Two-Dimensional Airfoil Wakes: Experiments and Numerical Simulation

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ABSTRACT

In order to have a better insight on the stalling properties of straight wings, a set of experiments and a computational code are under developement.
The code is based on discrete vortex simulation while the tests ar made on a flapped airfoil and on a corresponding flat plate.
Results show similarity in shapes and small dependence of the shape from the base pressure.
Turbulent quantities seems to show periodical nature related to the vortex roll-up mechanism even in time averaged data.

INTRODUCTION

The knowledge of the properties of separated flows, either in two or three dimensions is quite important for improving the flight qualities of any flying machine, either from the point of view of the performances or from the one of safety.

The ability to predict post stalling trajectories, forces and moments can improve the reliability of aircraft at low speeds or high accelerations.
In this sense a wide set of researches was undertaken in order to get an improved knowledge of the aspects of some separated flows.

Two are the leading ideas: the first is to investigate whatewer there are some common aspects in the separated flows past two dimensional airfoils, the second arises from the question about the simplest numerical procedure to get relevant information on separated flows.
In this sense both experimental and numerical investigations were undertaken, in order to answer to both questions.
Main interest was two-dimensional flow, because it is a simpler case and it is possible to correlate two-dimensional airfoil data to high aspect wings even in the post-stall regime, as shown by Jacob.(1)
Of course, while 2-D calculations are much easier than 3-D, plane flow is difficult to achieve in wind tunnels, but again 3-D effects, while quite large in the wall shearing stresses, are sometimes less significant in the overall flowfield.

THE FIRST EXPERIMENTS

The first experiments were carried on a model of airfoil available in the laboratory, with the simplest available instrumentation i.e. pressure probes.
Of course it was impossible to enter into the recirculating flow, but the tests could give the approximate boundaries of this part of the flowfield.
Due to the fact that the model was equipped with a control surface, it was possible to obtain two different kind of separated flows: the first with a separation close to the airfoil nose and the second close to the hinge line.
These two flows are respectively an image of a simple airfoil stall and of a separation on a trailing edge flap.

Due to the basic interest of the research, the wall interference was not considered a major limit and the airfoil chord was kept as long as possible to have reasonably high Reynolds Number and wide enough size compared to the instrumentation dimensions.
Having in mind a comparison to some numerical calculation, it was thought that the wall effect could either be represented numerically by boundary conditions or that a confined flowfield could be a simpler environement for a possible computation with finite difference or volume or element scheme.

Having verified that the flow in the middle part of the tunnel was reasonably plane, it was noticed that the shape of the recirculating bubble had certain similarity in both cases. An argument for this could be that the two shear layers issuing from the separation points may have similar boundary conditions and that the pressure recovery along these sheets is governed widely, although not exactly the self similarity of simpler shear layers.

The next step was therefore an investigation on a flat plate at incidence, in particular at the same incidences of the flap in the case of flap deflection and in the one of the airfoil itself, for the non deflected flap.

As further investigation tools the hot wire and the laser-Doppler Velocimeter were chosen: the hot wire for its capability of detecting Reynolds stresses and other turbulent quantities due to its high frequency response, the LDV for the capability of detecting the versus of the velocity vector in the backflow, while with this instrumentit is difficult to get high data rate without a very careful seeding of the flow.

Further on, the flow past the same airfoil was investigated with the same tools.

Finally, the wall shear stresses were investigated on the suction side of the model, by means of omnidirectional pressure probes.

All the tests were carried on in the same atmospheric, open circuit wind tunnel with a test section of .5 x .7 sq.meters, with a model chord of .5 m and at wind velocities ranging from 10 to 20 m/s approximately, the lowest values for LDV due to seeding problems.

THE MODELS

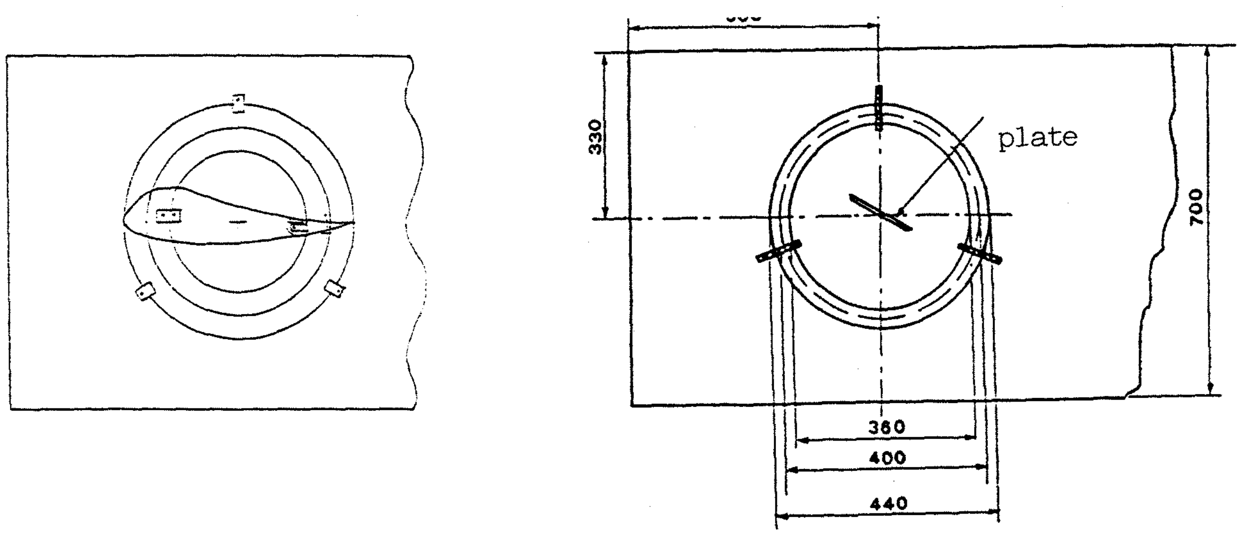
The flat plate model is a trapezoidal thin plate, with the leeside flat and a distance from the two sides of 3 mm while the chord is 166 mm. The chamfer angle at leading and trailing edge is 15°, the minimum possible. The body is made by acrylic shet with two thin plates of aluminum alloy to increase stiffness.

The second is an autostable airfoil of 500 mm chord, 18% thickness and a 30% chord govern surface, tiltable in both directions around a hinge.This latter surface has the same chord of the first model wich is used for comparison.

The airfoil model was designed with kink in the velocity distribution along the upper surface to fix the transition at the beginning of the deceleration in the design condition. The advantage for the present tests is that, slightly incresing the incidence, flow separation takes place just behind that kink and is fixed in a rather wide range of incidences: this fact allows a good test repeatibility and a clear, stright separation line with a reasonably two-dimensional wake. On the other hand, at lower incidences, it is possible to fix separation at the hinge line by deflecting the moving surface.In this way it is possible to obtain two different streams and to compare them.

DATA REDUCTION

The first results from pressure probes, hot-wire and LDV are plots of the component of the velocity vector in the flow plane. From pressure probes and hot-wire it was also possible to measure the third velocity component and to check that the motion was reasonably plane.



The airfoil and the plate models in the wind-tunnel

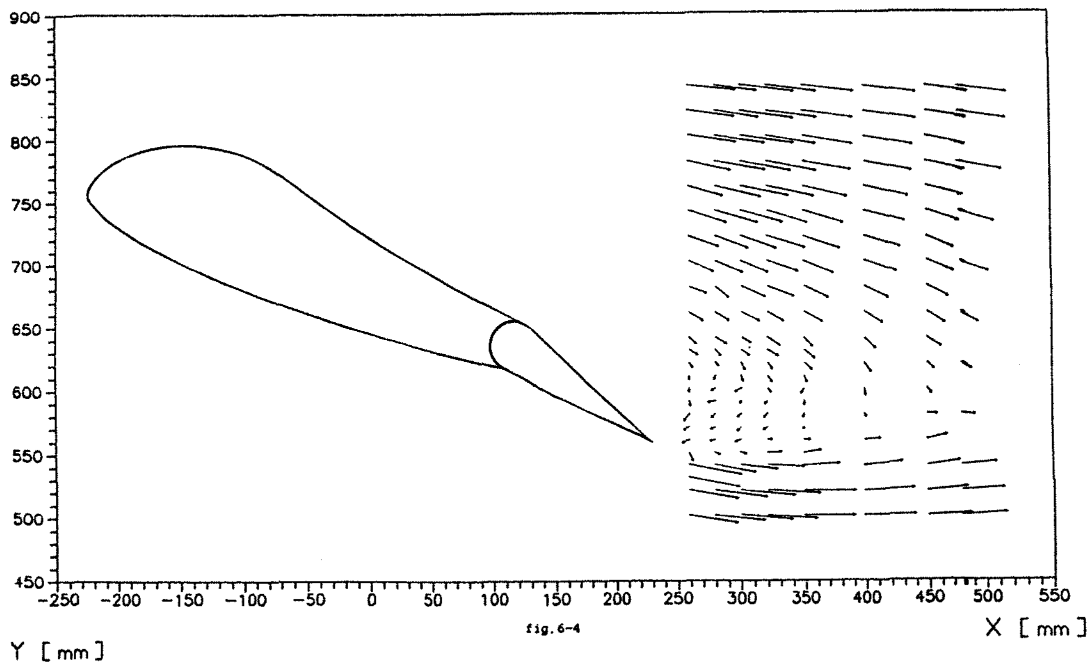


fig.6-4

Velocity vectors for α=20°, β=20°

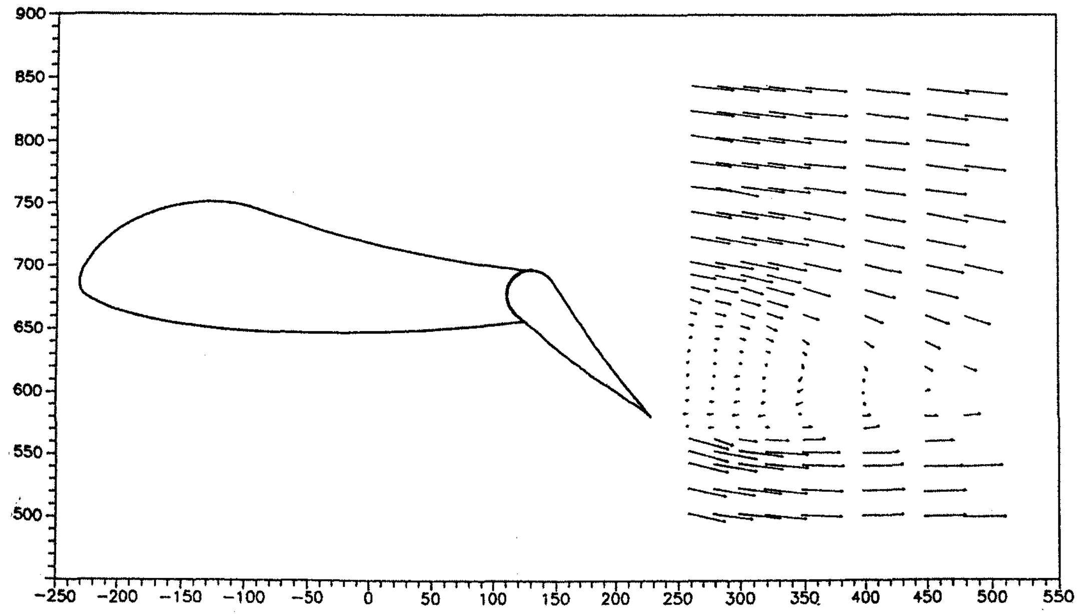
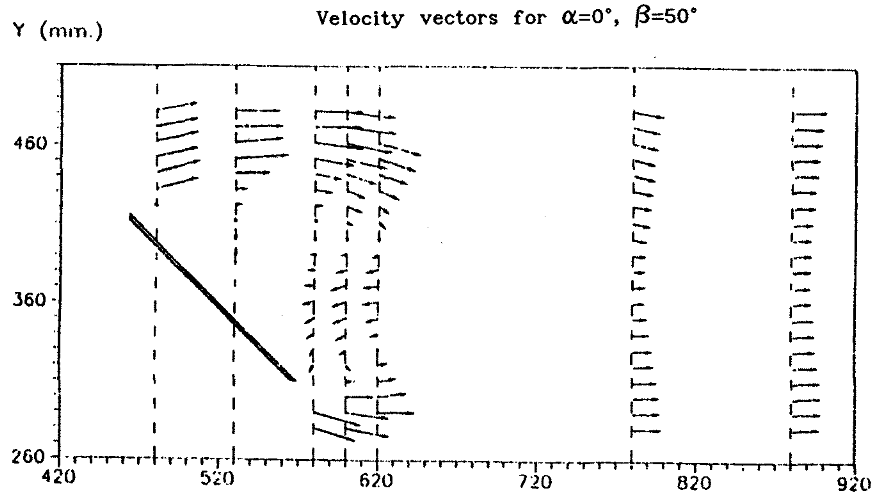


fig.6-5

Velocity vectors for α=0°, β=50°



Velocity vectors for the plate at α=50°

Furthermore the terms of production of Reynolds stresses and turbulent kinetic energy were obtained. Due to the fact that these terms require the evaluation of the velocity derivatives, which are affected by measurement errors, the velocities are first interpolated by Fourier series, filtered and the derivatives are then evaluated analitically.

From the velocity data it is possible to compute also the *recirculating mass flow*, which seems to be a very important parameter for comparisons.

The recirculating flow described in this paper is obtained by integrating in the y direction (normal to the free stream velocity) only there the streamwise component of the velocity is negative, i.e the mass flow :

$$\psi_{rec} = \int_{y1}^{y2} V_{neg} \, dy$$

where y is the normal direction, V_{neg} is the x component of the velocity vector, y_1 and y_2 are the *lower and upper points* of the region of backflow.

Velocities are normalized to free stream and lengths to the chord length of the airfoil.

The comparison of the different streams gives the results shown in the table:

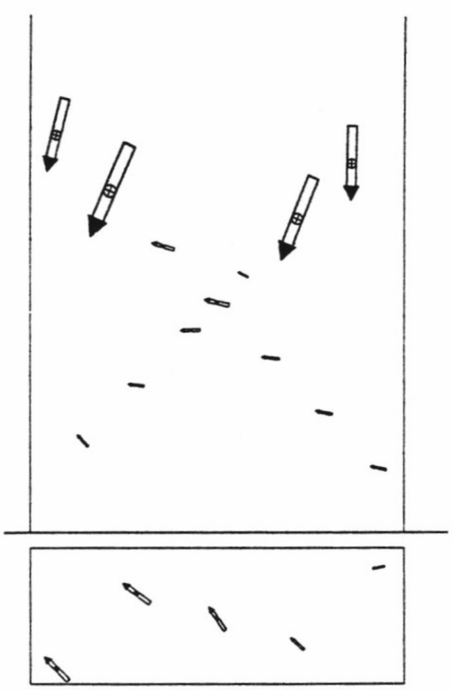
α=0°,β=50°	α=20°,β=20°	plate α=50°	d
.0193	.023	.0368	0
.025	.0258	.0445	40
.02	.0065		90

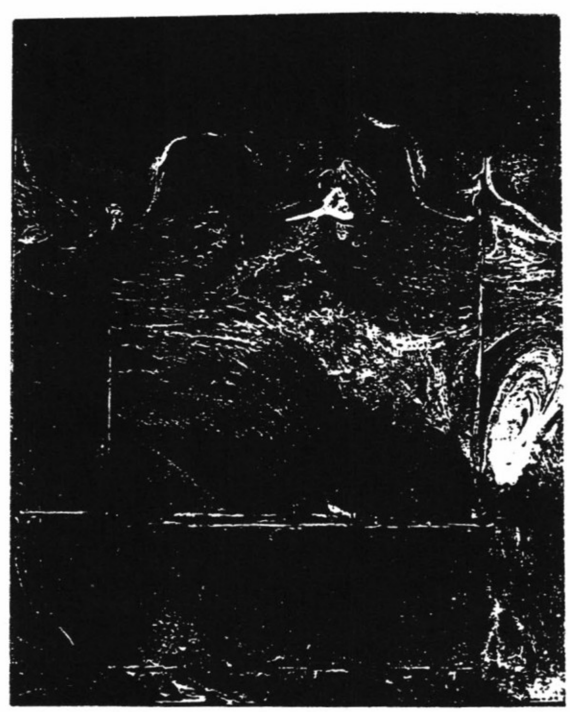
(d is the distance from trailing edge in mm)

It might be seen that the two flap configurations, α = 0 and β = 50 and α= 20 and β = 20 have comparable backflows, although in the second case the bubble is a little shorter, while the plate has a recirculating flow as mach as twice the airfoil.

WALL SHEAR STRESSES

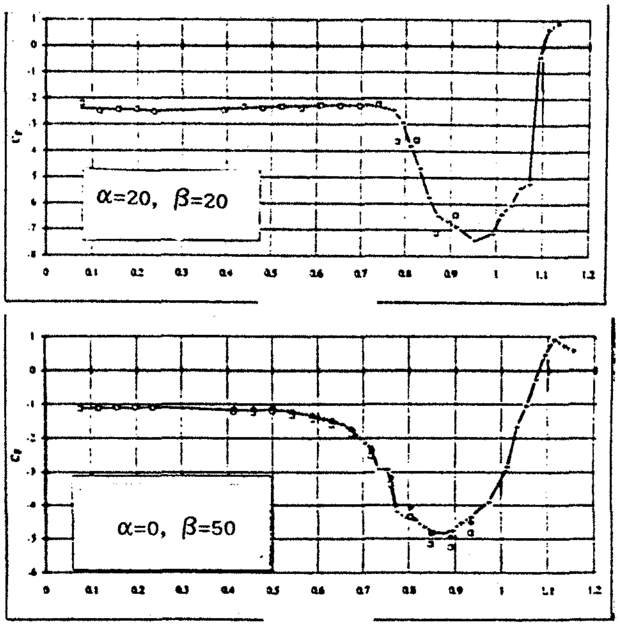
Wall shear stresses are measured by means of a triangular probe of Dexter,(2) as described by Ashill (3). The probes were calibrated in a plane boundary layer by a reference pair of Preston tubes of different diameters. Due to the fact that sometimes the viscous sublayer is thicker than the probe, a special calibration function was derived, in order to obtain the true value of the shear stress. If such a procedure would be neglected, the error could be of the same magnitude of the stress. The probe allows also the measurement of the stress direction all around and the results were compared to surface flow visualization made by means of a fluorescent powder dispersed in a volatile liquid. Even in the case of strongly separated flow the correspondence was rather good, as shown in the figure:





Comparison between wall shear stress and visualization

From the central pressure tap of the probes it was possible to evaluate the pressure distribution , as shown in the following figure:



Pressure distribution on the airfoil

It is possible to have an idea of the base pressure in the separated flow, which is approximately twice larger in the case of α=20,β=20 compared to α=0, β=50. Pressure coefficients are .24 and .12 respectively.

DESCRIPTION OF THE RESULTS

From the plots of the velocity vectors in and around the recirculation bubble five main features appear:

a) the bubble is shorter past the plate, compared to the one past the flap at the same angle of attack,

b) the recirculating velocities are larger in the case of the plate.

c) in the lower part, after the trailing edge, both flows are rather similar, while in the upper part are quite different.

d) there is a certain similarity between the shape of the two flap bubbles although the base pressure is quite different.

e) also the recirculating mass flow is quite similar for the two airfoil configurations

f) the *vertical* velocity component in the bubble of the two flap configurations is the only large difference: also on the plate is larger than on both airfoil configurations.

It may be due to the following facts:

1) the main airfoil and its circulation are reducing the load on the flap, compared to the plate at the same angle of attack

2) the angle of attack of the main airfoil is governing the stream direction at the hinge line and therefore the base pressure

3) the base pressure determines the acceleration of the flow towards the bubble and therefore the increase of the vertical velocity component

4) being the velocities on the lower part of the bubble larger than the ones on the upper part, the streamline curvature is larger on the upper part, giving larger vertical velocities to withstand the base pressure,

5) the boundary layer and turbulence structure at the hinge line are quite different from the ones at the plate leading edge.

6) the recirculating mass flow is probably much more related to the bubble *length to width ratio* than to the base pressure and the former is related to the boundary conditions at separation points

THE NUMERICAL APPROACH

The first idea of a simple numerical approach was the outflow scheme of Jacob,(1) with some improvements. It was noticed that a rlatively wide degree of empiricism is contained in the scheme and while it could be in the future an useful tool of investigation during the first stages of the design, something more complex would be necessary for a research purpouse.

The second degree of complexity was identified in a discrete vortex model carried on by Gibertini (4).

Two shear layers issuing from the separation points are represented in a Lagrangian way by a set of discrete vortices carrying out the vorticity at separation points, which are fixed at the two edges of the plate. In order to have a better representation of the flowfield, two secondary separations are also represented issuing from the leeside of the plate. The location of these secondary separations are roughly approximated by the velocity maxima, assuming that as soon as the flow decelerates, the "boundary layer" on the suction side separates.

The scheme may be representative of Euler Equations neglecting vortex diffusion and requires a relatively small memory capability and computational time, because the only points of interest are the ones in the vortex layers and not in the whole flowfield. On the other hand the influence matrix is full and changes at each time step incrising the computational time accordingly.

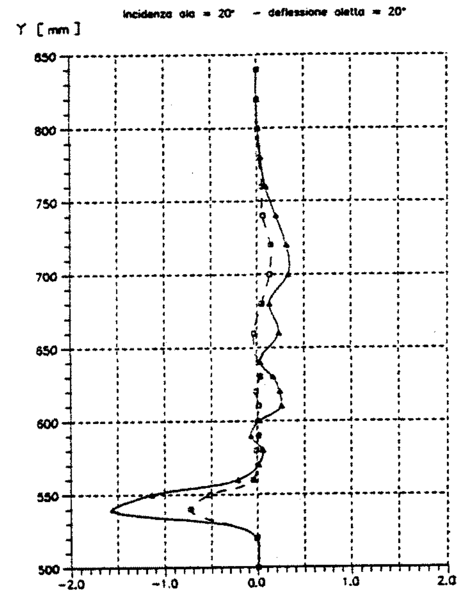
In order to have a "more Navier-Stoks" scheme, vortex diffusivity may be represented in some way, and even 3-D turbulent properties can be introduced in the smallest scales.

The results of the model are quite encouraging and will be presented later on.

NUMERICAL RESULTS

Numerical calculations on the flat plate at α=50°, have shown a rather good agreement with the experiments of Fage and Johansen(5)
Also the shed vorticity is in fair agreement with the visualized vortex centers and an outline of the vortical structure is shown in the following figure:

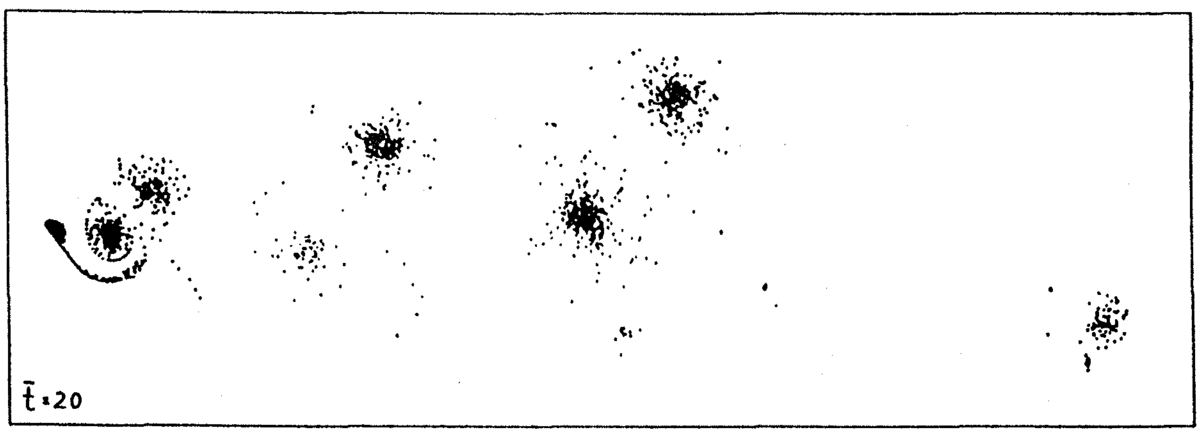
One of the result is shown in the following figure related to the airfoil measurement:



ΔΔΔΔΔ turbulent stresses prod.
□□□□□ kinetic energy production

Production of turbulent quantities past the airfoil at α=20°,β=20°

It is interesting to note that the



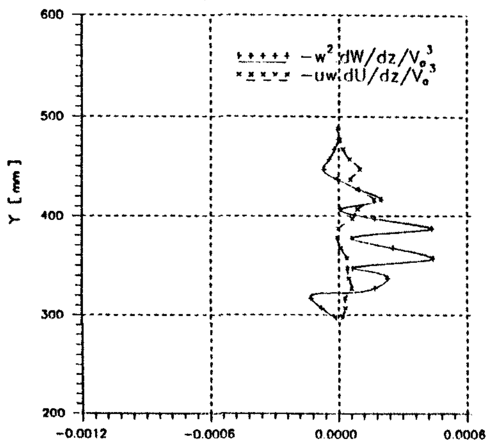
Vortices past the plate at α=50°

It is interesting to note that the maximum production is close to the trailing edge, according to the larger
Problems arising at lower incidence are described in a previous paper (6)

TURBULENT STRUCTURE

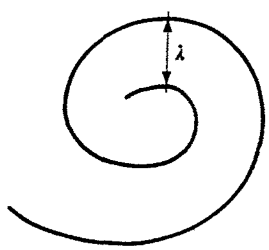
As told before, terms of production of both *Reynolds stresses and turbulent kinetic energy* were evaluated by computation on experimental data.

maximum production is close to the trailing edge, according to the larger vorticity into the boundary layer. On the other hand LDV could not allow to approach the suction side separation point, due to optical path problems.
But the most interesting thing is the *periodical nature* of the terms of production downstream. It was first supposed to be an experimental error, but successive smoke visualizations have



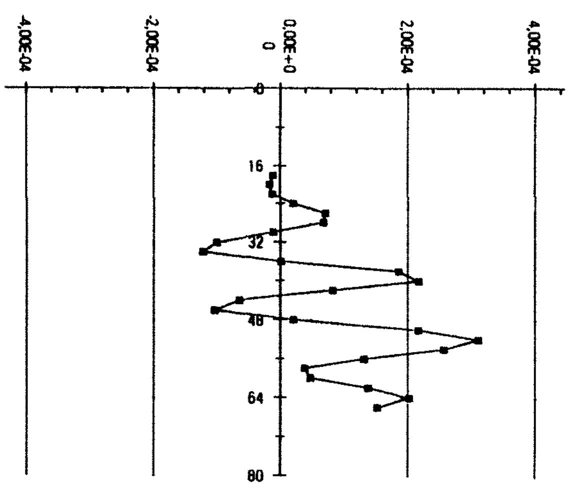
Production of turbulent quantities past the plate

shown that this periodical aspect could be related to the spiral distance in the roll-up of the vortex sheet



The roll-up of the vortex

The experimental points were not enough to give a sound answer, but two things seems to confirm the assumption: the wawelength is closely related to the



Further production measurements in a flap wake

spiral distance of the roll-up obtained by numerical calculation, and as shown in the figure a different trailing edge flow, recently investigated, (7) has shown the same periodical nature with more refined measuring mesh.
It may therefore be assumed that even in time-averaged measurement some feature of the unsteady roll-up mechanism are detectable and the mean flow structure has some *memory* of the time structure.

CONCLUSIONS
This first approach to a comparison of different wakes has shown some overall features of the recirculation: first of all the small dependence of the recirculating flow and bubble shape from the base pressure coefficient.
Another interesting aspect is that the upper part of the bubble seems to be governed mainly by the direction of flow at separation point and this gives a simplifying tool for the modelling of the bubble.
One of the most interesting things for further investigation is the aspect of the periodical nature of the turbulent structure of the roll-up of the vortex sheet and in this field a further improvement of the numerical approach could be very useful as interpreting tool, combined by conditional sampling of the velocity field and vith particle image velocimetry to get an overall comparison.

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