THE COLLEGE OF AERONAUTICS
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THE APPLICATION OF HOT-FILM GAUGES TO THE DETECTION
OF BOUNDARY-LAYER TRANSITION IN FLIGHT

by

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The Application of Hot-Film Gauges to the Detection of Boundary-Layer Transition in Flight

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SUMMARY

A detailed description of the construction of small hot-film gauges is given with an account of the application of these instruments to the specific problem of detecting boundary layer transition in flight. Typical oscilloscope records of gauge signals from experiments on a swept laminar flow wing are reproduced.
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1. Introduction

During the flight research programme on the Handley Page laminar flow suction wing a simple type of hot-film gauge was developed for the detection of transition in flight. These gauges have also been used successfully in wind tunnels.

The laminar flow test wing was of the slitted type, having about 100 slits of .004 inch width on either side of a symmetrical section. The slit spacing and suction quantities were designed to maintain laminar flow up to the trailing edge. This wing was highly swept (43° at the leading edge) and was thus somewhat different from other similar suction surfaces previously tested. The sweep affects the flow stability in the neighbourhood of the leading edge and without the application of suction the flow would almost certainly become turbulent there.

A modified Lancaster, with the laminar flow wing mounted vertically on the fuselage, was used as the test vehicle (see fig. 1). The test programme was carried out in the speed range 100 to 200 knots I.A.S. and most of the experiments were made at 10,000 ft. altitude.

2. The detection of transition

Some of the techniques used in the laboratory for the detection of transition can also be used in flight. Flow visualization methods which rely on the differential rates of mass transfer in a laminar and a turbulent boundary layer have been successfully employed on aircraft in flight. Gray (1952) obtained some excellent photographs of transition patterns on the leading edges of swept wings using both the naphthalene sublimation and the china clay liquid evaporation methods. In these tests the volatile material was sprayed on just before a flight, so that the resulting surface pattern was created by the entire flow history from take off to landing, although due to temperature effects most of the development arose in the low altitude part of the flight plan. To overcome this difficulty Atkins and Trayford (1955) arranged to spray paraffin in flight on to the wing of a Mustang which had previously been coated with china clay. However, a slitted wing surface presents additional difficulties in the application of these methods, and although naphthalene has been used on suction wings in wind tunnels (Pfenninger 1962), it was considered too difficult to apply in flight.

The shape of the boundary layer velocity profile can also be used to indicate the state of the flow. Velocity profiles obtained from Pitot-combs had previously been used by Burrows (1956) on a Midge wing which was also flight tested on the Lancaster. However, this technique only gives well defined profile shapes when the boundary layer is thick. Close to the leading edge, or further aft when suction was applied, inconclusive results were often obtained and it was not possible to determine whether the boundary layer control system was operating correctly.

To overcome the difficulties arising from the use of Pitot tubes attempts were made to use a hot-wire anemometer so that the turbulence in the boundary layer could be directly examined. Preliminary tests were made with a .001 inch platinum wire element 1/8 inch long which was soft soldered on to the steel wire prongs of a probe. The probe was mounted on the wing with cellulose tape with the
hot-wire about .010 inch from the surface. From wind tunnel tests it was found that this wire could safely pass a current of 0.8 amps at speeds above 100 knots and a constant heating current of this value was provided by a 24 volt accumulator and a series resistor. In flight the fluctuating voltage developed across the wire was displayed on a portable oscilloscope. With the probe mounted in an aft position on the test wing the difference between the almost steady laminar signal and the random fluctuations of a turbulent one was quite clear, but close to the leading edge where the boundary layer was thin inconclusive results were again obtained due to the poor frequency response of the .001 inch wire. To improve the frequency response of the instrument it was decided to use hot-film gauges, which work in a similar manner to wires, rather than the fragile thin tungsten wires employed in the laboratory. In fact the glass hot-film gauges proved to be far more robust than the thick wire elements.

3. Hot-film gauges

Hot-film gauges for turbulence measurements were first introduced by Ling and Hubbard in 1956. These gauges had a double bevel shaped on to the glass as shown in fig. 2. The sensitive element was provided by a thin film of platinum fired on to the surfaces of the bevel. The heat transfer from the electrically heated film gives a measure of the flow velocity in the same way as with the more conventional hot-wire, although the response of the wedge to the various components of turbulence is not so clearly defined. As the platinum films are quite thin the frequency response of these instruments depends mainly on the conductivity and specific heat of the base - using a Pyrex base and heating the gauges with a constant current the instrument responds to frequencies up to about 10,000 c/s. The attenuation at the high frequency end can be reduced by running the gauge in the constant temperature mode, where the current is automatically controlled by a high gain amplifier so that the bridge is always in balance.

For the purpose of indicating transition it is clearly unnecessary to use such an elaborate gauge as that employed by Ling for measurement of turbulence levels, and in the present tests only gauges of simple geometry were used. Since the simple directly heated system had sufficient range for our purpose it was unnecessary to use any complicated electronic apparatus to improve the frequency response of the instruments.

Two types of gauge were used and the shapes are shown in fig. 3. These gauges were made from Pyrex microscope slides. They were thin and thus only presented a minimum interference with the flow when strapped down on to the wing surface with adhesive tape. The gauges with blunt leading edges, type (a), were far easier to make but had less sensitivity than the bevelled type shown in fig. 3b.

3.1 Shaping the glass

Pyrex microscope slides were first ground to form a taper along one long edge and then the blank was sliced up into 3/16 in wide strips by an ultrasonic abrasive machine. The final beveling and polishing of the tip was carried out by hand. In the region where the film was to be fired it was essential to have a smooth scratch-free polished surface extending from 1/4 inch along one side,
round the tip to a similar point on the other edge without any discontinuities. It is usually recommended that the final surface be 'flamed' to obtain the desired smooth finish, but for the type of gauge described here this flaming was difficult to carry out without melting the tip. When the polishing was carried out properly and the tip was correctly blended to the sides the author found flaming unnecessary, perfectly satisfactory films being formed on the hand polished surfaces. The tip region of the gauge was shaped using various grades of wet silicon-carbide paper (400 - 500 - 600), followed by successive grades of dry polishing emery (blue-back) paper until the required finish was obtained. It was found to be important not to pass on to a finer grade of polishing paper until all the scratches from the previous grade had been eliminated, otherwise the coarse lines produced by the initial grades remained and could not be polished out. It was necessary to inspect periodically the surfaces of the gauges with a good quality powerful (x 10) magnifying glass to see when to change to the next grade of polishing material.

3.2 Applying the platinum film

After cleaning the glass with carbon tetrachloride, or some other similar solvent, a continuous line of liquid bright platinum (Hanovia 05 - X) was applied with a ruling pen along the polished sides of the gauge as well as on the tip. Other types of liquid platinum or gold preparation have been used by other workers from time to time, but 05 - X appears to be the most satisfactory for the present purpose as it has the largest temperature coefficient of resistance of about .0026 per degree centigrade. The liquid film was air dried for fifteen minutes or so and then the gauges were heated to 500° C with the oven door open. The door was then closed and the oven temperature raised to 740° C, where it was maintained for five minutes before the gauges were removed and allowed to cool naturally. The actual time and temperature used for the firing cycle is quite critical and it will depend on the glass used, the type of oven, the position and accuracy of the thermocouple etc. For the platinum to fuse with the glass it is necessary to allow the surface of the glass to soften slightly - the required firing cycle to achieve this without actually distorting the gauge too much can only be found by experiment.

If the film is correctly fired it is not possible to scrape or rub the platinum off; if the film does rub off, the glass surface has not been heated sufficiently to allow the platinum to fuse and a higher temperature should be tried. However, even when correctly fired, sometimes large holes appear in the film. This trouble arises through putting too thick a layer of liquid platinum preparation on the surface and allowing insufficient time for it to dry before firing. It has been found that the hot jet from an electric hair dryer can be of assistance in drying out this liquid layer and preventing the formation of these blisters.

A more robust film can be obtained by re-coating the gauge with a second layer of platinum preparation and repeating the firing cycle a second time. These double fired instruments have thicker lower-resistance films and are thus less sensitive than the single fired gauges; nevertheless the extra life and generally better reliability make the process well worth the extra trouble.

3.3 Finishing the gauges

To enable leads to be taken off, the sides of the gauge were tinned with soft solder using a resin flux ('coraline') to help the solder to flow smoothly. The
tinned regions were extended round the shoulders and on to the tip of the gauge, leaving only about 1/16 inch clear in the centre of the bevel. A photograph of a finished probe of the bevelled type is shown in fig. 4. For work near the leading edge the finished gauges were cut off 1/4 inch from the tip and cemented on to thin bronze strips 3/16 wide and 1 1/2 inches long. These strips could be bent so that when they were taped down on the wing the gauge tips were sprung on to the surface.

4. The electrical circuit

The heating current to the gauges was provided by a 12 volt 80 amp hour battery which had sufficient capacity to allow fifty gauges to be run simultaneously for the period of the flight tests which lasted from 1 to 2 hours. The current through each gauge was controlled by a 25 ohm variable resistor (see fig. 5). The gauges were fed through long lengths of twin screened miniature microphone cable, care being taken to isolate all the screens from the skin of the aircraft. One earth point was provided in the aircraft and all the screens were returned to this point.

A bridge circuit for measuring the gauge resistances was formed with the gauge element, the 20 ohm load, a fixed external resistor and a decade box. The necessary sockets were provided so that the external resistors and galvanometer (an Avometer set on the 250 mA range) could be plugged into any channel. Thus one could set up the bridge ratio so that a balance could be achieved for a given gauge resistance, usually from 1.3 to 1.7 times its cold value. Under operating conditions the bridge was brought into balance by adjusting the 25 ohm variable resistor until sufficient current flowed through the gauge to raise its temperature to the required level. For a given overheating ratio the setting of the decade box could be worked out for each gauge prior to the flight and all fifty gauges could then be individually balanced in flight. The voltage fluctuation developed across any gauge could be observed on the portable oscilloscope carried in the aircraft by plugging the scope input lead to the appropriate socket.

5. Operation of gauges in flight

The magnitude of the signal generated by a hot-film gauge depended largely on the temperature of the film, the higher temperatures giving the greatest signals. In flight, where difficulty was sometimes experienced through electrical interferences, an overheating ratio of 1.7 was employed to give a large signal. This means that the film was heated until its resistance reached 1.7 times its cold value; for films formed with 05 - X a temperature of about 270°C is implied. Gauge life seems to depend to some extent on this temperature and overheating ratios greater than 1.7 are not recommended from this point of view; in fact, if a sensitive oscilloscope is used and no troubles arise through electrical interference, sufficient signal strength may well be obtained at overheating ratios of 1.5 or less. Electrical interference could be considerably reduced by using an oscilloscope with a differential input. The pick-up on a cable shorted at the end was similar to that on an active one and by connecting them to opposite sides of the input amplifier the spurious part of the signal could be eliminated.

Before a flight took place all the 25 ohm variable resistors were set at maximum so that initially only a small current flowed through each gauge when the battery was switched on. At the test altitude, which was 10,000 ft. for most of the work in the present series, the aircraft was flown at the lowest speed of interest
and after switching on the battery all fifty hot-films were individually balanced to the correct temperature with the aid of the bridge circuit. Throughout the flight experiment runs were made at various speeds above that used for balancing, so that the gauges always ran at a safe temperature below that chosen for balance. Although at these higher speeds it would have been possible to re-balance the gauges and so increase the size of the available signal, it was found unnecessary to go to that trouble. Signal strength for a fully turbulent flow varied somewhat with the position and type of gauge; the bevelled type of hot-film generated up to 5 mV peak to peak in regions aft of about 50% chord where the boundary layer was thick, and signals of 1 or 2 mV near the leading edge. About half these values were obtained with the blunt type of gauge. The oscilloscope was normally set on either the 1 or 2 mV/cm range depending on the signal being observed.

Any gauge could be selected for observation on the oscilloscope screen by simply plugging the input leads into the appropriate socket on the control panel. To find the transition speed at any particular gauge station the signal was observed over a range of flight speeds. It was found convenient in these tests to increase steadily the aircraft speed from around 100 to 200 knots, the pilot calling out the speeds at say 5 knot intervals so that the flight observer could correlate the character of the hot-film signals with speed. The increase in flight speed was obtained by performing a shallow dive rather than by opening the throttle which tended to yaw the aircraft slightly and so alter the angle of incidence of the test wing. If the gauge indicated a change from laminar to turbulent flow at some speed within this range a second run was made just covering the critical range in order to give a more accurate estimate of the transition speed. Fig. 6 shows a series of oscilloscope photographs of gauge signals at four different speeds over the transition range. These pictures were obtained when the test wing was undergoing a sequence of tests in the 13' x 9' tunnel at R.A.E. Bedford.

6. Discussion

In the flight work each gauge signal was separately viewed by the flight observer. For large numbers of gauges this was time-consuming and attempts were made to employ electronics to interpret the hot-film signals so that a simple display could be used to show whether the flow was laminar or turbulent. This was accomplished by filtering out the high frequency part of the signal and using this to fire a trigger circuit when the amplitude was above some threshold. When the signal was large enough to fire the trigger the circuitry was designed to produce a full scale meter deflection. When the amplitude was small no switching took place and the meter showed zero. Patches of turbulence passing over the probe caused the meter to indicate the proportion of 'intermittency'. A single unit was developed and shown to operate satisfactorily in flight. A complete system of fifty similar units was then made and installed in the aircraft. The panel containing the fifty indicating meters could be photographed in flight to keep a record of the display.

Although fully laminar and fully turbulent regions could be identified in this way, the equipment has not been of great use as the electronics, in their present form, are not capable of interpreting correctly all the types of transition signals that have been observed. This is particularly true for stations far back on the wing where transition arises through the growth of small disturbances. More work clearly is needed to collect data on the various types of possible signal before the electronic processing can finally be developed.

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## References

1. Atkins, P.B. and Trayford, R.S.  
   A method of boundary layer flow visualization for use in flight.  
   A.R.L. Flight Note 22. (1958)

2. Burrows, F.M.  
   A theoretical and experimental study of the boundary layer flow on a 45° swept back wing.  
   College of Aeronautics Report No. 109. (1956)

3. Gray, W.E.  
   The nature of the boundary layer flow at the nose of a swept wing.  

4. Lang, S.C. and Hubbard, P.G.  
   The hot-film anemometer; a new device for fluid mechanics research.  

5. Pfenninger, W. and Bacon, J.W.  
   Influence of acoustical disturbance on the behaviour of a swept laminar suction wing.  
FIG. 1  THE HANDLEY PAGE LAMINAR FLOW WING MOUNTED ON THE LANCASTER

FIG. 2  HOT-FILM PROBE USED BY LING
Both Gauges Have The Same Dimensions.

(a) Blunt Tipped

(b) 45° Bevelled Leading Edge

FIG. 3 HOT-FILM GAUGES USED IN FLIGHT

FIG. 4 HOT-FILM GAUGE USED FOR DETECTION OF TRANSITION
FIG. 5 ELECTRICAL CIRCUIT FOR HEATING GAUGES

SWEEP SPEED IS 20MS/CM.
GAUGE STATION 87% CHORD AND 65% SPAN FROM THE ROOT.

FIG. 6 OSCILLOSCOPE RECORDS OF HOT-FILM SIGNALS
TAKEN ON THE SUCTION WING AT VARIOUS SPEEDS