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AERONAUTICAL RESEARCH LABORATORIES

AERODYNAMICS NOTE 110

THE USE OF AIR JETS
FOR BOUNDARY LAYER CONTROL

BY R. A. WALLIS

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AERONAUTICAL RESEARCH LABORATORIES

Aero. Note 110

THE USE OF AIR JETS FOR BOUNDARY LAYER CONTROL

by

R.A. Wallis

SUMMARY

A new method of controlling the boundary layer in regions of severe adverse pressure gradients is proposed. Preliminary experiments with small air jets, suitably located, have shown that

(a) *laminar separation at the leading edge of thin aerofoils can be eliminated, even at small Reynolds numbers, and*

(b) *turbulent separation can be delayed.*

The method appears to offer considerable improvements in the stalling characteristics of thin swept wings; the principles are equally applicable, however, to any region of adverse pressure gradient.

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CONTENTS

NOTATION

C_p Pressure coefficient $\left(1 - (\frac{U}{U_o})^2\right)$

C_Q Flow coefficient $\left(\frac{Q}{U_o c}\right)$

U Local velocity outside boundary layer

U_o Velocity at infinity

Q Quantity flow/ft. span

c Aerofoil chord

1. <u>INTRODUCTION</u>

As the result of a recommendation by the Common-
wealth Advisory Aeronautical Research Council, which met in
Canada in September 1950, attention in these Laboratories has
been focussed on the problem of improving the high lift
characteristics of thin swept wings.

2. <u>STALLING CHARACTERISTICS OF THIN WINGS</u>

One of the problems of high speed flight is the
achievement of relatively low drag at high Mach number.
When a shock wave of sufficient strength is formed, flow
separation occurs immediately downstream of the shock.
Resulting changes in pressure distribution, and the adverse
effect of the wake on the control surfaces, seriously impair
the longitudinal and lateral stability of the aircraft.
The onset of flow separation can be delayed to higher Mach
numbers by the use of a thin symmetrical wing, with or with-
out sweepback, having the point of maximum thickness between
0.4 and 0.5 of the chord (ref.1).

Unfortunately, this type of wing has poor stalling
characteristics.   At moderate lift coefficients, a large
suction peak is present at the leading edge where the radius
of curvature is small.   The flow is usually laminar at this
point of minimum pressure, and hence laminar separation will
occur shortly after the flow moves into the region of increas-
ing pressure.   Provided the adverse pressure gradient is not
too great, transition occurs in the separated laminar layer
and the layer rejoins the surface as a turbulent one a small
distance downstream.   Very thin aerofoils possess a similar
stall to that associated with a flat plate.   The turbulent
layer at a certain incidence fails to re-attach immediately
but rejoins the surface some distance from the leading edge.
The region of separated flow increases with incidence until
it extends over the whole upper surface.   Aerofoils possess-
ing thickness/chord ratios of 7% or less are usually affected
in this manner.   This figure is only approximate, as Rey-
nolds number and aerofoil design will have a large bearing
on the precise value.   On aerofoils with thickness/chord
ratios in excess of those just mentioned, the nose stall is
experienced at a lift coefficient greater than the flat plate
maximum, namely C_L = 0.8 to 0.9.   When this occurs, the
flow separates over the whole upper surface of the aerofoil.

The above considerations apply to the two-dimensional aerofoil. When the wing possesses sweepback, another un-desirable feature develops. Owing to strong spanwise press-ure gradients, the slow moving boundary layer air is swept towards the wing tips; any laminar separation will only result in an even greater migration. This boundary layer growth at the wing tips induces an early tip stall which impairs the stability of the aircraft and may lead to an un-stable stall (ref.2). The tip stall also reduces the maxi-mum lift and the lift curve slope. This latter characteristic means that the maximum lift is reached at higher angles of attack.

Thus it can be seen that an important factor in improving the stalling characteristics of thin swept wings is the prevention of laminar separation.

3.   EXISTING METHODS OF LEADING EDGE
     BOUNDARY LAYER CONTROL

Before embarking on new experimental work, a review of leading edge high lift devices was made (ref.3). This work emphasised the fact that there are a number of ways in which substantial maximum lift increments can be obtained by the use of known devices. Some of these devices are still in the laboratory stage and require considerable development before being used in practice. This is particularly true of continuous boundary layer suction as the porous material used is very susceptible to contamination by dust, ice or water. The removal of the boundary layer through a nose slot on a thin aerofoil would introduce structural problems and in opera-tion would probably require appreciable powers (ref.3). This is due to the low pressures prevailing at the nose, and unless considerable pressure recoveries are made in the slot, very low suction box pressures will be necessary. The surface dis-continuity due to the slot may be an undesirable feature at high speed; to avoid drag increases, suction would need to be applied continuously.

Reference 3 suggested that leading edge flaps appeared to be the most promising of the boundary layer con-trol devices, being effective on either straight or swept wings. It would appear that the main function of a flap is to modify the pressure distribution in the vicinity of the leading edge. Flaps, however, have definite disadvantages

for high speed flight.   Even when the flaps are accurately
manufactured, some surface discontinuity in the retracted
state is certain to be present.   This at high speed will
almost inevitably lead to transition and a subsequent drag
increase.   Finally, it is suspected that this device can
never be used in high speed manoeuvres, and because of this
its high lift applications are limited.

4.   USE OF AIR JETS AS METHOD OF BOUNDARY LAYER CONTROL

4.1 General Principles

In the light of the above facts, an endeavour was
made to develop a new method of delaying or preventing the
onset of separation.   It is well known that a turbulent
boundary layer is far more capable of overcoming an adverse
pressure gradient than a laminar layer.   In the former case,
momentum is transferred rapidly from the free stream to the
slower moving particles near the surface by eddy motion,
whilst transfer in a laminar layer is on a molecular scale.
With this in mind, we set out (a) to prevent laminar separation
by making the flow turbulent, and (b) to delay turbulent
separation by increasing the rate of momentum transfer.

Since it is known that the maximum lift of thin aero-
foils increases with Reynolds number (ref.3), it seems logical
to suppose that this is due to the greater tendency of the
boundary layer to become turbulent near the leading edge.
This fact would indicate that if a turbulent boundary layer
could be produced before the flow turned round the leading
edge from the stagnation point, laminar separation would be
prevented and the maximum lift be increased.

By providing spanwise rows of small holes suitably
located and blowing air jets through the boundary layer, both
main objectives have been achieved.   Although this use of air
jets to produce a turbulent layer is not new, it has not, to
the author's knowledge, been used as an effective means of
preventing laminar and/or turbulent separation.   It is known
that blowing through a porous surface will decisively reduce
the inherent stability of the laminar layer (refs.4 and 5).
In the region of the stagnation point and the leading edge,
however, it is doubtful whether porous blowing will produce

a turbulent layer.   By using jets to inject very small
quantities of air, Fage was able to produce transition down-
stream of the leading edge in shock wave-boundary layer inter-
action experiments (ref.6).

When jets are used for the control of separation,
the outflow velocities have to be large enough to create tur-
bulence on the jet boundaries.   As a product of the jet shear
flow, boundary layer air is induced to flow outwards from the
surface, and this results in an inward flow midway between the
holes.   In other words, a secondary flow of scale $P/2$ is cre-
ated, where P is the pitch of the holes.   This has been
observed in smoke experiments (ref.6); tuft studies have, in
our case, verified the existence of a strong superimposed
vortex flow.   Hence it is apparent that discreet blowing holes
not only produce turbulence, but also provide a means of trans-
porting turbulence and momentum into the boundary layer.   It
is believed that this method of producing a turbulent layer is
fundamentally different to the action of porous blowing.   In
the latter case, transition is probably caused by the thicken-
ing of the boundary layer and a reduction in the stability
limit at which small disturbances become amplified.

4.2 Preliminary Experimental Work

Experiments have shown that air jets, suitably
located, eliminate laminar separation at the leading edge of
thin aerofoils, even at small Reynolds numbers.   However, the
mechanism by which the air jets induce the laminar boundary
layer to become turbulent has not yet been investigated.
Nevertheless, it is believed that the secondary flow carries
the turbulence created by the jets into the boundary layer.

In this preliminary work, it has been assumed that
the nose stall is mainly dependent on the severe local adverse
pressure gradients downstream of the leading edge.   On thin
aerofoils in particular, the minimum local pressure coeffi-
cient, $C_{p_{min}}$, can be taken as a measure of the pressure

recovery which has to be effected without separation.   In our
investigations interest has been centered on the following
two aspects:-

(1)   The elimination of laminar separation;

. (2)   A good measure of turbulent boundary
         layer control as indicated by the
         minimum pressure peak reached just
         prior to separation.

The first experiments were carried out in the
36" × 20" low speed wind tunnel.   Owing to the desirability
of testing a model of moderately large dimensions, a nose
flap of 15% chord was used, the basic section being a 6%
thick, 10 ft. chord ellipse.   The nose flap was hinged to a
two-dimensional fairing with a tail flap.   Most of the experi-
mental work on this model was carried out with holes (0.028"
dia.) drilled at a pitch of 1/4" along the span at a surface
dimension of 1" from the leading edge.   This arrangement is
near, but does not necessarily constitute, the optimum.   Un-
less otherwise stated, it can be assumed that all flow condi-
tions were investigated qualitatively with a hot wire.   Most
of the experiments were carried out at a tunnel speed of
60 f.p.s.

Without blowing, laminar separation was present, and
the minimum C_p reached near the leading edge prior to the nose
stall was -7.4.   By injecting a small amount of air, the
boundary layer became turbulent on the lower surface approxi-
mately 0.6" along the surface from the leading edge.   Laminar
separation was thus avoided and before nose separation occurred,
a minimum C_p of -20 had been attained.   The pressure then
increased to C_p = -3 in the first 3.5% of chord, which
represents a remarkable recovery rate;   the local pressure
distribution for this condition corresponded to the theoretical
distribution for a lift coefficient of 0.85.   Very little
scale effect was noted within the limited speed range of the
experiments (max. speed 80 f.p.s.).   The volume flow through
the jets to achieve these results was not measured directly,
but a conservative estimate would suggest that the flow
coefficient, C_Q , was not more than 0.00004.

In order to obtain a quick confirmation of the above promising results on a full chord aerofoil, a 3 ft. chord NACA 64A006 aerofoil of 2 ft. span was fitted to an existing endplate arrangement and mounted on the balance in the 9' × 7' wind tunnel. Supplementary tests on the same aerofoil were carried out in the 36" × 20" wind tunnel, the aerofoil span being 20". The detailed experimental results will be published at an early date.

Laminar separation was eliminated from this aerofoil. Although an appreciable amount of boundary layer control was achieved as a result, the minimum pressure could not be reduced below a C_p of -12 before the nose stalled. This compares with values of from -3 to -6.5 without blowing for the Reynolds number range covered (0.75×10^6 to 3.75×10^6). Very little scale effect was noted for the case of blowing. One row of air jets (0.028" dia. holes) situated approximately 3/8" along the surface from the leading edge and at a pitch of 1/8" sufficed for the 36"× 20" tunnel experiments. However, an additional row, 1/8" closer to the leading edge, was required to prevent laminar separation in the 9' × 7' tunnel tests.

The nose stall, with blowing, was due to a turbulent separation having its origin in the region of the 10% chord position; this separation moved forward very rapidly with increasing incidence. Onset of complete separation over the upper surface then followed a similar pattern to that described previously.

Before analysing these results further, the action of air jets on the turbulent boundary layer will be discussed. As mentioned previously, the air jets produce a secondary flow which transports momentum from the free stream into the boundary layer. A close interaction between this induced flow and a turbulent layer can be expected, as the turbulent boundary layer transports momentum in a similar fashion. This should result in an intense momentum transfer.

Qualitative tests were carried out to check the above theory. For these experiments, a rear stalling aerofoil was chosen in order to ensure that turbulent separation was the only factor involved. An existing model of an NACA 2214 aerofoil with a 17" chord was found to meet the above requirement. Tests on this model in the 36" × 20" wind tunnel with 1/16" dia. holes at 3/4" pitch drilled on the

suction surface at the 50% chord position demonstrated the
efficacy of air jets in delaying turbulent separation.   With
a moderate amount of air, trailing edge separation was delayed
to an appreciably higher incidence, the stall being reached
when turbulent separation moved rapidly from the trailing
edge to the nose.   Unstalling could only be achieved by sub-
stantially reducing the incidence.   To ensure that the stall
was a turbulent one, in subsequent tests laminar separation
was eliminated with small jets situated between the front
stagnation point and the leading edge.   No substantial change
in the stall was noted.

Owing to these promising results, it was decided to
apply this knowledge to the nose of the 64A006 aerofoil in
order to control the turbulent separation encountered.   The
most effective arrangement tried consisted of two rows of holes
(0.028" dia.) at 1/4" pitch situated 1/4" and 3/8" along the
upper surface from the leading edge, in addition to the row of
lower surface holes.   With the optimum amount of blowing, a
C_p of -17.5 was achieved at 40 f.p.s.;   at the higher speed of
of 80 f.p.s. the pressure coefficient was -15.5 and still fall-
ing with increasing box pressure.   The maximum mean jet velo-
cities were of the order of 350 - 400 ft/sec.   As before, the
nose stall, which occurred at a higher incidence, resulted from
a turbulent separation moving forward from the 10% chord posi-
tion.   However, the difference between the nose stall incid-
ence and the complete stall had been reduced owing to the
extension of unseparated flow conditions.   These tests were
carried out in the 36" × 20" wind tunnel.

Experiments have shown that laminar separation can
be eliminated, thereby delaying the nose stall which is then
influenced by turbulent separation moving from a region just
downstream of the leading edge.   As a result of this control,
one would expect appreciable improvements in the stalling
characteristics of thin wings.   From the balance readings in
the 9' × 7' wind tunnel the following points of interest were
noted:-

(a)   Maximum lift increased by 10% ;

(b)   Maximum usable lift coefficient increased
      by approx. 0.2 ;

(c) Drag greatly reduced at high incidence;

(d) Pitching moment virtually constant
until nose stalled.

These results were obtained with two rows of air
jets on the lower surface, the flow coefficient, C_Q, being
0.00043 at a chord Reynolds number of 3.8×10^6. The flow
coefficient is higher than the value used in the nose flap
experiments; this is due to difficulties in implementing the
device on a smaller chord aerofoil and the use of a jet flow
in excess of the minimum requirement.

Much remains to be done in exploring the potentiali-
ties of the device, particularly on thin swept wings. Here
one may expect outstanding improvements when laminar separation
is eliminated; encouragement in this respect is obtained from
the large scale effect which has been found on thin swept wings.

Discussion so far has centered on the low speed
landing case. High lift, however, is also required for high
speed manoeuvres. It can be assumed tentatively that at high
speed the turbulent boundary layer produced by air jets will
be far more effective in resisting separation than a laminar
layer or the normal turbulent one. Actual flight tests may be
necessary to confirm or disprove the above assumption.

4.3 Maximum Lift Considerations

The foregoing experimental work has been centered on
wings of 6% thickness. On such aerofoils large increments in
maximum lift cannot be expected by this blowing technique alone.
To illustrate this point, the local minimum pressure coeffi-
cients near the leading edge of the 64A006 are -22 and -32 for
lift coefficients of 1.0 and 1.2 respectively; unless means of
dealing with the subsequent pressure rises are found, the lift
of this type of unflapped aerofoil will be severely limited.
If, however, we consider that the usable lift is limited by the
point at which nose separation occurs on a two-dimensional wing,
or the tips stall on a swept wing, then the use of the above
form of boundary layer control will give an appreciable in-
crease. An attempt has been made to estimate the probable
maximum lift increments on aerofoils with a thickness greater
than 6%. Assuming, as before, that the severe local pressure
gradients at the leading edge are the governing factors in nose

stall and that the minimum pressure near the leading edge is
a measure of the gradient, $C_{p_{min.}}$ has been presented as a
simple function of C_L in Fig.1. The data are taken from the
systematic tests reported in references 7 to 9 and illustrate
very clearly the two types of nose stall. By extending these
curves, it will be seen that considerable maximum lift incre-
ments are possible on the NACA 63009 and 64A010 when it is
assumed that C_p values of -20 are obtainable with this device.

It is conceivable that the complete stall will be a more
gradual one with turbulent separation from the rear being the
basic cause. Hence the application of the principle to the
thicker aerofoils also appears warranted.

Whilst the above gains appear attractive, the
desired increase in lift may not, in all cases, be obtainable
with air jets alone. Therefore it may be necessary to use
this method of control in combination with other high lift
devices. Since, however, the flow is controlled in the region
which normally presents great difficulties, other known devices
such as suction slots and trailing edge flaps will be more
effective due to the absence of separated flow. The flow
over the ailerons will also be improved, thus giving greater
lateral control on the thin swept wing in the high lift condi-
tion.

4.4 Laminar Flow Considerations

With increasing aircraft speeds, the maintenance
of laminar flow on the upper surface of thin swept wings is
becoming difficult. For instance, the lift coefficient
beyond which adverse gradients appear on the NACA 64A006 is
only 0.02; this is less than the usual flight values. Hence
in flight, adverse gradients may occur over most of the upper
surface, thus making laminar flow impossible. On the lower
surface, however, care must be taken to preserve the laminar
flow as long as possible.

It is obvious that at high speed, i.e. low incidence,
the holes may influence flow conditions over the lower surface
as the stagnation point is ahead of the holes. Any small
outflow will probably produce early transition, and hence
safeguards should be taken to ensure this does not occur. As
the holes are in a region of high pressure, the pressure box could

be vented to a region of low pressure* when the device is not required, in order to counter small leaks which may develop in the shut-off valves from the compressor. Another possible effect of small outflows is discussed in section 5.

The size of hole visualised is too small to constitute a surface irregularity likely to cause transition in this very stable flow region. If this assumption proved to be wrong, a small amount of suction as suggested above would stabilise the flow. Hence it appears that this device, when inoperative, does not adversely affect the laminar boundary layer and in this respect differs from most of the other leading edge high lift devices known.

4.5 Installation and Power Considerations

One main application of this device is to high speed aircraft. Such aircraft will normally be powered with either a jet or gas turbine engine, and hence the engine compressor is the natural choice for an air supply. A preliminary investigation on its suitability disclosed that the bleed quantities only amount to a few per cent even under idling conditions. The box pressures, which at the moment appear to be of the order of 0.5 to 1.0 lb/in. relative to atmospheric pressure, may be difficult to obtain when idling, although sufficient pressure will probably be available for normal engine speeds at landing. Alternative power supplies would be an auxiliary compressor, or an ejector system powered by either high pressure air or a liquid fuel rocket. Studies on the latter system have been carried out at N.P.L. by Williams (ref.10).

Owing to the intermittent use of the device, it is envisaged that operation will be on a fully automatic basis. A suitable controlling instrument for landing and take-off would be the A.S.I. When the more general application of high speed manoeuvres is considered, either an incidence meter or a ratio meter to measure C_p would be required. Actuation of a switch would then provide power to open or close the necessary valves; quick acting valves would ensure a rapid application or removal.

* Reference 6 suggests a similar scheme for the whole aircraft wing as a means of minimising the effect of inadvertent leaks.

Insufficient data are available to make an accurate estimate of the power requirements. From the assumptions that $C_Q = 0.00004$, $U_o = 150$ ft/sec., $c = 8$ ft, and the box pressure relative to surface static = 1 lb/in., the air power per foot span lost across the aerofoil skin is approximately

$$\text{Power/ft. span} = p\ C_Q\ U_o\ c/_{550}$$

$$= 0.013\ \text{H.P.}$$

Even when liberal allowances are made for losses in the tube from the compressor, the power required is likely to be low and of no importance. This calculation applies, of course, only to the case of one row of holes on the lower surface as used on the nose flap model. If blowing were applied to the upper surface, power considerations would be of greater importance.

Fundamentally, this form of boundary layer control differs from most other methods. The air jets can be considered as activators which accelerate the transfer of momentum. This in fact corresponds to an increase in the skin friction drag, which means that the engine power has been used in a simple, indirect way to provide a measure of boundary layer control. Alternatively, use has been made of the known advantages of a turbulent boundary layer, and an attempt has been made to increase its effectiveness.

With increasing Reynolds number it is expected that the flow coefficient, C_Q, will decrease sharply owing to the greater ease with which turbulence can be produced. The above considerations promote optimism concerning the power requirements likely to be encountered in flight.

5.   OTHER APPLICATIONS

Air jets have been considered as a means of boundary layer control on thin swept wings. It is obvious, however, that the principles involved are applicable to many other fluid flow problems. For instance, the air inlets and ducting of jet engines may benefit appreciably from either the prevention of laminar separation or the control of the turbulent layer. In fact, the above principles warrant investigation, wherever rapid diffusions occur e.g. in wide angle diffusers.

As a wind tunnel tool, the blow principle offers a means of eliminating large scale effects; this may increase the usefulness of low speed wind tunnels in testing high speed aircraft. The high speed tunnel application has been mentioned before (ref.6).

Finally, it has been noticed that blowing with air jets can spoil the flow over the leading edge. Although this does not appear to present a hazard, it is worth mentioning as it could form a very effective form of air brake at high speed where flutter and compressibility effects are dangerous. This spoiling effect was noted on the nose flap model when a minute outflow was permitted. The reason for this behaviour is not at all clear, but it appears to be related to the stability of the stagnation point as this moved from the surface into the free stream. This phenomenon was absent during all the tests on the 64A006, and hence cannot be considered as a normal feature of this device. However, owing to the speed with which a brake of this type could be applied, the original phenomenon may warrant investigation as speed of operation is essential where flutter and compressibility troubles call for a sudden reduction in aircraft speed. If this were a practical proposition, it might mean a separate system with a different arrangement of holes from those used at high lift.

6.   EXPERIMENTAL WORK IN HAND

In addition to the work which has previously been outlined, plans are well advanced for flight testing the device on a Vampire fighter. Another flight project is an application to a high speed target aircraft now in production, where increased maximum lift is very desirable. A model of this aircraft will soon be tested in the wind tunnel.

Wind tunnel experiments have either begun or are projected in the near future on (a) a swept wing (North American Sabre aircraft); (b) high speed tests on a small chord model; (c) use of jets to delay trailing edge separation on an NACA 23012 aerofoil; and (d) fundamental studies.

7.   CONCLUSIONS

In conclusion, it may be said that the use of air jets to control flow separation appears very promising.

Experimental work has shown clearly that worthwhile increases
in either usable lift or maximum lift appear possible.
Because of its simplicity, the method could readily be applied
to aircraft already in production or in the process of design.

It is realised that a great deal of work is still
necessary before the limitations of the above device can be
ascertained.

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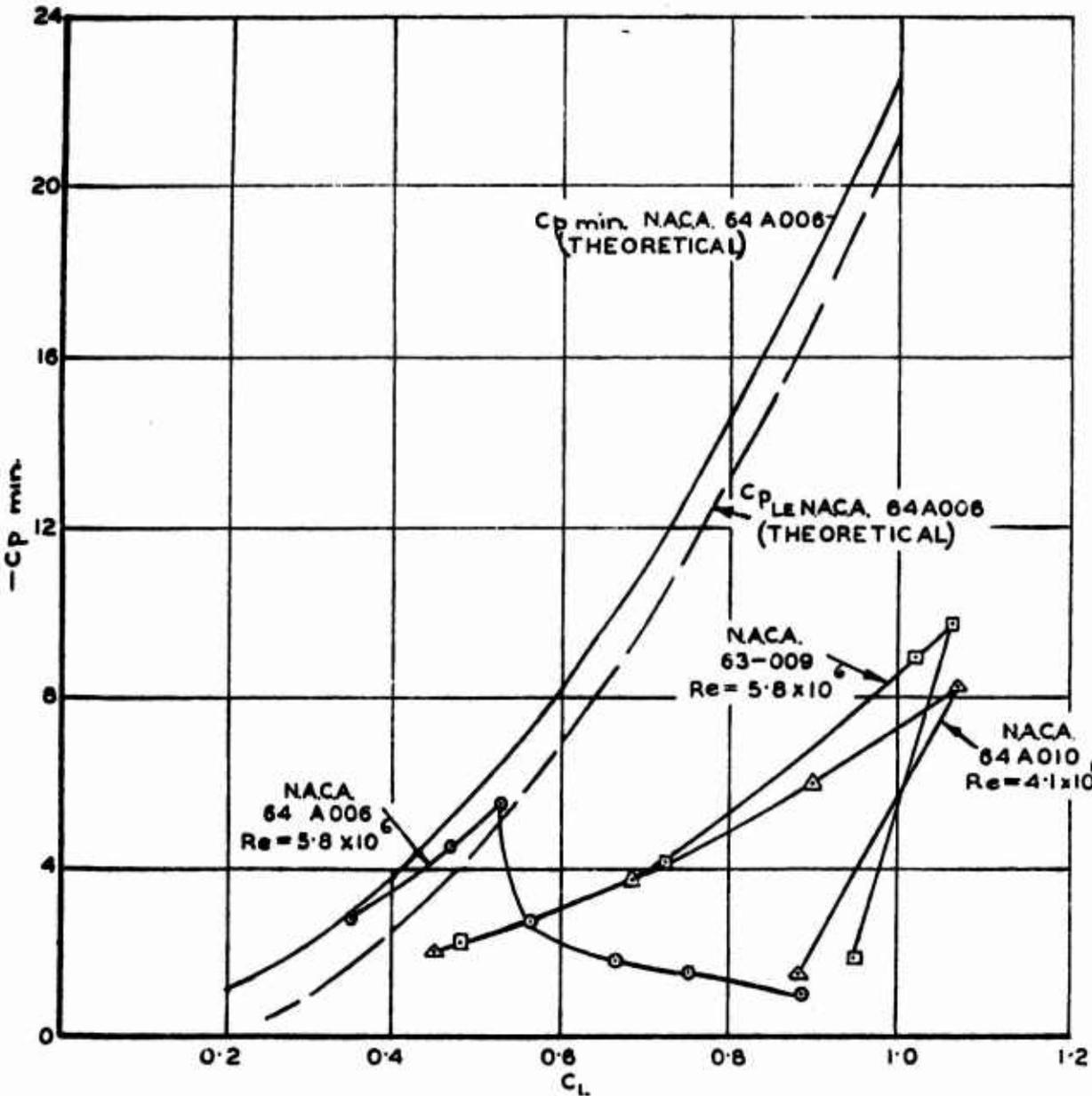6. Fage and Sargent   The Air-Injection Method of
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Cp min. N.A.C.A. 64 A006
(THEORETICAL)

Cp_{Le} N.A.C.A. 64A006
(THEORETICAL)

N.A.C.A.
63-009
Re = 5.8 x 10⁶

N.A.C.A.
64 A010
Re = 4.1 x 10⁶

N.A.C.A.
64 A006
Re = 5.8 x 10⁶

C_L

$-C_P$ min.

MINIMUM SURFACE PRESSURE VERSUS LIFT COEFFICIENT

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AERONAUTICAL RESEARCH LABORATORIES

ADDENDUM TO AERO. NOTE 110

"THE USE OF AIR JETS FOR
BOUNDARY LAYER CONTROL"

by

R.A. Wallis

It has been suggested that we might enlarge
on one or two of the points mentioned in Aero. Note 110.
As the application of air jets to the problem of producing
transition in the region of the stagnation point is new, a
brief discussion of the flow stability based on experi-
mental data and observations might prove useful.

In a favourable gradient on a smooth surface,
there are three ways in which transition may occur.

(i)   Two-dimensional instability (Tollmien-Schlichting)

(ii)   Dynamic instability due to inflexion point
        velocity profiles (Rayleigh)

(iii)   Three-dimensional instability on curved
        surfaces (Görtler-Taylor)

Calculations show that in the region of the
jets, the critical $R_{\delta *}$ above which small two-dimensional
disturbances become amplified is approximately 12,000.
Hence the first type of instability can be ruled out as
the Reynolds number based on the displacement thickness
of the boundary layer, $R_{\delta *}$, at the jets is of the order
of 70 for a chord Reynolds number of 4×10^6.

The second type of instability could very easily
have a bearing on the question of transition as the jet
flow will almost certainly produce inflexion point profiles
close to the jets. Due to the marked convexity of the
surface it is not expected that the Görtler-Taylor type will
have any effect other than to possibly damp out some of the
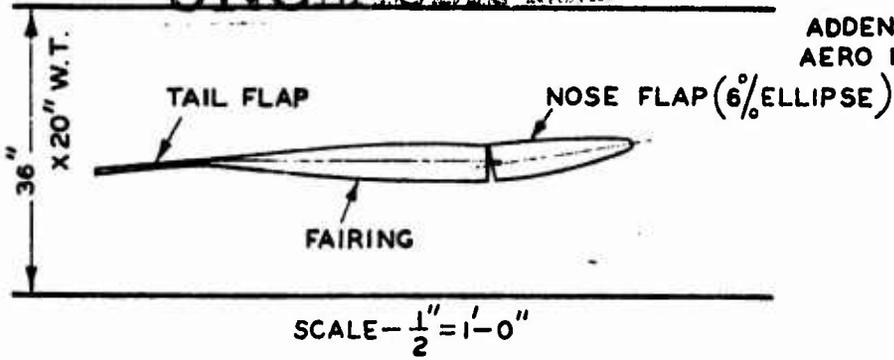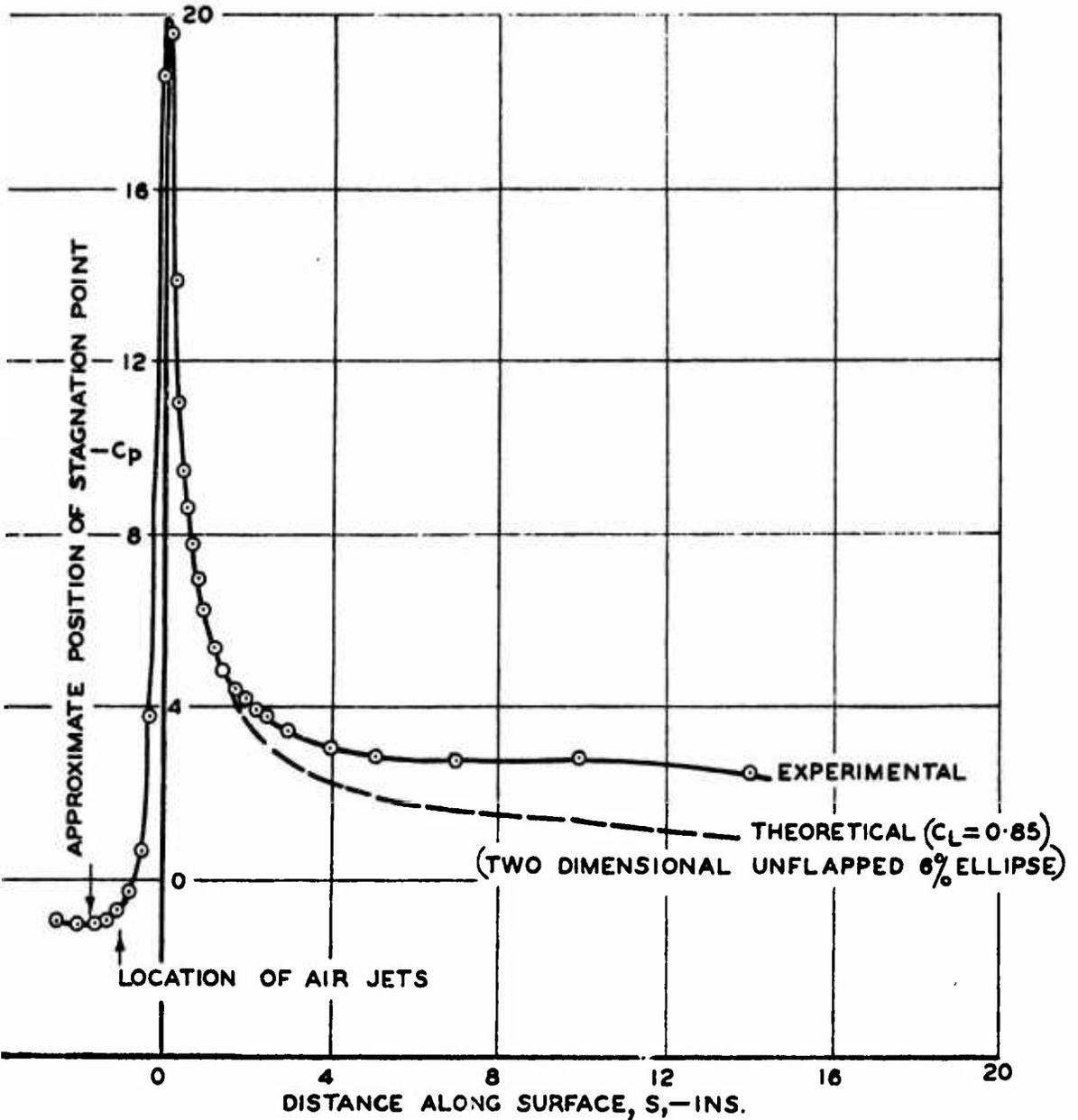component frequencies of the turbulent flow.

FIG. 1   DIAGRAM OF MODEL

FIG. 2   PRESSURE DISTRIBUTION