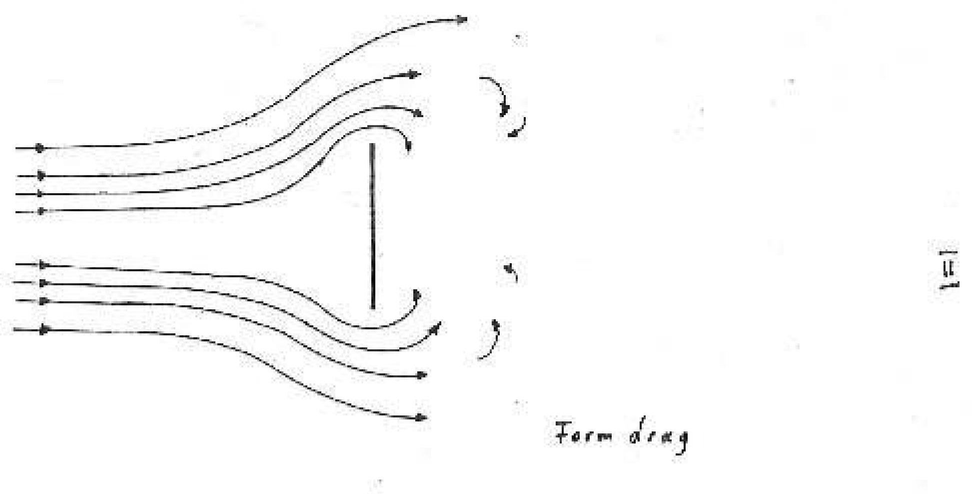


Fig. 7 Form drag

If the plate is hold parallel to the stream the drag is mainly caused by skin-friction, form drag is almost negligible. (fig.8)

fig. 8 Skin friction

Skin friction is caused by the irregularities on the surface. This irregularities slow down the streamlines so that these stand still very close to the surface and at a smooth surface this stagnation layer is very thin. The rougher surface, the thicker the layer. This layer is called the boundary layer. Total skin friction depends on roughness of the surface, surface area and velocity.
The boundary layer and the layers immediately to these flow are partly laminar and become sooner or later turbulent. This affects the shape of the lift raising Row. When the profile is situated parallel (zero angle of attack) to the flow the streamlines try to follow the contour oft the profile. But the angle of attack, the shape of the profile, skin friction, velocity and the density of the fluid play all a role how long laminar flow is maintained and where this becomes erratic and changes into a turbulent flow.

Fig. 9 shows a normal symmetrical section (NACA section series 000) and fig. 10 a symmetric laminar section (about series 63). The pressure distribution and the position of the minimum pressure have a large effect on the boundary layer (BE) flow, which in turn affects the flow outside of these. The effects are shown magnified.

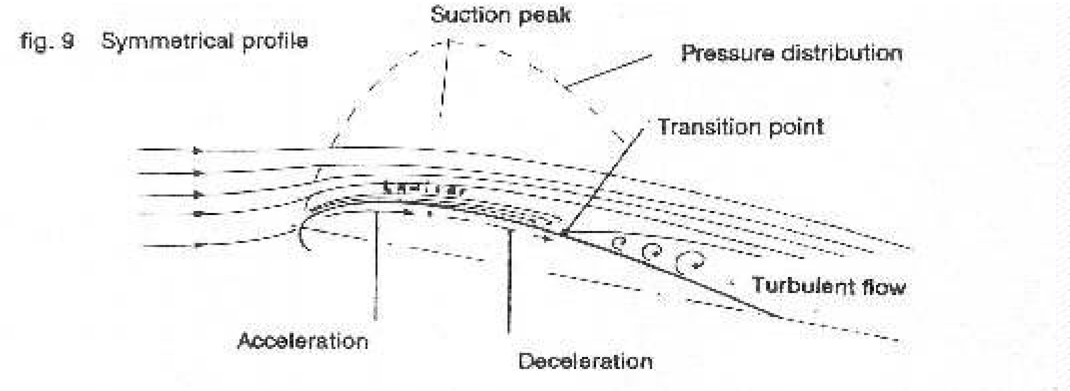


Fig 9 Symmetrical profile

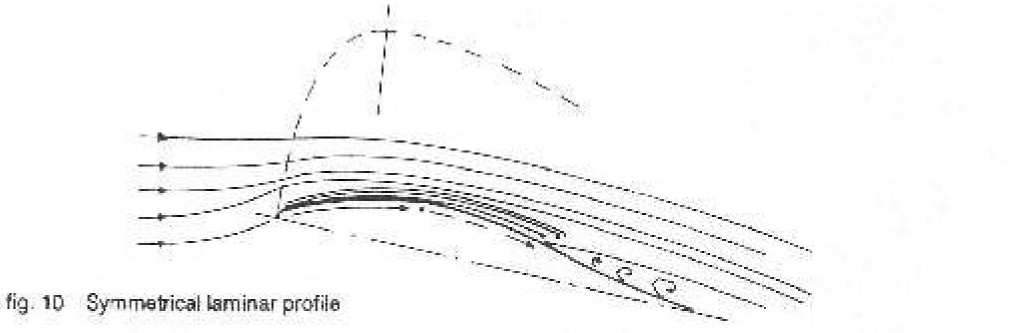


fig. 10 Symmetrical laminar profile

In short the water particles accelerate till the suction peak, but further along there way they lose momentum moving slower and slower, the laminar flow becomes erratic and at last turbulent. The point where this takes place is called the transition point.
It is logical that a laminar flow creates less drag then a turbulent flow. But be careful not to misinterpret the drawings: remember all flow patterns are magnified. Interesting is only that the laminar flow on a laminar section is over a greater part laminar, but on the other side has the tendency to stall earlier as a normal section (see fig.11).
This is due to the lift distribution differences between laminar and a non laminar section. (See fig.11.1). As you can see, the lift grows very fast on a laminar section, already at a low angle to the flow. But because of the steep increase of the lift it is more difficult for the flow to follow the line of the sections body at a high angle of attack. Thus the point where the streamlines "break away" will be much earlier as on a normal section, this means that a laminar section stalls much earlier.

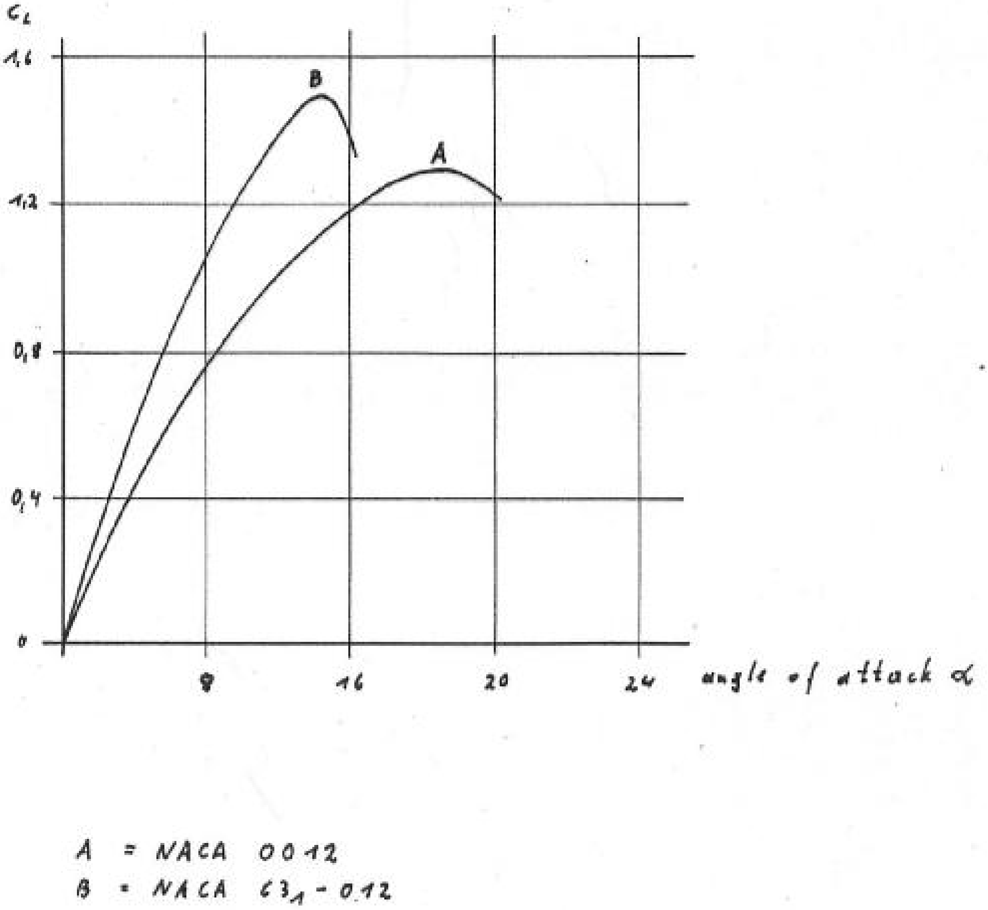


Fig. 11.1

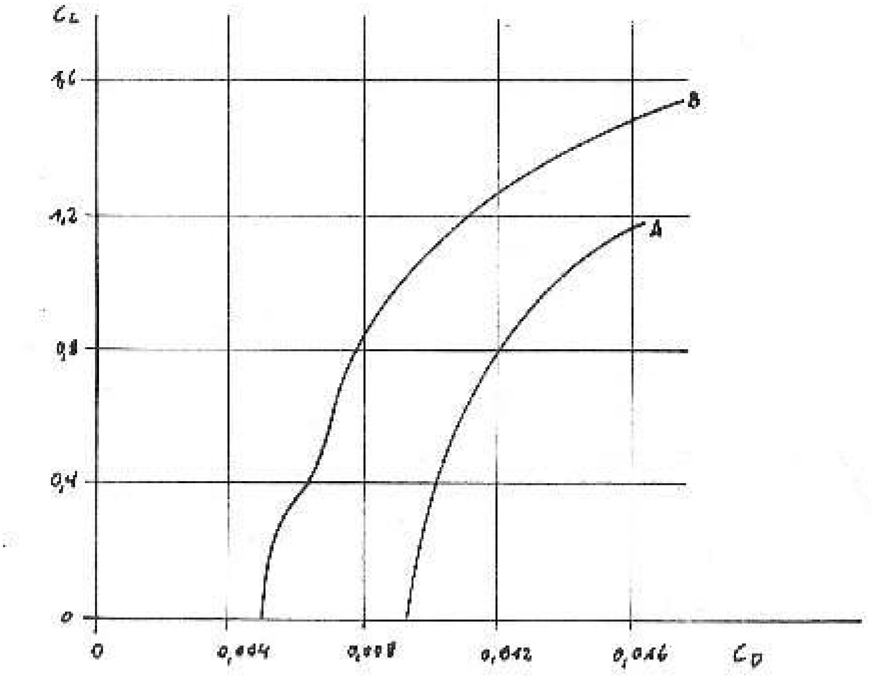


Fig. 11.2 CL = Lift coefficient A = NACA 0012 CD = Drag coefficient B = NACA 63(1)-012

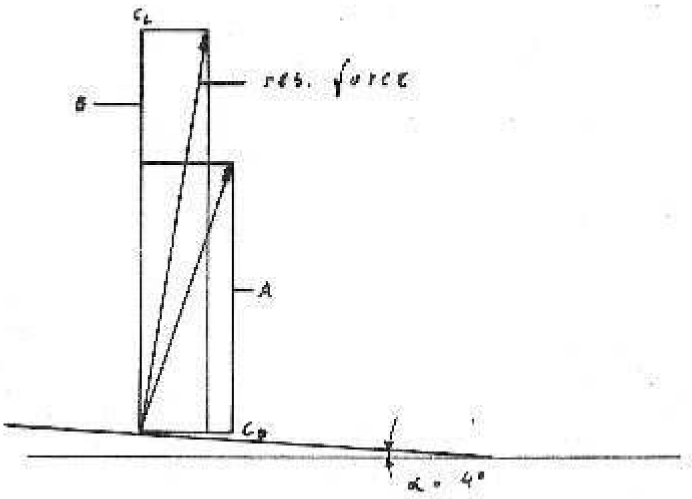


Fig. 11.3

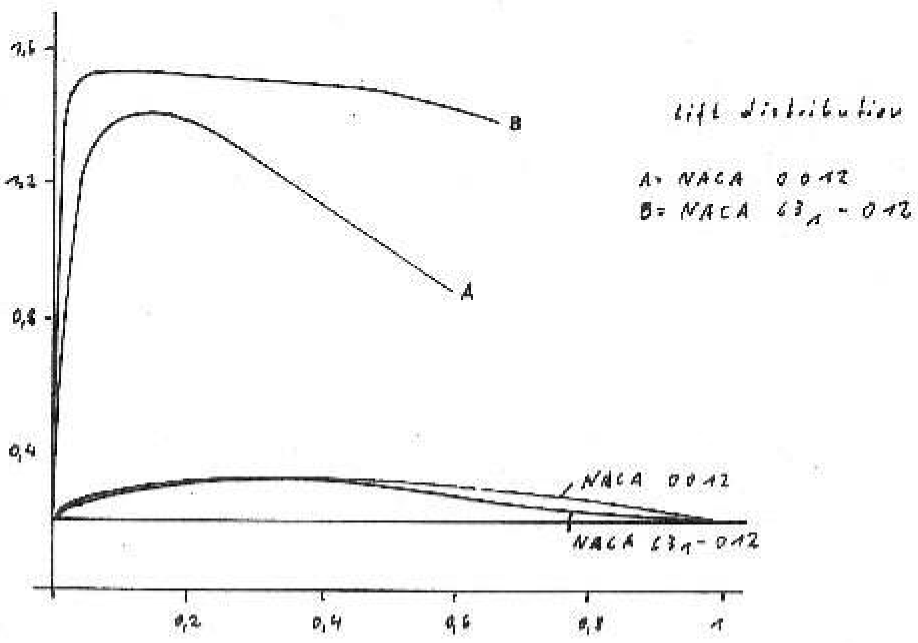


Fig. 11.4

Conclusion

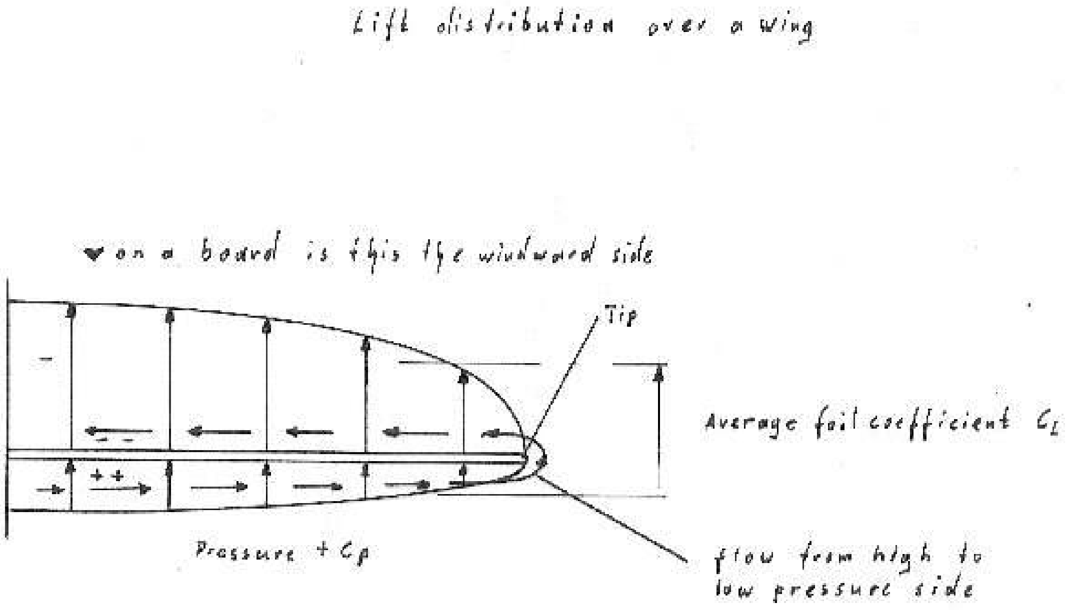
A normal wing section is more suitable for a rudder because it will hold power (lift) for a greater angle of attack and it stalls more gently. A laminar wing section which operates in the leeway angle of the boat gives more lift and less drag. Said another way, a better total force coefficient Ca at a low angle of attack so it is obvious that such a section should be chosen for a board. Sections of the new GAW family should be chosen for center boards and low aspect ratio keels. Fig. 11 shows this very clearly. It is dimensionless but the forces are drawn to scale.

Much more can be told about sections. For instance Reynolds numbers, an important part, are not explained. In short, a profile is only as good as its surface quality. The better the surface finish the lower the drag.

Rudders

A rudder or board can be described as a foil which stands vertical in the water. It is obvious that the same is true for hydro foils no matter to which angle these are set. Important is to bear in mind that we discuss these without interference from the air/water connection, in other words, deep immersed and without ventilation.

Till now we have bean looking only to foil action parallel to the foil. Rut foils have a given span with one or two free tips (keels, boards, spade rudders) .The hull can be seen as an end plate. Now, no matter how they are mounted or standing, fluid in motion follows the universal rule to flow from high pressure to low pressure by every available path. Boards and rudders make no exception.



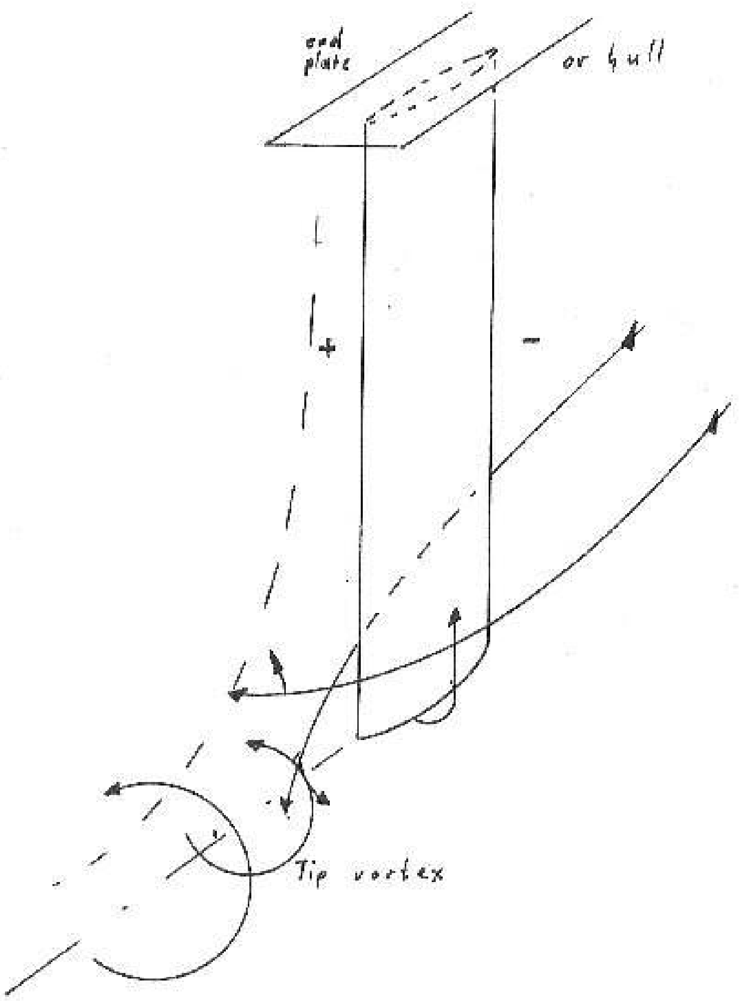


fig. 12 Lift distribution over a wing *fig 12.1 Tip vortex*

When we look at fig. 12 this becomes clear and it is obvious that the optimum lift of a section can

never be reached on a wing. The flow from the high to the low pressure region wipes out the pressure difference at the tip and reduces it on the whole span.
By this stream over the tip the streamlines are bent up on the low pressure side and downward on the high pressure side, so that these leave the sail, wing, board, or rudder in a twisted form. This we call the tip vortex. It is logical that towards the tips from the rudder or hull, the twisting already starts and that these in itself rotate around the tip vortex. Fortunately the vortices towards the hull along the span are formed so far behind the board, that these do not induce noticeable drag in contrast to the tip vortex.

Some remarks concerning rudders

Fig. 12.1 shows the lift distribution on a wing with at one side a end plate. On a boat the hull forms on one side a sort of a end plate but if we look at a rudder the situation changes. Consider a through-hull mounted rudder. As long, as the rudder is in the midship position the hull acts as an endplate. But at the moment the rudder is turned, a gap develops between the rudder and the hull. Now there is no end plate effect any more which means a pressure reduction of at least 25%,. Rudders which are mounted on the transom must be seen as normal wings with high tip losses.
From all this it is clear why high aspect ratio boards and rudders like high aspect ratio sails, wings and hydrofoils are more efficient. From a hydrodynamic point of view the best geometry have elliptical boards and rudders. Surely a rudder is at first glance easy to build. The problem is, that the profile cord changes from the top to the bottom and with it its thickness.
Such boards and rudders are difficult (expensive) to manufacture. The chance that these are damaged if the hit an object or the ground are big. The remaining gab of the dagger board case will induce more drag as with a rectangular dagger board. A medium aspect ratio rudder (1 : 4) will be a good chaise for a transom hung rudder

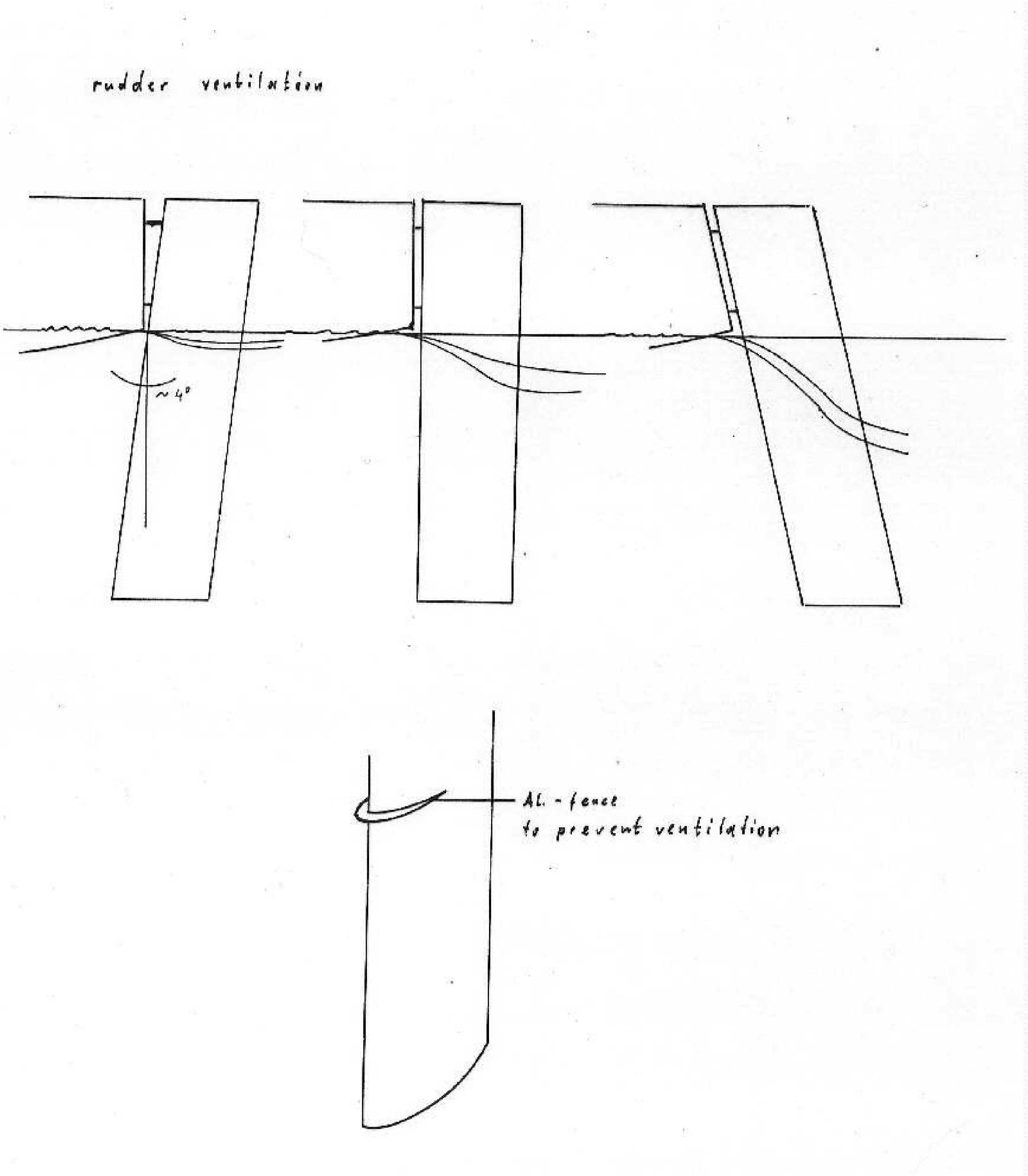


Fig 13 rudder ventilation

Boards

At last some remarks regarding boards. The best aspect ratio for a board is about 1: 5. The gap between board and case must be as narrow as practical. If center boards are used the choice of the profile is more critical than on a dagger board. The maximum thickness should be at about 55% of the cord shown from the leading edge. I am convinced that a correct designed center board can be almost as effective as a dagger board.