Some Notes on the Possibilities of Progress in Aviation.

AN AERODYNAMIC STANDPOINT

Paper read by Mr A G von Baumhauer (Sub-Director of the Government Aeronautical Laboratories, Amsterdam), before the Institution in the Lecture Room of the Junior Institution of Engineers, 39, Victoria Street, London, S W 1, on 16th November, 1926 Lieut -Colonel J T C Moore-Brabazon, M C , M P , in the Chair

IN introducing the Lecturer, Colonel Moore-Brabazon said that Mr von Baumhauer was a distinguished aeronautical engineer and scientist in his own country, and that the Institution felt very grateful to him for coming over for the special purpose of giving aeronautical people in England some information regarding his work and its results The Chairman then called upon Mr von Baumhauer to deliver his paper

Mr A G von Baumhauer We want progress in aviation because we are convinced that efficient air traffic will give interesting and useful new possibilities

Wind channel tests have shown that wings can be made with a lift-drag ratio of far more than 20, and that streamline-bodies may have a resistance which at high speed is so small for a body of the cross section of modern transport machines that the lift drag ratio of the whole could still be over 20 (*e g* , at a speed of 160 m p h) So it would seem quite simple to build efficient aeroplanes

But it is not really so simple

An aeroplane has not only to fly, it should be able to take off and land, and therefore have a landing gear It should have an engine which needs cooling, exhaust and induction pipes Pilots want to sit in the open and look in any direction

Military machines need machine-guns mounted in such a way that they can easily pivot The wings and the landing-gear have to be attached to the body

All these factors make it impossible to use ideal forms They force the designer to " break the lines " at many places The art of making an efficient aeroplane, seems to me, to be the tact and wisdom for making those departures in an appropriate way, such that they do not spoil too much the efficient machine imagined before

To appreciate the effect of disturbances one should know in what way they alter the air-flow along the bodies The knowledge of this subject has been developed in the last years in a considerable way Though the theory is not yet ready, the general principles of the theory have been confirmed by several facts, in such a way that they give a good explanation of some phenomena which have startled many of us

I this respect I should like to remind you of the fact, that a rotor, a cylinder rotating at high speed, has given in the wind-channel a lift coefficient of over 4 (Abs Br Coeff) More recent experiments have shown that a thick wing, which normally has a lift coefficient of about 0 65, can show a lift coefficient up to 2 5 when air is sucked into the model at the upper surface

The explanation of these facts is given by the theory of the boundary layer, in which are discussed the conditions which lead to the phenomenon of "departure" This occurs when the general flow departs from the surface of the body, and is accompanied by the production of a wake—"dead water"—a region filled with eddies

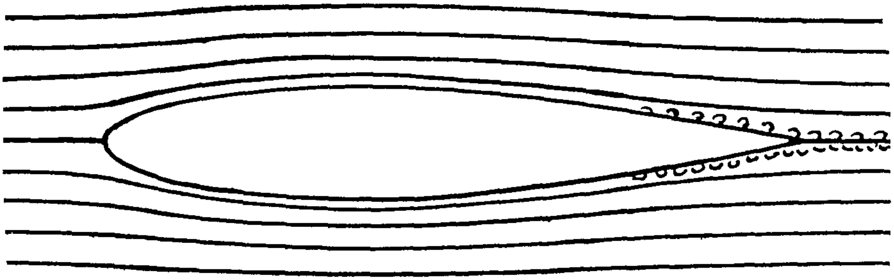

FIG 1

Great similarity with the flow of a perfect fluid, excepting the small wake at the rear

The conditions of departure discussed by Prandtl as early as in 1904 (Ref No 1), are of great interest because the departure of the flow from the walls of a body has an important influence on the whole flow, and therefore on the efficiency of the aeroplane part considered

In the second section of my paper I shall discuss the flow around different types of wings and bodies, applying the principles of this theory

I now want to follow an elementary description of the phenomena and of the explanation given by Prandtl * Let us therefore compare the flow around a streamline strut and a cylinder

Along the strut the streamlines follow the body nearly to the end

Behind the cylinder is found a wake filled with eddies, where mechanical energy is dissipated The resistance of the cylinder is about 15 times as great as the resistance of the strut for the same cross-section The flow along the strut resembles quite well the flow calculated for the perfect fluid, *i e*, a non viscous incompressible fluid The question arises why does the real flow around the cylinder differ so greatly from that calculated for a perfect fluid ?

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* At the end of this paper is given a list of references to the theoretical treatment of the subject and also to reports on experimental work

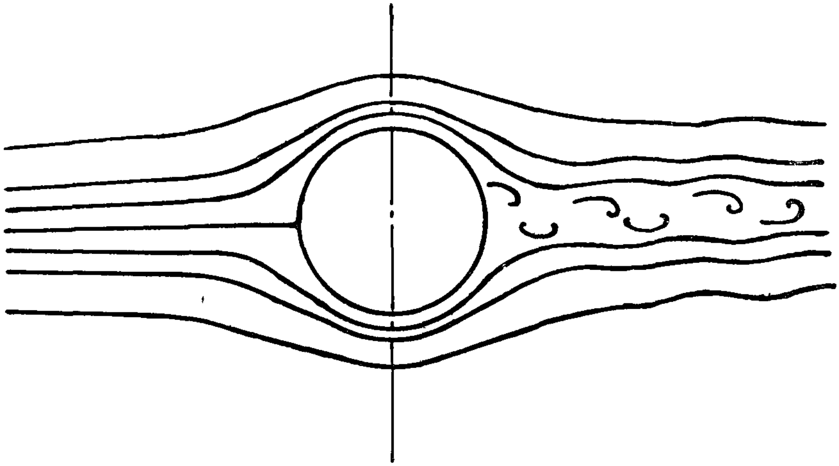


FIG 2
Great difference from the flow of a perfect fluid , big wake , to be compared with Fig 3

Before we can go further into the question of where the eddies come from we must consider the pressures at different points of the cylinder as they may be calculated for the flow of a perfect fluid How this has been done can not be considered now (See text books, Ref 3, 4, 5, 9)

In this fluid the pressure is given by Bernoullis equation

$$p + \frac{\rho}{2} v^2 = C$$

(p = pressure , ρ = density , v = speed)

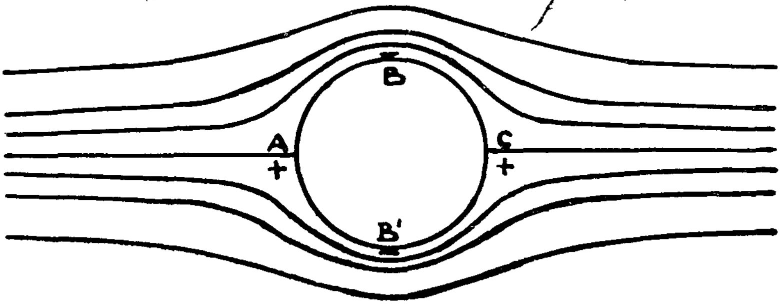


FIG 3
Flow of a perfect fluid around the cylinder

In the flow-pattern the change in speed may be seen from the distance of two neighbouring streamlines, a contraction of the lines means a higher speed and therefore a lower pressure

When the fluid comes to rest the pressure is a maximum The increase in pressure is equal to $\frac{1}{2}\rho v^2$, which is called the velocity head of the flow, (p_v), the difference in the pressure found at a certain point and that of the undisturbed fluid (speed v) may be expressed in terms of the pressure head At the front and rear points of the cylinder (A and C) the speed is zero The change in pressure is $+p_v = +\frac{1}{2}\rho V^2$ At the points of maximum width B and B^1 the speed is $2V$, the difference in pressure is $-3p$

Now let us see what happens along the walls From A to B the fluid is accelerated by the drop in pressure along the cylinder From B to C the flow is retarded, the kinetic energy is transformed into energy of pressure

The pressure distribution is symmetrical for a line perpendicular to the flow, thus there is no drag in this case

In a real fluid we must recognise that the facts are different At some distance from the body the influence of the viscosity is very small in comparison to the forces due to accelerations It has been found that the air quite near to the body is at rest, it sticks to the wall, at a small distance from the wall the speed is finite As the shear in the air increases with the slope of the speed curve perpendicular to the flow (*i e*, the speed gradient normal to the flow) the friction in the layer quite near the body can no longer be neglected

Theoretical and experimental studies have shown that there is formed in the flow along bodies, a skin, called the boundary-layer, which may be laminar, but the greater part of which is turbulent at normal full scale (high Reynolds Number)

The approximate theory of the stability of the laminar layer and the structure of the turbulent layer have been given (Ref 7-16) The mathematical difficulties of the complete problem and of that dealing with the turbulent boundary layer seem to be considerable From experiments, however, we may conclude that the stability is influenced by the same factors as that of the laminar layer in the approximate calculations, though there may be numerical differences

It seems useful now to treat the problems qualitatively, especially with the object of the application to practical questions

The principles of this theory may be formulated as follows —

(*a*) The thickness of the boundary layer is small in comparison with the radius of curvature of the surface,

(*b*) In the boundary layer the pressures are the same as those in the outer flow (the pressure gradient normal to the wall may be neglected),

(*c*) At the wall the speed is zero

Several investigators have measured the distribution of the speeds near a wall The results give us a clearer impression of the structure of the boundary layer I should like to show you some results of the experiments made at Delft by *Burgers and Van der Hegge Zijnen* (Ref 11, 12, 13 and 14)

By means of a hot wire anemometer the speeds have been measured along a smooth flat wall formed by a polished glass plate The leading edge was sharpened In the upper curve of Fig 4 we see the speed curves for sections at 2 5 cm up to 100 cm from the leading edge (from left to right) at a windspeed of 1000 cm

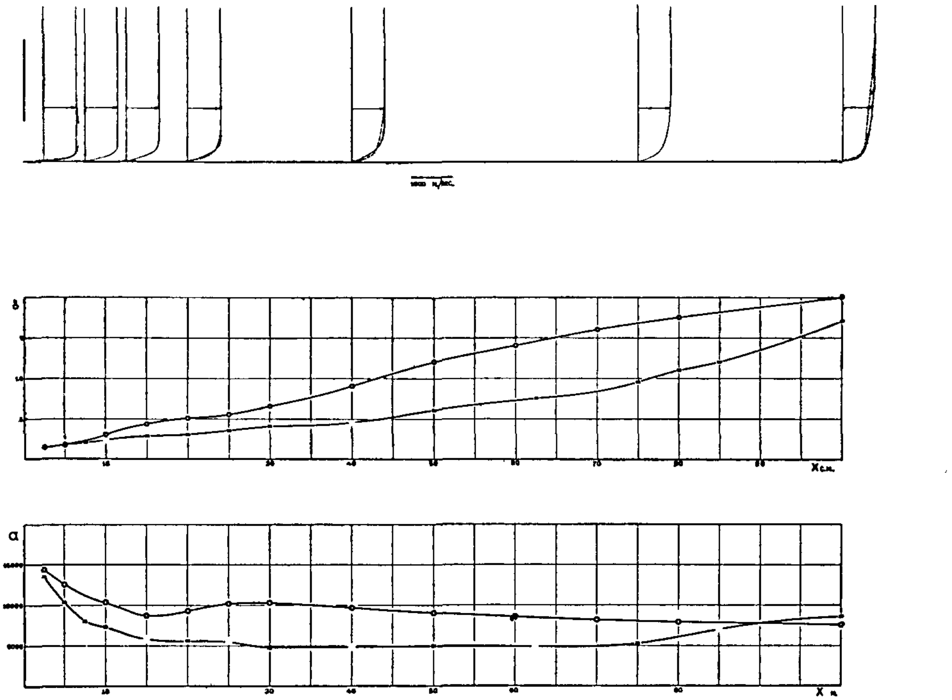


FIG 4

Flow along a smooth wall measured by Van der Hegge Zijnen (*Top*) Speed curves near the wall (*Centre*) Thickness of the boundary layer (*Below*) Speed gradient at the wall = Steady flow o Air current made more turbulent by a gauze in the channel

per second (about 35 ft per sec) The velocity increases from zero at the wall, first proportionally to the distance, then less rapidly, gradually attaining the speed of the outer flow

The thickness of the layer is shown in the centre At 90 cm (about 3 feet) from the leading edge it has a thickness of 1 3 c m (about half an inch)

The slope *a* of the speed-curve at the wall is a measure for the skin friction

The values of *a* are plotted in the lower diagram It is constant for a certain distance, but increases between 75 and 90 c m This increase corresponds to the change of the laminar into the turbulent motion This transition may happen earlier if the outer flow is more turbulent This was shown by putting a wire gauze at some distance in front of the plate, when the structure of the boundary layer seemed to have changed a great deal The latter data have been plotted by little circles The formation of the turbulent state happens between 15 and 25 cm from the leading edge, as shown in the lower diagram by the increase of *a* The friction is now considerably increased At 90 cm from the leading edge the thickness of the layer is increased from 1 8 to 1 9 cm

The movement of a part of the boundary layer will depend on the resultant of the following components —

(a) Friction with the wall
(b) Pressure gradient along the wall
(c) Inertia forces

If the pressure gradient is directed with the principal flow the particles of boundary layer will be accelerated If on the contrary the pressure increases when moving with the principal flow the boundary layer will be decelerated, thus coming to rest or even showing a contrary movement In this case the pressure gradient is directed against the movement of the outer flow In what follows I shall call this an *adverse pressure gradient*

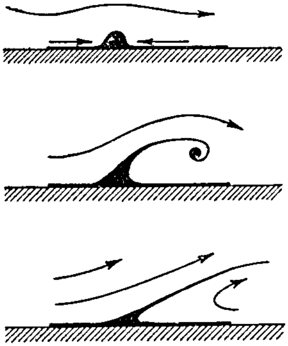


FIG 5

Reversed motion in the boundary layer produces departure

Fig 5 shows what happens when the movement of a part of the boundary layer is reversed

It gives rise to a stagnation, and the layer departs from the surface An unstable sheet of discontinuity is formed and is rolled up, giving rise to eddies Under certian limiting conditions (with certain restrictions) the flow pattern has been calculated for a laminar boundary layer in an adverse pressure gradient (Ref 16 and 17)

Fig 6 shows the speed curves

Point 4 is called the *point of departure*

Returning to our cylinder of Fig 3, we see that the pressure decreases at the front from A to B, but increases at the back from B to C, thus we have an adverse pressure gradient from B to C, which will lead to a reversal of the movement of the boundary layer

We will now consider what happens when we give a small speed to the cylinder, which was first at rest In the beginning the flow corresponds to the perfect flow, but after a small displacement the boundary layer will introduce departure

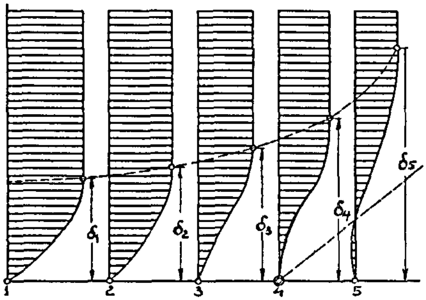


FIG 6

Flow from left to right , departure at point 4 δ = thickness of the boundary layer

The fatal scene now beginning is well described by Prandtl (Ref 2) of which I try to give a translation

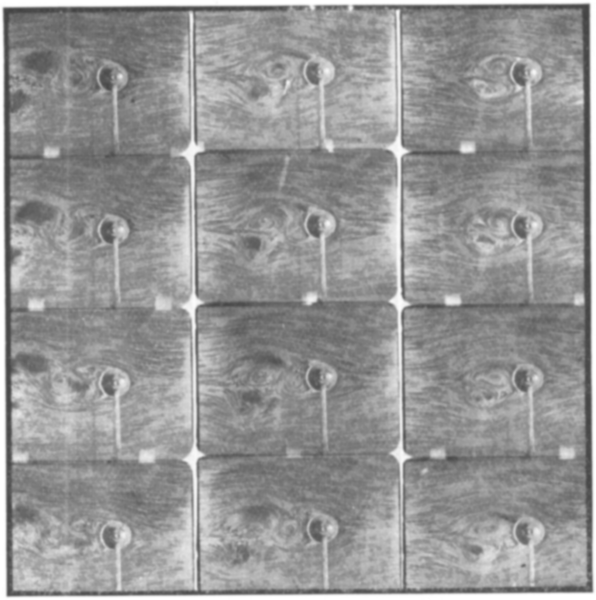
" The mostly retarded sheets nearest to wall will return first, the next layers follow Only the outer sheets of the boundary layer are dragged over the former ones Because the layer continually brings new retarded material, which returns as well, there will be formed between B and C a " clew " which will gradually grow It consists of fluid brought into rotation by the friction, which will move in the direction of B by the action of the adverse pressure gradient It will now collide with the forward flow and be pushed into the free fluid in the form of vortices Starting from the minor phenomena in the boundary layer a complete transformation of the flow is gradually produced The flow now shows a departure from the wall somewhere near B, continually forming new vortices , a region with irregular slower movements is formed between the flow and the cylinder "

Photographs of these phenomena have been made at Gottingen by Prandtl and Tietjens, to whom I am indebted for the cinematographic views of Fig 7 and 8

We now understand that departure only will be found in a region of an adverse pressure gradient Because generally departure causes breakdown of the flow, means have been studied for preventing it

We may mention —

(1) Diminishing the friction along the wall, by moving the wall in the same direction as the mean flow
(2) Diminishing the pressure gradient, by fairing the pressure curve
(3) Increasing the speed in the boundary layer (giving impulse) at upstream points
(4) Sucking away the boundary layer into holes of the wall



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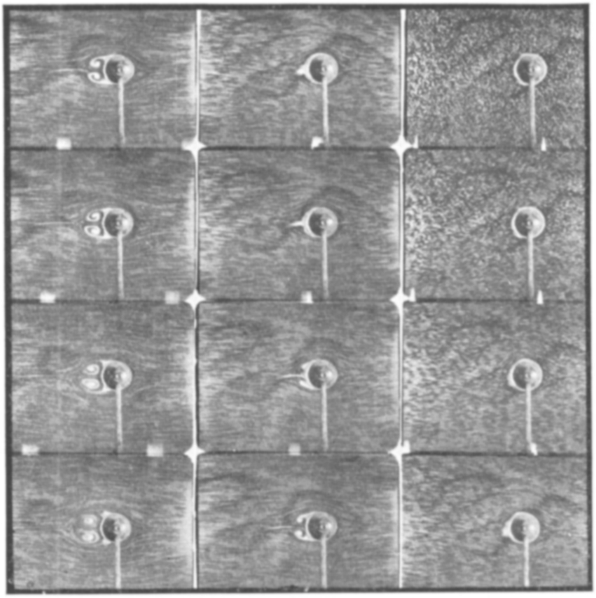

Figs 8

Flow pattern of a cylinder set into motion (Prandtl and Tietjens)

If disturbances are wanted, departure can be produced, for instance, by putting a ridge on the surface, as illustrated in Fig 9

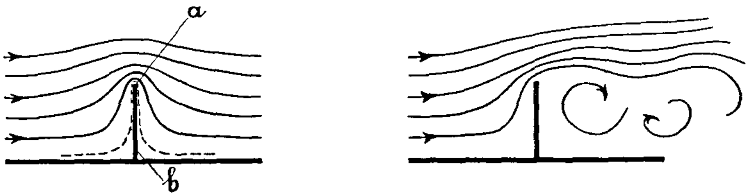

FIG 9

(*At the left*) Perfect flow (*At the right*) Real flow

At the top (*a*) the speed is higher than at (*b*) thus giving an adverse pressure gradient on the back of the ridge

This means an additional pressure gradient which may lead to departure on a body where only a small adverse pressure gradient was present before

Thus a relatively small ridge may cause a great breakdown of the flow

The departure will be most easily produced if the disturbance is located where the stability of the boundary layer is small , this occurs in a region of an appreciable adverse pressure gradient on the body Only in the case of a sufficient downstream pressure gradient will the ridge do no harm

During the model experiments at Amsterdam with landing flaps on the suction side of wings, it was observed, that the disturbance was not limited to the surface behind the flap directly in the line of flight, but that it was diverging at an angle of about 45 degrees (Ref 27)

The reversed flow in the boundary layer also spreads laterally, owing to a transverse pressure gradient, thus undermining a part of the good flow

The first example deals with the disturbances produced on a model of an airship, by a small needle

The results of the experiments on this subject made at Amsterdam are shown in Fig 10 The figure shows in the centre the longitudinal section of Fuhrmann model No IV (Ref No 22), and at the right the needle to the same scale The resistance of the model was measureed with the needle at different places The increase in resistance produced by the presence of the needle is plotted at the top of this figure as Δ W, the percentage of the resistance without the needle The values are represented by dots vertically above the point where the needle was placed

Below is given the pressure line as measured by Fuhrmann and expressed in terms of the dynamic pressure ($\frac{1}{2}\rho v^2$) It may be observed that an unexpectedly great breakdown of the flow is produced if the needle is placed near the maximum cross-section

From these results it is clear that the means of suspension of a model, such as thin wires, may have a great influence on the resistance measured In the above

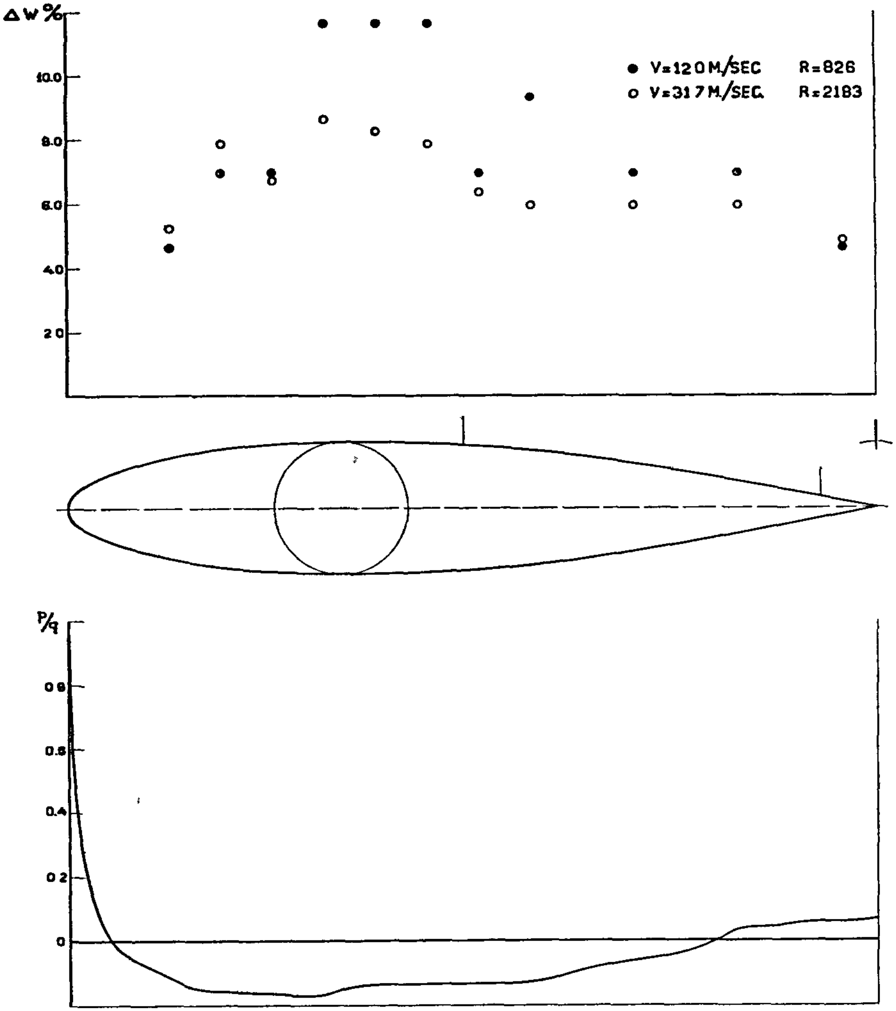

FIG 10

A needle causes an appreciable increase (Δ W) of the resistance (W) tests the absolute value of the resistance without the needle may not be correct as the model was suspended by thin wires

Referring to wings,* one may observe that the lift reaches a maximum as the angle of incidence increases This is due to the departure of the flow from the upper surface, and is called " stalling " in the case of aerofoils

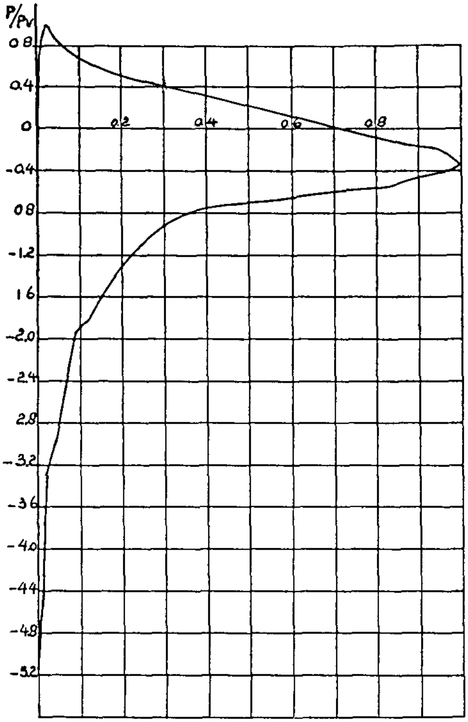

FIG 11
Pressure distribution on R A F 15, at 14° incidence (Full Scale)

Fig 11 shows the pressures on the R A F 15 wing The general character is the same as of other simple sections The pressures on the lower surface are plotted at the top The maximum is near to the leading edge, decreasing to the rear

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* I do not want to deal with the problem of the production of lift , in another chapter of applied aerodynamics it may be shown that the existence of the circulation is due to the departure of the boundary layer when the motion begins

Thus the boundary layer is accelerated by the pressure drop, in the direction of the main flow This explains why disturbances on the pressure side have only a small influence

The contrary is seen on the upper side , the depression is shown in the lower part of the figure to have its maximum near the leading edge Behind this point there is an appreciable adverse pressure gradient

When the angle of incidence increases the pressure gradient increases till a maximum is reached and departure is developed (stalling)

Consequently the defection of the flow is not increased when the angle is still further increased , and there is a maximum value of the lift *

By fairing the leading edge, the pressure curve is smoothed showing a less sharp peak This explains why thicker aerofoils and those with a blunter leading edge show a higher maximum lift-coefficient (Ref 25)

When aerofoils are disturbed at the upper surface, especially near to the leading ege, the maximum lift is decreased It has been shown that a disturbance produced only in the centre, will give an appreciable decrease in lift and increase of the drag This drag results partly from the energy dissipated by the irregular eddies formed, but also from the increase in induced drag The aerofoil has no longer a lift-distribution which resembles the elliptical one; but the lift grading curve is split up into two parts Both of these have an increased downwash as they are comparable with two separate aerofoils of about half the original aspect ratio

An example is given in Fig 12, showing lift and drag as they were measured in Amsterdam on a model of an aeroplane (Ref 26, 27 and 28) The experiments were made with the normal wing and with a wing of which parts were cut away The maximum lift is diminished, the resistance is doubled

I should now like to mention several means by which the lift is increased and the drag is reduced, which may now all be reduced to preventing the departure

In the first place I wish to refer to slotted wings, with which lift coefficients have been attained far greater than those of simple aerofoils (Ref 29 and 30) The explanation for these phenomena given by Betz (Ref 31) is based on the theory of the boundary layer He made pressure plottings as shown in Fig 13

Two equal aerofoils were disposed such that the trailing edge of the leading one is placed in the region of low pressure of the second wing This changes the pressure at the trailing edge such that the curves 2 were found instead of 1, as measured for the single aerofoil Now the pressure gradient on the nose of the leading aerofoil is diminished so that the angle of incidence could be increased without stalling The lift increased appreciably (curve 3) The influence on the rear wing is shown by the change of curve 4 into 5, which shows a considerable fairing of the pressure curve

One may suppose that the second aerofoil could be set at an appreciably greater angle before departure could occur Thus the lift of the combination is increased by a great amount

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* The fact that the departure normally starts at the centre-section of the wing and has certain interesting influences on balance and stability of an aeroplane was mentioned in the discussion

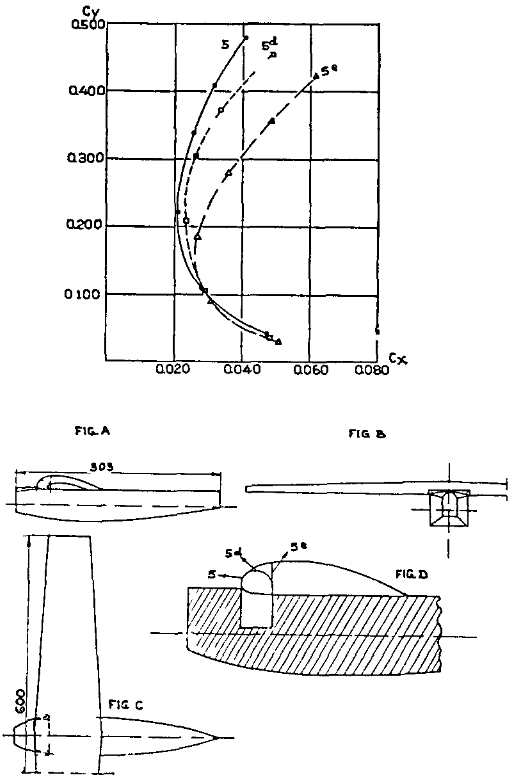

Fig 12
Lift and drag influenced by a part cut out of the leading edge of a Fokker F III Model

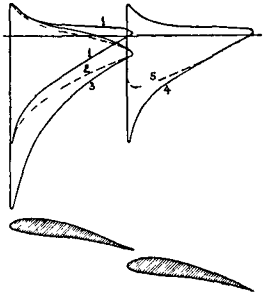

Fig 13
1 Single aerofoil 2 Influenced by rear aerofoil 3 At greater angle
4 Single rear aerofoil 5 Influenced by front aerofoil

The decrease of the suction on the rear wing is explained by the reduction of the speed due to the circulatory components of the air speed under the trailing edge of the front wing

This reduction in speed and in suction has been calculated by Lachmann (Ref 32, 32a)

The next example deals with' the rotor, a cylinder rotating about an axis perpendicular to the flow Experiments have shown that the flow is deflected through a great angle giving a lift coefficient up to 4 5 Br Abs Coeff (Ref 33)

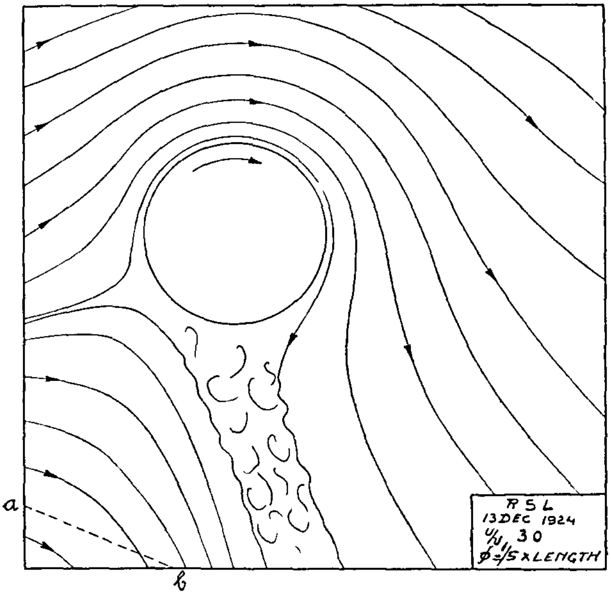

FIG 14

Flow around rotating cylinder, circumferential speed (u) is three times the wind speed (v) , the diameter of the cylinder is 1/5th of its length

The streamlines reproduced at the top of Fig 14 have been drawn after a study of the flow in the Amsterdam wind channel They seem to agree fairly well with the flow of the perfect fluid round a cylinder, calculated for the case in which circulation is added (see below)

At the top of the cylinder the speed may be three times the undisturbed speed, giving a depression of eight times the pressure head The pressure gradient at the back has thus a considerable value still The departure only occurs at a low point This is explained by the fact that the boundary layer, dragged by the friction of the moving wall, possesses sufficient kinetic energy to overcome the retarding action of that pressure gradient

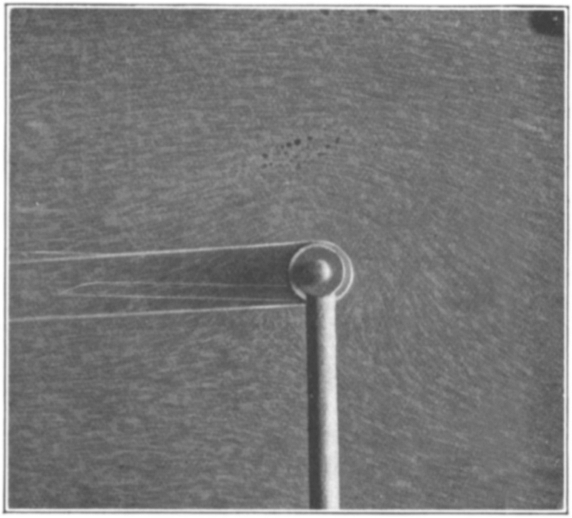

FIG 15 —Photograph made by Burges (Delft)

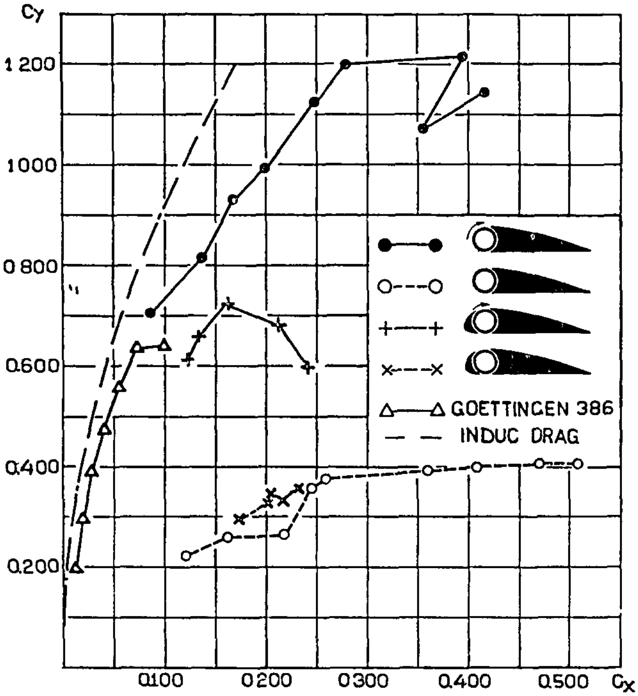

FIG 16 —Lift and drag measured on an aerofoil with a cylinder as a leading edge With the cylinder at rest the drag is big, the lift is small, due to the sharp edges (—o— —x—)

Fig 15 shows a photograph taken by Burgers at Delft of the flow round the rotor (See also Ref 34)

In studying an application allowing a small drag at high speed (low lift coefficient), similar tests have been made in Amsterdam (Wolff and Koning, Ref 35, 36, 38 and 39), in which the boundary layer of an aerofoil is accelerated by a rotating cylinder Fig 16 shows lift and drag-coefficients of the aerofoil, both with the cylinder rotating and at rest (Br Abs Units)

Lift coefficients up to 1 2 are found

The speeds in the boundary layer on the same model have been measured by Van der Hegge Zijnen in Delft (Ref 37)

Fig 17 shows the increase of speed in the boundary layer at the points III and IV

If the cylinder does not rotate the maximum lift is very small This is explained by the departure produced by the sharp edge of the body close to the cylinder

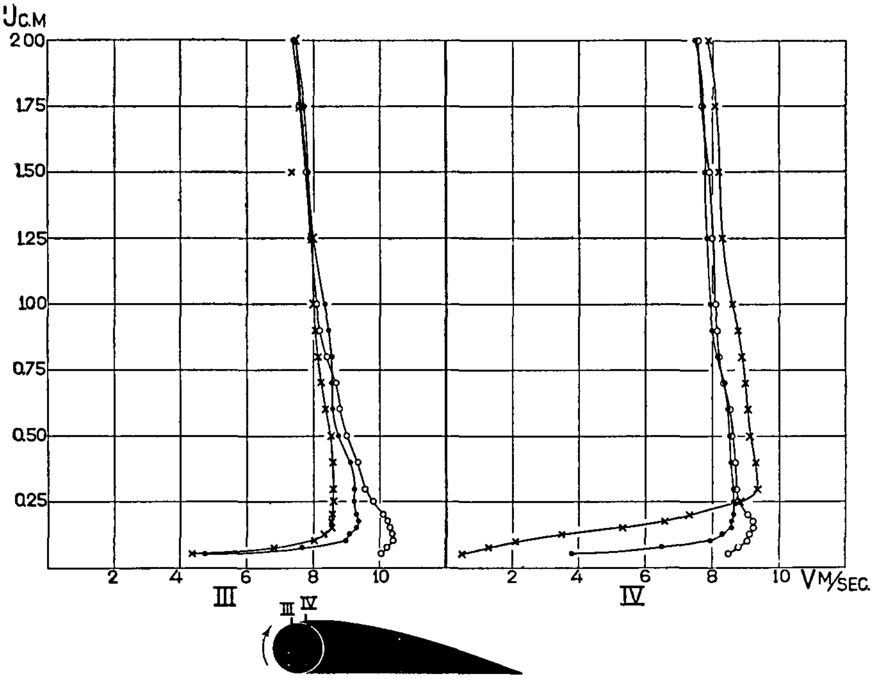

FIG 17

Speeds measured in the neighbourhood of the model, points III and IV o Cylinder rotating
x Cylinder at rest ● Gap filled
The rotating cylinder increases, the sharp edges reduce, the speeds in the boundary layer

When the slot is closed by paraffin wax the speeds in the boundary layer are much higher

A similar experiment has been made by Frey (Ref 40), who produces an increase in lift by inserting a rotor in the slot of a complex aerofoil (Fig 18)

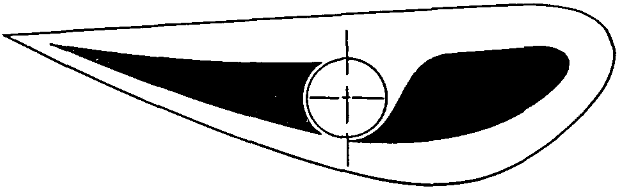

FIG 18
Slotted wing combined with rotor, investigated by Frey

We must now consider another means of preventing departure, of which data have only recently been published

As early as 1905 Prandtl made experiments on the effect of sucking fluid into the body Fig 19 shows the flow coming from left to right, a part of the fluid being sucked into a slit in the hollow cylinder through a tube The flow is deflected asymmetrically

The explanation may be stated as follows In the region of high adverse pressure gradient the air of the boundary must have sufficient speed to withstand the retarding action Therefore the boundary layer should continually be refreshed by air having a high speed This will occur when the slow layer is sucked into the body and replaced by air coming from the outer flow with the full kinetic energy present in a region of depression

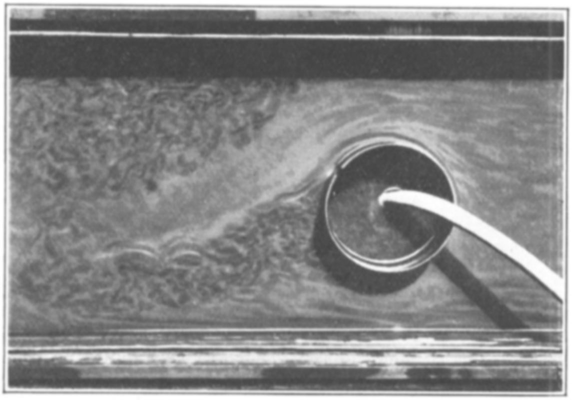

FIG 19
Asymmetric deviation of the flow along a cylinder produced by sucking fluid into the body

A more recent application of this phenomenon is made by Betz and Ackeret (Ref 41) The upper surface of a model aerofoil is partially made of wire gauze through which air is sucked into the model Departure now only occurs at a much greater angle of incidence, with a greater lift The provisional tests indicate that a lift coefficient of 2 (Br Abs Units) may be attained The energy necessary for sucking the air into the wing may be expressed as a drag coefficient, and this was found to be smaller than the profile drag of the aerofoil

The resistance of a body may be decreased by diminishing the area at which departure is produced Experiments of this sort have also been at Gottingen with a sphere the rear half of which was made with wire gauze strips The resistance of the sphere could be reduced to 20 per cent of the value for a normal sphere under the same conditions (Ref 42)

Wonderful applications of these methods seem possible The deflection of an air current through 180 degrees was produced by sucking air into a semi-cylindrical wall of wire gauze

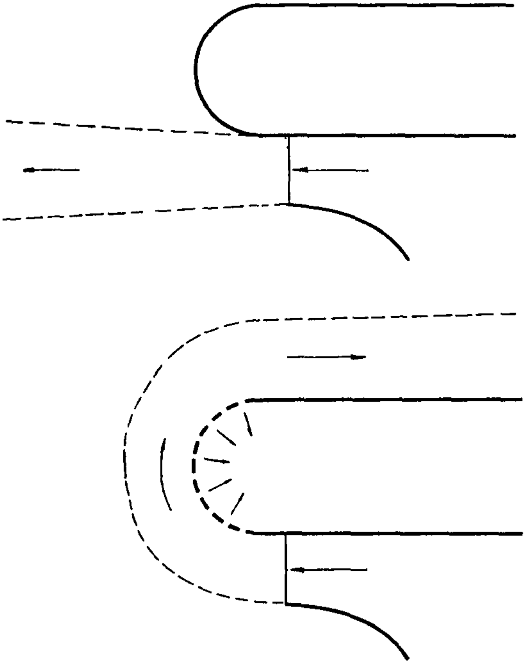

FIG 20
Jet of air, with and without suction

Fig 20 shows a diagram of the experiment When no air is sucked in, the air current is directed as indicated by the arrows I and III (left) At the right we see that with suction the arrows I, III and IV indicate a complete deflection (Ref 43)

Conclusions

For practical work we may conclude

Even small disturbances should be avoided especially on the suction side of wings

Slotted wings and rotors show how departure may be prevented

The new method of sucking air into the body may be applied in several ways

I doubt whether applications on the whole length of a wing will be practicable

I imagine that this method will be useful for diminishing the damage done by struts, etc , to bodies or wings, by sucking air into the main part over a small area behind the inevitable disturbance

The quantity of air which it is necessary to suck in is relatively small, *e g* , smaller than the intake of the engine

REFERENCES TO DIAGRAMS, ETC

Bodies	23, 23, 24
Wings (stalling)	25
Wings with disturbances (those at the centre may also double the induced drag)	26, 27, 28
Slotted wings	29, 30, 31, 32
Rotor	33
Wing and Rotor	34, 35, 36, 37
Slotted wing and rotor	38
Sucking the boundary layer into the wall of wing and diffusor	39, 40, 41

Titles are translated into English

The classical works and older papers are not given, *e g* , those by Stokes, Lord Raleigh, Reynolds, etc , to which many papers refer

ABBREVIATIONS

Congress, Innsbruck Proceedings of the International Congress for Hydrodynamics, Innsbruck 1922 , Entitled Papers on Hydro- and Aero-dynamics, Springer, Berlin

Congress, Delft Proceedings of the International Congress for Applied Mechanics, Delft 1924 Waltman, Delft

Z F M Zeitschrift fur Flugtechnik und Motorluftschiffahrt (Aeronautical Journal) Oldenbourg, Berlin and Munich

Z A M M Zeitschrift fur Angewandte Mathematik und Mechanik (Journal for Applied Mathematics and Mechanics) v Mises, Berlin

Rep R S L Verslagen en Verhandelingen van den Ryks-Studiedienst voor de Luchtvaart, Amsterdam (National Aeronautical Laboratories) Booksellers van Cleeff, The Hague

Ref No

1 L PRANDTL " On fluid motion with very small viscosity " Proceedings III Intern Math Congress, Heidelberg 1904 Leipzig p 484 (Discussed in Ref 5 and Ref 7)

2 L PRANDTL Paper read to the Physical Society, Gottingen, Die Naturwissenschaften , 6th Febr 1925 p 94

TEXT BOOKS

3 H LAMB " Hydrodynamics " Cambridge University Press

4 L BAIRSTOW "Applied Aerodynamics," 1919

5 R Fuchs and L Hopf "Aerodynamik" R C Schmidt & Co, Berlin, 1922

6 H Glauert "The elements of Aerofoil and Airscrew Theory" Cambridge, 1926

7 L Bairstow Paper read to the Royal Aeronautical Society, Aeronautical Journal, p 3, 1925 (With many references)

8 Th v Kármán "On laminar and turbulent friction" Z A M M 1921 p 223

9 Th v Kármán "On the skin friction of a fluid" Congress Innsbruck, 1922, p 146

10 Th v Kármán 'On the stability of the laminar flow and the theory of turbulence" Communications of the Aerodynamic Institute, Aachen Part 4, Springer, Berlin, 1925 Also Congress, Delft p 97

11 J M Burgers and B G van der Hegge Zynen "Preliminary measurements of the distribution of the velocity of a fluid in the immediate neighbourhood of a plane smooth surface" Royal Academy of Sciences, Amsterdam, 1923

12 B G van der Hegge Zijnen "*Measurements of the velocity distribution in the* boundary layer along a plane surface" Waltman, Delft, 1924 Thesis, Delft, (in English)

13 J M Burgers "The motion of a fluid in the boundary layer along a plane smooth surface" Congress, Delft, p 113

14 J M Burgers "Experiments on the fluctuations of the speed in an air flow" Royal Academy of Sciences, Amsterdam xxxv, No 1, 1926

15 R V Southwell "Note on the stability under shearing forces of a flat elastic strip and an analogy with the problem of the stability of laminar fluid motion" Congress Delft, p 266

16 K Hiemenz "The boundary layer on a cylinder" Thesis, Gottingen, 1911, also Dinglers Polyt Journal, 1911 p 321 (Theoretical and experimental investigation on the departure of the laminar boundary layer)

17 K Pohlhausen "On the approximate integration of the differential equations of the laminar boundary layer" Reports of the Aerodynamic Laboratory, Aachen I, 1921, p 20 Also Z A A M I 1921, p 252

18 A Betz "Vortices and related principles in hydrodynamics" Z F M 1921, p 193 (An elementary treatise of this subject, also on the formation of eddies)

19 L Prandtl "Notes on the formation of turbulence" Z A A M I 1921, p 431

20 L Prandtl "On the formation of vortices in the perfect fluid, with application to aerofoil theory and other problems" Congress Innsbruck p 18

21 O Tietjens "Notes on the formation of turbulence" Thesis, Gottingen, 1922, also Z A A M V 1925, p 220

22 G Fuhrmann "Theoretical and experimental investigations on airship models" Thesis Goettingen, 1912, also Annual Report of the Motorluftschiff, Studiengesellschaft, 1911-1912

23 A G v Baumhauer "Calculations and experiments on the flow along a body" Techn Stud Tydschrift, Delft, 1914, p 349

24 C Wieselsberger "The Resistance of Spheres" Reports of the Gottingen Aerodyn Lab Z F M 1914, p 140

25 Measurements of the pressure on aerofoils at incidences under and above the critical angle, reports of several aerodynamic laboratories, e g, Aeronautical Research Committee, Reports and Memoranda No 895, London, Dec 1925, and Ergebnisse II Gottingen 1923, p 43

26 R S L 'Preliminary Experiments on the influence of the means of suspension of models on the results of wind-tunnel measurements" Report A 14, R S L, Part I 1921

27 R S L "Experiments with a device for shortening the glide and the landing run of an aeroplane' Reports R S L Part II, 1923, p 3 "Experiments on the effect of cutting away part of the leading edge of a Fokker F III wing" Reports R S L Part II, 1923 p 19

28 C Wieselberger Some title as Ref 26 Reports of the Gottingen Aerodyn Lab Z F M 1922 p 188

29 F Handley Page 'Slotted Wings" Report of the International Air Congress, London 1923 p 68 (Aeron Journ 1921, 263)

30 H GLAUERT "The Handley Page slotted Wing" Technical Report of the Advisory Committee for Aeronautics 1922-23, p 114 (R & M 834)

31 A BETZ "On slotted wings" Wissenschaftliche Gesellschaft fur Luftfahr Ann Report, 6, 1922 p 23

32 G LACHMANN "The flow on a wing with an auxiliary one in front of it" Z F M 1923 p 71

32A P KONING Remarks on Ref 32 Z F M 1924, p 13

33 J ACKERET "New investigations of the Aerodynamic Laboratory, at Gottingen" Paper read to the Scientific Society for Aeronautics, Frankfurt, September 1924 Annual Report 1924 12 July, 1925 p 57

34 E F RELF "Experiments on the flow behind a rotating cylinder in the water channel" Reports and Memoranda, 1909 London 1926

35 E B WOLFF "Preliminary investigations on the effect of a rotating cylinder on a wing" R S L Report A 96, Amsterdam 1924 Translated U S A Technical Memorandum Nat Adv Comm for Aeronautics, No 307

36 E B WOLFF and C KONING Item R S L Report A 105 U S A, N A C A No 354 See also III International Air Congress, Brussels, Tome I p 477

37 B G VAN DER HEGGE ZIJNEN "Measurements of the velocities in the boundary layer of an aerofoil, in which is built a rotating cylinder" De Ingenieur 1926 p 878 No 43

38 FLIGHT "Preliminary Study on the influence of a rotating cylinder on a wing" Flight 1925, Jan 1915 Vol 17, p 30 Summary of Ref 34

39 G W LEWIS "Tests on rotating cylinders" U S A, N A C A Technical Note No 209 Summary in Flight 1925 Jan 8, Vol 17, p 17

40 K FREY "Experiments on a rotating cylinder combined with a (slotted) wing" Z F M 17, 1926, 16, p 342

41 J ACKERET, A BETZ and O SCHRENK 'Experiments on a wing the boundary layer of which is sucked away into the model" Provisional Reports No 4, 1925, Gottingen Aerodynamic Laboratory

42 O SCHRENK "Experiments on a sphere the boundary layer of which is sucked away" Z F M 1926, p 366

41 J ACKERET "On the influence of sucking away the boundary layer" Zeitschr d Vereins Deutscher Ingenieure, 1926

DISCUSSION

Mr **BRAMSON** I have been very greatly impressed with what I have heard I have read quite a lot about what has been told us, but until now I have not really understood it

I should be very much obliged if the lecturer would tell us how to get hold of the literature which he mentions

It would be very interesting to know exactly what order of magnitude are the volumes which it is necessary to put into the body in order to determine their ratio, that is to say, to bring about a breakdown when the flows of the higher lift can be obtained

There seem to be a large number of machines in this country which exceed the angles of incidence of the facts of which Mr Baumhauer has told us It seems absurd to put the tanks on the top of the wings instead of on the bottom

At an early part of the lecture he mentioned the effect of turbulence being present before reaching the wing That applies to a very large portion of the air which reaches the wing, and it would be interesting to know whether he has any figures on the basis of the general performance of the wing caused by the propeller slipstream, and whether he regards the ideal machine of the future as being of the pusher type

Dr THURSTON I should like to add my very warm appreciation and admiration of the wonderful lecture Mr von Baumhauer has given us He has provided us with the very latest exposition of the subject of the boundary layer and the methods of dealing with it for the purpose of improved performance of aircraft

The chief problem of aircraft designers is how to get through the air with the minimum of energy, and the study of this problem in the laboratory is undoubtedly of very great help to the practical designer Undoubtedly, by the instruments which we have at present it should be possible to find out the points in a flying machine which are the source of greatest loss, and not only in flying machines, but in steamships and locomotives and motor-cars

During the war while crossing the South Atlantic in a liner I amused myself with some aeronautical apparatus on board, and investigated the air flow round the funnels of the steamer I had previously investigated the air flow round small cylinders in a wind tunnel, and I found a very close analogy between diagrams obtained from the huge funnels on a liner going at the maximum speed, and those obtained in the laboratory In both cases the compression on the front side faded away into a negative pressure or suction at points blending angles of 40 degs on either side of the centre line of the wind The maximum suction was at about an angle of 70 degs , and then the whole of the rest of the boundary surface was in suction The effects of obstructions such as small pipes going up the side of the funnel were very marked, and could be studied quite well by the hot wire anemometer This hot wire anemometer was first used in aeronautical experiments at the East London College, University of London, and not as stated by the lecturer, and I took a set of these instruments out to Brazil a year or two before the war, to find out how the various parts withstood exposure in the tropics

It would appear that if the air flow around every part of an aeroplane in flight was carefully studied, a vast insight into the losses due to each part would be obtained For instance, in most flying machines the air is expelled from the engine not in the direction in which maximum efficiency can be obtained, but in a direction in which the maximum disturbance of the air is set up around the aeroplane How great this loss is, nobody knows, but it should be studied The same remarks apply with regard to the air intake It seems to me a valuable suggestion that the air intake of the engine should be carefully studied, so that it may be taken at the point at which the resistance of an aeroplane would be reduced to a minimum

CAPTAIN SAYERS I should like to express my appreciation of Mr Baumhauer's interesting paper It is very difficult for anybody in England with a limited mathematical knowledge to get a clear idea of recent development in aerodynamic theory The Aeronautical Research Committee has done much work, but its results are published in piecemeal form in odd reports, and when you wish to get a general idea of progress you have to hunt through many many reports and reduce them to some sort of order for yourself

So far as Mr Baumhauer's actual paper is concerned, he has impressed on us the very serious results which quite small irregularities may produce on the air flow over an otherwise well-shaped body We have a fair amount of experience that such things do happen, but I think it is now becoming generally realised that these very small disturbances in the flow can create the most appalling results, and it is extremely useful and interesting that we should have a sound reason for such phenomena, given in a form that we can easily understand

Mr GLAUERT I should like to remark first on the parodoxical results one gets when one thinks of the Handley-Page wing and this new idea of sucking away the boundary layer We can either add energy to the boundary layer to make it flow smoothly, or we can pull it away It seems peculiar that both systems give the same effect

With regard to the boundary layer on a flat plate and on a curved surface such as a wing , it is true that the mathematics of each are the same, but there is this interesting point—that one can make quite a thick wing which will have less drag than a flat plate, and a thin symmetrical wing section gives a drag of something like half that amount There is therefore something more in it than simply the boundary layer It is possibly due to the fact that the pressure distribution is such that if you cut the wing in two the two halves would fly apart If the nose is quite flat you have lost this suction on the nose, and that may be the explanation

Mr RELF I should like to thank the lecturer very much for the very clear exposition he has given us of the various problems with which his paper deals Some of us have read of the work that has been done abroad, but I think that there must be many engineers and others who have not had an opportunity of knowing it It seems of the utmost importance that we should know just what is happening in the layer of fluid near the body From the way Mr von Baumhauer has explained it I am sure it is quite clear to you what happens Although we have not a complete theory we have enough knowledge to avoid the dufficulties there are, and I think that by attention to these principles we should avoid a good many troubles

It seems to be very difficult to get high lift without an enormously increased drag, but I expect we shall be able to overcome that later on Our designers will have to face new problems, because we cannot change the slope of the lift curve much , we can only continue the straight part of the curve by various means of preventing " departure " What we do is to put up the angle at which we can use our wings before the flow completely breaks down I think designers will in future have to face the proposition of making wings moveable in relation to the body, as, otherwise a prohibitively high undercarriage would be necessary if full advantage of the high lift is to be taken in landing

MR VON BAUMHAUER'S REPLY TO THE DISCUSSION

In the first place I wish to thank all the speakers for their very kind remarks and criticisms

Mr Bramson asked about obtaining literature on the subject This can best be procured from Major Low at the Air Ministry

Mr Bramson also asked about the quantity of air necessary for sucking in the boundary layer to the body There have only been a few tests of this, and I think it is better to refer to the work done by Mr Schrenk

Experiments were made on a sphere the resistance of which to the drag is reduced 20 per cent of the original by sucking air into the sphere The energy necessary for sucking in this quantity of air is a fraction of the energy saved by decreasing the resistance There is the same effect with a wing By sucking the boundary layer into the body there is a reduction in drag, the amount of this is such that it is three times as much as the energy necessary for pumping the air into the body

For a wing, the quantity to be sucked in would be ten times the quantity you intend to pump in

Re bottom or top of wing for position of tanks That is very bad, but if the forms are well chosen, and if the tank gives a new aerofoil form with a good slope of the pressure line, I do not think it would be so bad, except that perhaps it will increase the energy of the machine, because it may give rise to stalling, but the departure flow in the middle will occur at a smaller angle than the angle for the rest of the wing The pilot will be warned in the elevator control, and will not stall the machine, also when the flow departs in the middle section only, we shall have the flow as if it were two separate wings coming on the upward point of the pressure, that is, increasing the point of the pressure in the middle, and so preventing the machine from stalling, so that in that one respect it may right the danger, and in another way it may warn the pilot and so increase the safety of the machine

With regard to the pusher type of machine, I rather think this would be better, but have not made sufficient tests to prove it It is not impossible, however, to have a body with a propeller on the back of it It has some difficulty with regard to landing gear, but perhaps on multi-engined machines or light planes it may be possible to put the passengers in a well shaped body, and not disturb it in any way by intake of any kind

Dr Thurston said that a great deal might be done in the laboratory I should like to say that the subject of stalling, the maximum lift of a wing, and such questions as the minimum drag on a body, and all questions of departure, and tests with a full-scale boundary layer, may be done in the laboratory on sections of wings This should be done by a portion of the wing cut away

I was interested in Dr Thurston's remarks regarding his experiments on the funnels of steamships

Captain Sayers is more critical of the National Physical Laboratory than we are, and I would say that in a laboratory where new things are tried you cannot always give a new review on the standpoint of theory or practice, but the N P L sometimes gives interesting reviews of both model and full-scale work

Mr. Glauert remarked on the paradoxical results you get with regard to disturbances by blowing or by sucking. I think you will agree that there is a great difference, but with regard to the Handley-Page wing I will not say that it is flowing air over the surface. You think of the Handley-Page wing cut into pieces, and say it is a solution. Practice and theory have shown that it is necessary to round off, or you get departure at the sharp edge. If you get a flow upwards the boundary layer moves its psoition ; it goes outside the body and we reverse the boundary layer in some respects. It is, as it were, not the same boundary layer, but the old one which is given a new impulse.

The wonderful fact of which Mr. Glauert spoke is something new to me, and I am very interested to hear it.

The CHAIRMAN : Our lecturer has dealt with a very technical subject of a varied nature, and I do not think there is anything more difficult than that. I am not qualified to express an opinion on the technical side of the subject which he has considered, but I can pay him no greater compliment than to tell him that, duffer as I am, I have followed with enormous interest the lecture he has given us to-night. Also I should like to tell him that by giving this lecture he is not speaking to this meeting alone, but to all the engineers in England, and what he has put before us will be studied by them and they will profit by it, and it is for this reason that we are so very grateful to him, not only for ourselves, but for everyone in England who is interested in this subject. I now have very much pleasure in asking you to give Mr. von Baumhauer your cordial thanks for this lecture.

The vote of thanks was passed with acclamation, and Mr. von Baumhauer suitably responded.

Mr. Bramson, in proposing a hearty vote of thanks to the Chairman said that on a recent occasion Colonel Moore-Brabazon had remarked that he always liked to be present at critical meetings of the Institution. The speaker (Mr. Bramson) was glad to think that the President considered this occasion as critical, and he hoped the Institution would be able to arrange many more crises for him.

The vote of thanks was warmly responded to, and the meeting then closed.