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Experiments on Distributed Suction Through a Rough Porous Surface

By

The Cambridge University Aeronautical Laboratory

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Experiments on Distributed Suction Through a Rough Porous Surface

- By -

The Cambridge University Aeronautical Laboratory

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Summary

Flight tests in which suction was applied through a slightly rough porous surface to maintain laminar flow in the boundary layer have shown that when the pressure on the surface was uniform there was an upper limit to the airspeed outside the layer above which no reasonable suction would prevent transition to turbulence. Comparison between these and similar tests on a smoother surface suggest that there will be, associated with every porous surface, two limiting speeds, one above which no reasonable suction will maintain laminar flow and one below which the surface can be regarded as aerodynamically smooth. Consideration is given to the way in which these speeds will vary with the kinematic viscosity of the air, in conditions which lead to dynamical similarity.

1. Introduction

1.1 The report describes a few experiments which have a bearing on the influence of surface roughness when suction is applied through a porous surface to maintain laminar flow in the boundary layer. The apparatus and experimental technique are described in Ref. 1 which deals with a similar though more extensive series of experiments on a very smooth porous surface of calendered nylon fabric which occupied the region between $4\frac{1}{2}$" and 28" from the leading edge of a model aerofoil exposed to the airstream beneath the fuselage of an Anson aircraft. With the pressure on this surface uniform, transition to turbulence occurred in the absence of suction at about 11" from the leading edge of the model but, with suction, laminar flow could be maintained over the entire surface provided that the ratio (v_s/U)* was not less than about 1.5×10^{-4}, a value which was found to be roughly independent of the flight speed and of the height at which the experiment was performed.

1.2 For the experiments described in the present report the nylon was replaced by a sheet of phosphor-bronze gauze of 1/120" mesh which although electroplated and rolled to reduce its porosity and roughness was still appreciably rougher than the nylon. When tests similar to those on the nylon were performed on this gauze it was found, at the lower flight speeds, that the smallest suction ratio which would prevent transition was substantially the same as with the nylon, but at higher speeds it increased progressively until a speed was reached above which no suction available would maintain the laminar flow.

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* v_s is the velocity of the air through the porous surface and U is its velocity outside the boundary layer.

1.3 It is thought probable that this behaviour observed with the gauze surface may be typical of what will happen when suction is applied through any porous surface and that there will be, for any surface tested under given conditions, a speed below which it can be regarded as aerodynamically smooth and a greater speed above which no reasonable suction will maintain laminar flow. Since these two speeds may be expected to depend upon the form and magnitude of the surface irregularities, the fact that they were not observed with the nylon may have been due to its surface being smooth enough for the lower of the two limits to lie above the highest speed at which it was tested. Actually, the critical suction ratio at the highest speed was slightly greater than at the lower speeds, but the increase was scarcely sufficient to be regarded as significant. Before discussing the detailed results obtained with the gauze it will therefore be convenient to consider the arguments upon which the above supposition is based and which throw some light on the way in which, in certain circumstances, these limiting speeds for a given surface may be expected to vary with the kinematic viscosity of the air through which it is moving.

2. Preliminary Discussion

2.1 It can reasonably be assumed that when transition to turbulence is caused by surface irregularities their significance depends, amongst other things, on their size relative to the thickness of the boundary layer, and that when the relative size is increased, a greater stability of the flow will be required to suppress transition. Distributed suction increases the stability of the flow within the boundary layer but also decreases its thickness and this suggests that, in given circumstances, there may be a limit to the absolute size of the irregularities above which no suction will prevent transition, the limit occurring when, as the suction is applied, the relative size becomes too large before the flow has been sufficiently stabilised.

2.2 When the airspeed outside the boundary layer is increased while the suction is adjusted to maintain a given state of stability, the thickness of the layer is reduced and this, in turn, suggests that if there is, at any one speed, a limit to the size of the irregularities above which transition cannot be prevented, there will also be for any one size (i.e. for a given surface) a corresponding limit to the speed above which no suction will maintain laminar flow. Since no porous surface can be entirely free from irregularities, if only at the holes through which the air is sucked, this conclusion, if correct, must be applicable to any porous surface. From a similar argument we may expect, for every porous surface, a speed below which its irregularities have no significant influence on the suction that will prevent transition: in other words, below which it can be regarded as aerodynamically smooth.

2.3 In this report the least value of the ratio v_s/U that will maintain laminar flow is called the "Critical Suction Ratio", symbol $(v_s/U)_{crit}$, and the speed above which no suction will maintain it is called the "Critical Speed", symbol U^*. In certain circumstances the variation of U^* in different atmospheric conditions can be deduced

2.4 If suction is similarly applied to bodies which are similar in all respects, including their surface irregularities, and if the disturbances which cause transition arise solely from these irregularities and compressibility can be neglected, then the form taken by the flow depends only on two parameters, v_s/U and $U\ell/\nu$, where ν is the kinematic viscosity and ℓ is a length which may define either the size of the body or of the irregularities. In such circumstances, $(v_s/U)_{crit.}$ will be a function of $U\ell/\nu$ and, for a particular body, it will be a function of U/ν only and U^*/ν will retain a constant value, the same at all heights.

2.5 In this report, however, $(v_s/U)_{crit.}$ is for convenience expressed as a function of $\nu_0 U/\nu$ where ν_0 is the kinematic viscosity of air at sea-level in the standard atmosphere. This expression is represented by the symbol U_0, which is thus the sea-level speed corresponding to any given value of U/ν; its critical value is represented by U_0^* and is called the "Standard Critical Speed". In the circumstances defined in the previous paragraph, $U^*/U_0^* = \nu/\nu_0$ and the true and indicated critical speeds therefore vary with height in the standard atmosphere in the manner shown in the following table, which also applies to the speed below which the surface can, in this connection, be regarded as aerodynamically smooth. It must however be emphasised that U^* may not vary as shown in the table if transition is appreciably influenced either by compressibilities or by external disturbances such as vibration or noise which, on an aircraft, may not vary with height in the manner required for dynamical similarity.

Height (ft.)	U^*/U_0^*	U^* indicated$/U_0^*$
0	1.00	1.00
20,000	1.67	1.22
40,000	3.22	1.60
50,000	5.20	2.02

2.6 The ideas discussed in the previous paragraphs were suggested initially by a comparison between results obtained with the porous surface of gauze and those described in Chapter 4 of Ref. 1 obtained when a single excrescence was attached on the smoother surface of nylon fabric. When the height of this excrescence was changed in successive experiments in which the speed remained unchanged, there was a height above which no suction would prevent transition and a height, about 2/3 of this value, below which the excrescence had no measurable influence on the suction required to prevent transition. At a height between these values, there was both a lower and an upper limit to the effective suction, the latter due presumably to the relative height becoming sufficient to cause transition, despite the increased stability.

2.7 In the experiments on the gauze, in which the speed was altered while the surface remained unchanged, there was always a speed above which no suction was effective and a lower speed below which $(v_s/U)_{crit.}$ was the same as for the smoother nylon surface. Between these limits, in some of the tests, upper and lower limits were observed to the effective suction, as in the tests on the single excrescence.

3. Detailed Discussion of Experiments on the Gauze

3.1 The observations obtained with the porous surface of metal gauze are shown in Figs. 1 and 2, those at the lower heights in very difficult conditions in which the air was so unsteady that no great accuracy could be expected. Since the tests were all made with the model at one particular incidence, namely that which gave uniform pressure, it may be assumed that had transition been caused solely by the surface irregularities, the points in Figs. 1 and 2 would all have fallen, within experimental error, on a single curve and that the standard critical speed (U_o^*) would have been the same on all occasions. A glance at the figures will show, however, that in fact U_o^* varied widely from one experiment to another, the variation appearing to depend mainly on the height at which the experiment was performed. It will be noticed, however, that those points for which the speed was below its critical value for the particular experiment do lie roughly along a single curve, and since no points lie significantly below this curve, it may perhaps be inferred that it represents approximately the variation of $(v_s/U)_{crit.}$ when the disturbances which caused transition arose solely from the surface irregularities. Its value as shown on this curve at the lowest speeds agrees, within experimental error, with those found for the much smoother nylon surface.

3.2 The results taken as a whole suggest that when this lower limit is exceeded and $(v_s/U)_{crit.}$ begins to rise with increase of speed, transition may become sensitive to external disturbances such as vibration or noise which are always present on an aircraft in flight. If this is in fact the explanation of the observed variations of the standard critical speed, it suggests that if distributed suction is to be used reliably in service, it may be necessary to make the surface so smooth that there is no significant increase of $(v_s/U)_{crit.}$ up to the maximum contemplated cruising speed.

3.3 From the few experiments performed on the gauze it has not been possible to ascertain the nature of the external disturbances which may have caused the low critical speeds at the greater heights. At first it was thought that they would be found to depend on the engine revs. which, in level flights with U_o constant, were not the same at different heights. In the final tests recorded in Fig. 2, observations were therefore taken, not only in level flight, but when descending throttled back and when climbing with full throttle. These, as can be seen in the figure, showed some variation of U_o^* with revs.: but not nearly enough to account for the much greater variation with height.

3.4 Another factor which might conceivably have influenced U_o^* is the change of temperature with height, which might have distorted the model. But this seems to be ruled out by the fact that one experiment at 7,200' and 0°C. gave a value that did not differ significantly from that obtained in another experiment at 11,000' and -24°C., whereas in a third experiment at 2,500' and -5°C., a much greater value of U_o^* was recorded.

/3.5

3.5 The alternative scale of abscissae on the figures, showing the Reynolds number (R_E) based on the spacing of the holes in the gauze, has been added because it is thought that when different gauzes of given type of weave are tested under similar conditions, the variation of $(v_s/U)_{crit.}$ with a Reynolds number based either on the spacing of the holes or the diameter of the wires, might conveniently be regarded as defining the effectiveness of the treatment to which the gauze has been subjected.

4. Notes on the Individual Tests

The following notes relate mainly to observations which could not conveniently be recorded in Figs. 1 and 2, but which have helped to decide the forms given to the curves drawn through the recorded points.

4.1 In the first test on 16/10/50 at 7,200', no suction would prevent transition when U_0 was 112 m.p.h. or greater. The three lower points in Fig.1 show the least suction ratios that would maintain laminar flow at speeds lower than the critical and the upper point at U_0 = 110 m.p.h. shows the suction ratio above which the flow was turbulent. Similar upper limits to the suction ratio were found at the two lower speeds from very rough observations made with a larger flowmeter; they showed upper limits to $(v_s/U) \times 10^4$ of the order of 20, and it is for this reason that the upper part of the curve has been drawn nearly vertical. Similar tests on the same day at 1,800' gave the points shown as circles in Fig. 1 and here, although the critical speed was not actually reached, the distribution of the points suggests that it would have occurred at a value of U_0 only slightly above 180 m.p.h.

4.2 In the next experiment on 13/3/51, conditions were deteriorating so rapidly that only four observations were obtained at 4,000'. These, shown as square points in Fig. 1, agree well with those previously obtained at 1,800'.

4.3 Fig. 2 shows results obtained in two flights on 30/3/51. The three points obtained in level flight at 11,000' and shown as crosses, agree fairly well with those in Fig. 1 obtained at 7,200' and, although no upper limit to the effective suction was observed, the standard critical speed was very precisely determined at 116 m.p.h. When this test was repeated at about the same heights with the engine throttled back and the aircraft descending, the standard critical speed was a little greater than in level flight, say 122 m.p.h., for there was at 121 m.p.h. a very definite upper limit to the effective suction and no suction would prevent transition at 130 m.p.h. or above. The single point shown as a star gives the least suction that maintained laminar flow when climbing at full throttle at the same height.

4.4 A similar test performed under very difficult conditions on the same day, at 2,500' gave the points shown as circles in Fig. 2. Here, with U_0 = 167 m.p.h., no suction would prevent transition and it was just possible to maintain laminar flow intermittently at 155 m.p.h., with $(v_s/U) \times 10^4$ round about 3.5. The standard critical speed at low heights was thus appreciably less than in the earlier tests and this, together with the rather high values of the critical suction observed when U_0 was 116 and 129 m.p.h., suggests that the porous surface may have deteriorated. The lower curve in Fig. 2 has been added merely to facilitate comparison with Fig. 1.

4.5 In the above discussion the marked difference of behaviour with the gauze and nylon coverings respectively has been attributed to greater roughness of the gauze. This is probably right, but there is the possibility that it may have been due to some undetected defect of the surface, as for example, at the junction between the gauze and the solid nose of the model. The conclusions reached must, therefore, be accepted with reserve until they have been checked by more comprehensive experiments on surfaces of different roughness. In particular it remains for future research to discover whether systematic variation of the standard critical speed with height, observed in these experiments, was due to some unexplained fundamental cause or merely to the manner in which the external disturbances happened to vary with height on the particular aircraft on which the experiments were performed

5. Conclusions

If it is assumed that the behaviour on the gauze, as compared with that on the nylon, was due to its greater roughness, the following tentative conclusions can be drawn:-

5.1 When distributed suction is applied to a body through a porous surface, there will be, in any given circumstances, a lower limit to the flight speed below which the surface can be regarded as aerodynamically smooth and an upper limit beyond which no suction will prevent transition even in the absence of external disturbances.

5.2 Between these limits, transition is likely to be sensitive to external disturbances of a kind which will always be present on an aircraft in flight and which may vary in an unpredictable manner in different circumstances.

5.3 It may be, therefore, that if complete reliance is to be placed on obtaining laminar flow by distributed suction, the porous surfaces will have to be so smooth that the lower of these two limits is not greatly exceeded.

5.4 If the influence of compressibility on transition is found to be negligible and if the disturbances which initiate transition arise solely from the surface irregularities of a given body at given incidence, then these limiting speeds may be expected to vary in proportion to the kinematic viscosity of the air in which the aircraft operates.

Reference

No.	Author	Title, etc.
1	M. R. Head	The Boundary Layer with Distributed Suction. R. & M. 2783. April, 1951.

FIG. 1

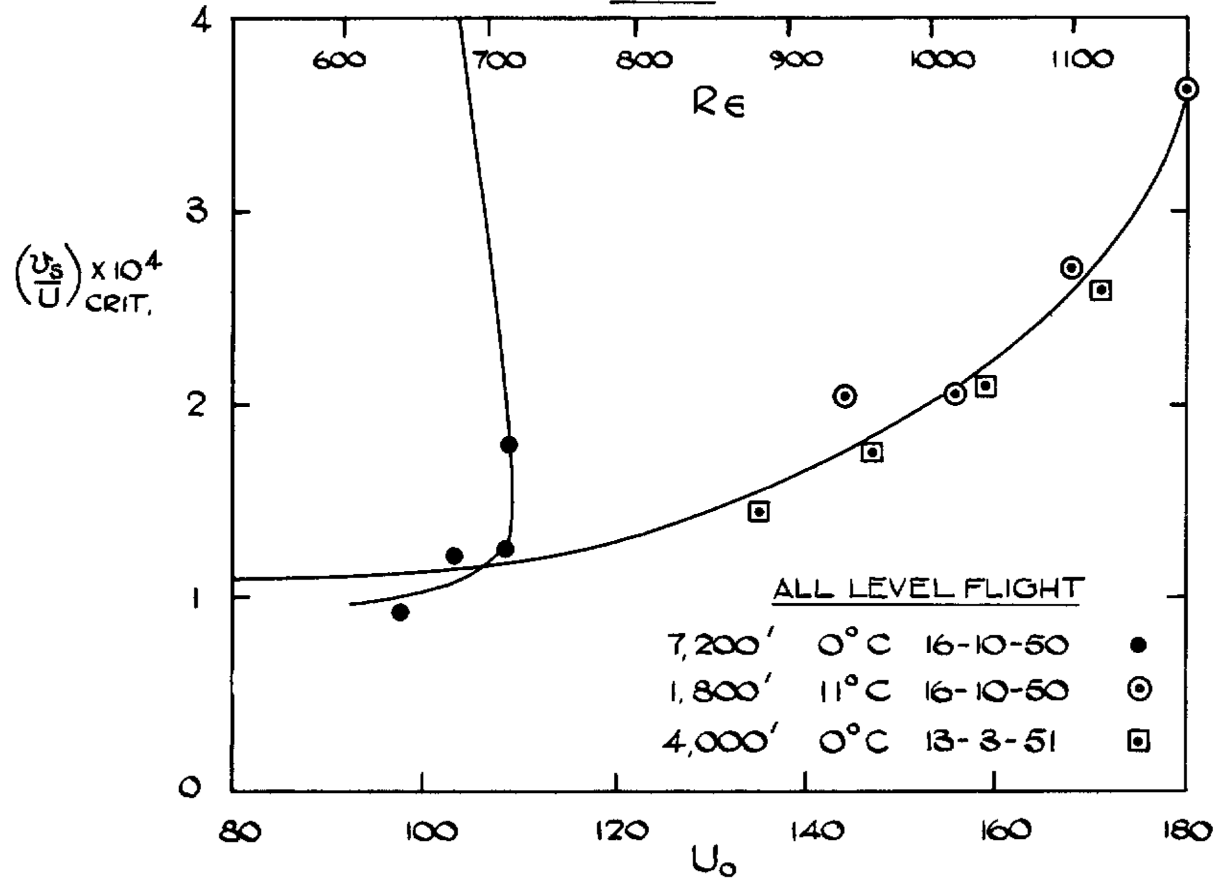
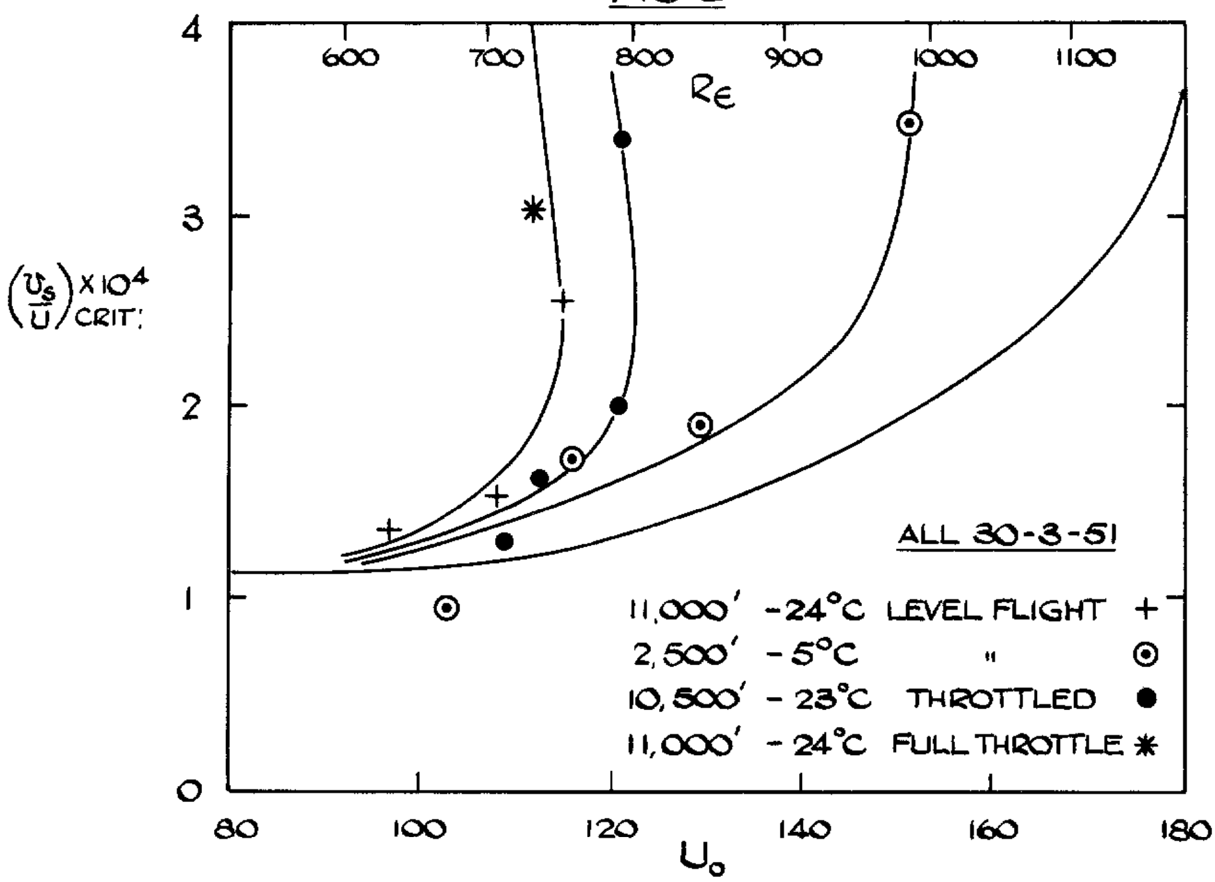


FIG 2



U = AIR SPEED OUTSIDE THE BOUNDARY LAYER

v_s = AIR SPEED THROUGH THE POROUS SURFACE

ϵ = HOLE SPACING OF THE GAUZE

ν_o = KINEMATIC VISCOSITY OF THE STANDARD ATMOSPHERE AT SEA LEVEL

$U_o \equiv \left(\frac{U}{\nu}\right)\nu_o$ (mph) $\qquad R_\epsilon \equiv \frac{U\epsilon}{\nu}$

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