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MARCH 1970 AIAA JOURNAL VOL. 8, NO. 3

Transition Experiments on a Flat Plate at Subsonic and Supersonic Speeds

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A new method of detecting boundary-layer transition at supersonic speeds is described. The majority of methods such as schlieren and those of maximum surface temperature and peak surface Pitot pressure, locate positions near the end of transition, which, as will be shown in the paper, have a strong Mach number and unit Reynolds number dependence. A more complete picture of transition dependence on these parameters has been obtained by measuring the change in the root mean square of the voltage fluctuation across surface thin film gages operated at constant temperature. This technique enables the effects of Mach number and unit Reynolds number on the beginning and length of transition to be established more precisely than with previously used methods.

I. Introduction

SINCE transition from laminar to turbulent flow can account for significant changes in such important parameters as skin friction, heat transfer, and wake structure, it is important that the variation of transition Reynolds number with Mach number be accurately determined. However, there is much speculation at present regarding the effects of Mach number and unit Reynolds number on transition, although much of the scatter in the data can be attributed to differences in the methods used in observing transition and, as recently reported in Ref. 1, to differences in wind-tunnel disturbance levels. But the problem is complicated still further by the difficulty of isolating the large number of individual factors that are known to effect transition at supersonic speeds.

An insight into the mechanism of transition has resulted from records of velocity fluctuations in transition regions measured by hot wires showing intermittent bursts of laminar and then turbulent flow. Emmons[2] introduced the idea of turbulent spots that originate in more or less random fashion and increasingly overlap as they enlarge during their transit downstream, finally covering the entire flowfield and resulting in fully turbulent motion. The passage of these spots over points on the surface results in alternations of laminar and turbulent flow. These alternations can be quantitatively described by an intermittency factor γ which represents the fraction of time any point spends in turbulent flow. Dhawan and Narashima[3] showed that the intermittency factor can be used to predict the velocity profile and skin-friction variations within the transition region at subsonic speeds and that the origin of the turbulent boundary layer is approximately coincident with the onset of intermittency.

At supersonic speeds an analysis of a large body of heat-transfer data by Bertram and Neal[4] has shown that the choice of the virtual origin at the point of peak shear or peak heating gave the most consistent results. The problem of choosing a consistent virtual origin is, however, far from resolved as evidenced in the discussion on boundary-layer transition at the AGARD meeting in May 1968.[5] Thus it is felt that the more accurate location of onset, peak fluctuation level, and end of transition provided by heated thin film gages should help to resolve the difficulty of choosing consistent transition and virtual origin positions.

II. Subsonic Boundary-Layer Transition

Because of the importance of correctly determining the onset and extent of transition and the location of the virtual origin of the resulting turbulent boundary layer from wall

Presented as Paper 69-9 at the AIAA 7th Aerospace Sciences Meeting, New York, January 20–22, 1969; submitted February 24, 1969; revision received August 20, 1969. The work described in this report forms part of a program supported by the Ministry of Technology. The author wishes to express his thanks to B. J. Bellhouse and D. L. Schultz for their help and encouragement.

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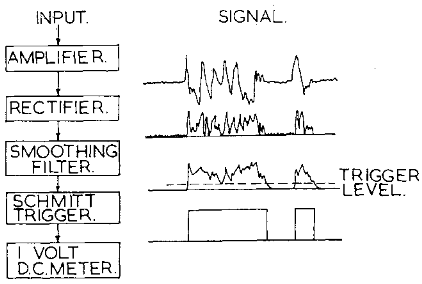

Fig. 1 Block diagram of intermittency meter.

fluctuation measurements, it was decided to compare intermittency measurements obtained with thin film gages with more conventional hot wire data before extending the work into supersonic flow.

These tests were conducted on a flat plate model in the Oxford University 18 × 12 in. tunnel at speeds up to 180 fps.

Figure 1 shows an over-all block diagram of a circuit to measure intermittency factor adapted from the one given in Ref. 6. A schematic diagram of a hypothetical signal as modified by passage through the various blocks is also given.

The value of capacitor in the smoothing filter must be sufficiently large to provide a d.c. signal that will fire the Schmitt trigger circuit during a turbulent burst, and yet must not be so large that the trigger circuit does not cut off until some time after the end of the burst.

Once a suitable value of capacitor has been chosen, it is then a process of observing simultaneously the output from the trigger circuit and the filtered turbulence input signal, and adjusting the level of the input signal or possibly the d.c. trigger level, until the Schmitt trigger output is coincident with the turbulent bursts. For this purpose a storage oscilloscope was used. The calibration of the circuit was then checked by feeding high-frequency pulses of known intermittency factor into the meter from a square wave generator.

To give further confirmation of the hypothesis of localized laminar breakdown, close to the virtual origin of the resulting turbulent boundary layer, the distribution of intermittency during transition on a flat plate was measured by traversing a hot wire close to the surface.

It is shown in Ref. 3 that the application of the point breakdown hypothesis together with Emmons' theory gives

$$\gamma = 1 - e^{-A\xi^2} \tag{1}$$

where $\xi = (x - x_t)/\lambda$; λ being a measure of the extent of the transition region characterised by

$$\lambda = (x)_{\gamma=0.75} - (x)_{\gamma=0.25}$$

and A is a constant equal to 0.412. Figure 2 shows that the data is in good agreement with Eq. (1).

The distribution of γ across the boundary layer will be a function of the shape of the turbulent spots. Schubauer and Klebanoff[7] have shown that the spots have a nearly constant cross-sectional area close to the surface, but they taper towards the outer edge. This would indicate that wall measurements of γ using thin film gages should give results in good agreement with hot wire measurements close to the surface. The results in Fig. 3 show that this is indeed the case, the values of γ at the surface agreeing very well with the values obtained by extrapolation of the hot wire data. The measured $\gamma(y)$ distributions during transition and fully turbulent flow are similar to those reported by Corrsin and Kistler[8] in fully developed turbulent boundary layers, i.e., γ varies from a constant maximum value close to the wall to zero towards the edge.

While this $\gamma(y)$ variation is probably of importance to the detailed structure of turbulent motion associated with the spots, the γ value close to the wall is the characteristic property of importance for the transition region. It would appear, therefore, that a surface thin film provides an excellent means of detecting boundary-layer transition and of measuring intermittency during transition.

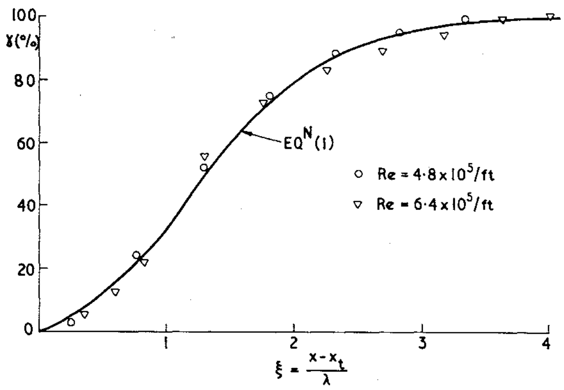

Fig. 2 Universal intermittency distribution.

This technique has also been compared with the more usual methods of skin-friction and heat-transfer variation at subsonic speeds. The results show that the origin obtained from the minimum values of skin friction and heat transfer are in close agreement, but that the onset of intermittency always occurs upstream of this point. However, both skin-friction and heat-transfer techniques rely on changes in mean velocity profile through the transition region which, from an examination of the velocity profiles reported by Schubauer and Klebanoff[7] show little change even at $\gamma = 0.16$, so some delay would be expected. For this reason it is felt that intermittency measurements give a more precise location of the onset and length of transition at subsonic speeds.

III. Supersonic Boundary-Layer Transition

Previous work in subsonic flow just described and also that reported by Bellhouse and Schultz[9] has shown that the voltage across a constant temperature heated film on the surface of a model responds to turbulent fluctuations in the boundary layer, and that these voltage fluctuations are readily visible on an oscilloscope. In supersonic wind tunnels, the sensitivity of the hot film, as with the normal hot wire, is much lower than at subsonic speeds owing to the higher velocities involved. But preliminary work has shown that transition is still easily recognizable by comparing shadowgraph and schlieren photographs with oscilloscope records. This is not usually the case with films operated at constant current as the voltage fluctuations are much lower and are not directly observable on an oscilloscope.

A more precise method of locating boundary-layer transition, reported in Ref. 10, is the change in the root mean square of the voltage fluctuation across a heated film maintained at constant temperature from the laminar to the turbu-

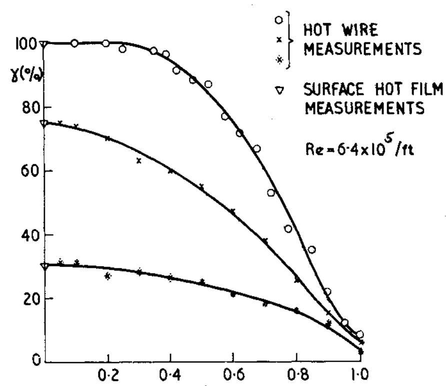

Fig. 3 Intermittency distribution across subsonic boundary layer.

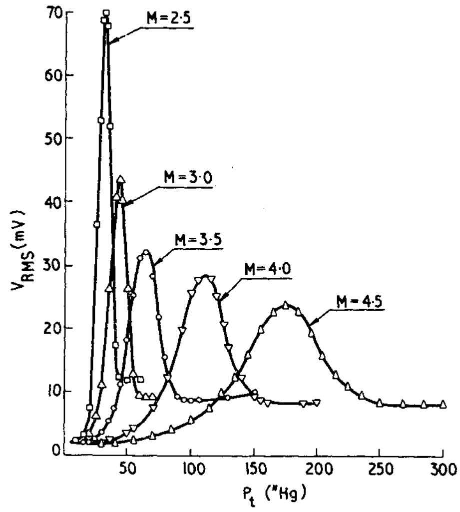

Fig. 4 Variation of rms film voltage fluctuation with Mach number.

lent level, with an intermediate peak close to the positions of maximum surface Pitot pressure and maximum surface temperature. This technique has previously been used by Mabey[11] with gages operated at constant current. The observed fluctuations were, however, several orders of magnitude smaller than those in the present series of tests. Potter and Whitfield[12] measured the unsteady signal from a hot wire operated at constant current through the transition region of compressible boundary layers. These hot wire signal contours, when extrapolated to the surface, indicated a peak near the position of maximum surface temperature. However, as pointed out in Ref. 12, the fact that these disturbances were of the same order creates a source of error in the determination of transition data from hot wire traverses, since a different point might be indicated for each different height above the surface. For this reason a probe mounted flush with the surface and having much greater sensitivity has obvious advantages.

Experimental Details

Thin platinum films deposited on a pyrex glass substrate were mounted flush with the surface at distances of $\frac{1}{2}$, 1, 2, 4, 8, 14.5, and 24.5 in. from the leading edge along the model centre line. The gages were controlled by a constant temperature feedback bridge (DISA 55 A01) at 100°C above the local recovery temperature.

The transition data were obtained on an adiabatic flat plate with a bevel angle of 10° and leading edge thickness of 0.010 in., at unit Reynolds numbers up to 14×10^6 per ft at $M = 2.5$ and 10×10^6 per ft at $M = 4.5$.

The tests were conducted in the 3 × 4 ft continuously running High Supersonic Speed Tunnel at the Royal Aircraft Establishment, Bedford, England.

Discussion of Results

Natural transition

Typical values of the root mean square film voltage fluctuation 14.5 in. from the leading edge for several Mach numbers are shown in Fig. 4 for a range of tunnel total pressures. All curves clearly show the rise from the laminar to the turbulent level with an intermediate peak. The laminar level is independent of Mach number, whereas the turbulent level tends to decrease with increasing Mach number. There is also a consistent trend of decreasing peak rms signal with increasing Mach number.

Data from three streamwise positions shows the variation of film voltage fluctuation level with unit Reynolds number for a range of Mach numbers in Figs. 5 and 6. Although the

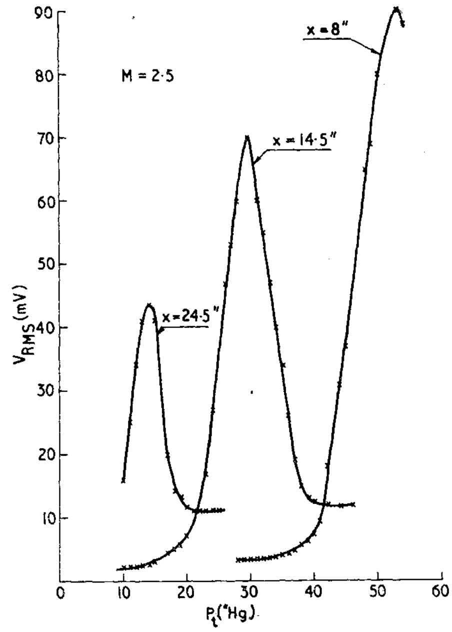

Fig. 5 Uncontrolled boundary-layer transition at M = 2.5.

data from different films should not be directly compared it is evident that the fluctuation level increases rapidly with unit Reynolds number.

However, of particular importance is the fact that three distinct points in the transition region can be accurately located. Namely, 1) the start of transition, defined as the point where the rms signal begins to increase from its laminar value, i.e., where intermittency begins; 2) the peak rms signal which will be shown to be close to the position of maximum surface Pitot pressure; 3) the end of transition.

The fluctuation diagrams in Figs. 4, 5, and 6 also include the effects of changes in bluntness Reynolds number since each curve was obtained by increasing the unit Reynolds number to bring transition over the heated films (x const). Although this will affect the relative positions of the onset, peak, and end of transition on each fluctuation diagram, the transition "point" data obtained from these curves, when plotted against unit Reynolds number, will be the same as those obtained by varying x over a range of constant unit Reynolds numbers for a given leading edge bluntness.

The influence of Mach number and unit Reynolds number on the magnitude of the transition Reynolds number and the extent of the transition region is presented in Fig. 7. The position of the peak rms signal and end of transition show the usual upward trend with increasing Mach number and unit Reynolds number. But the start of transition can be seen to have much less dependence on these parameters.

The effects of bluntness Reynolds number on the transition data have been eliminated in Fig. 8 by crossplotting the data against Mach number for a constant unit Reynolds number. Figure 8 shows the influence of Mach number on the magnitude of the transition Reynolds number and the extent of the transition region. The tendency of transition Reynolds number to increase with increasing Mach number has been observed before. However, it can be seen that the dominating effect of Mach number is to increase the length of the transition region; transition onset is relatively insensitive to Mach number.

These data suggest that, for a given configuration, the Reynolds number at which spot breakdown occurs is relatively insensitive to Mach number and unit Reynolds number and that these parameters only affect transition "point" data due to their influence on subsequent spot behavior. It is considered that a lot of the scatter in transition data can be

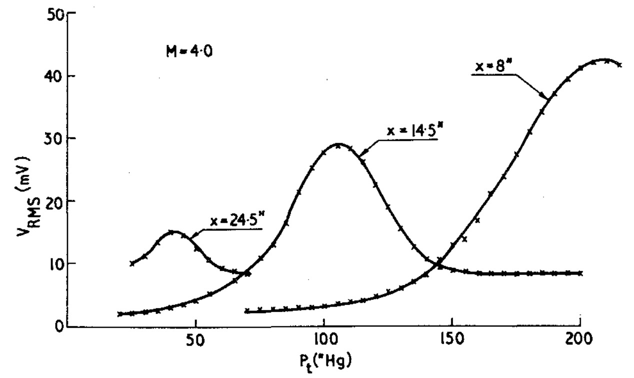

Fig. 6 Uncontrolled boundary-layer transition at M = 4.0.

attributed to inconsistent choice of transition "point" indicated by different techniques, mostly locating positions near the end of transition, which have a strong Mach number and unit Reynolds number dependence. A more complete picture of transition dependence on these parameters can only be obtained from experiments in which the positions of the beginning and end of transition are accurately determined. It is of interest to note that transition data reported for supersonic and hypersonic flows are not generally based on observations of turbulent spots but rather some macroscopic quantity such as skin friction, heat transfer, or surface Pitot pressure, whose departure from laminar values can be detected only when γ is appreciably greater than zero.

Forced transition data

The effect on transition of a roughness band of 0.011 in. ballotini 0.1 in. from the leading edge and 0.15 in. wide is shown in Fig. 9. As with natural transition, the importance of defining a consistent transition "point" is obvious. The results also suggest that the transition front cannot reach the roughness. Indeed, it was only possible to achieve a fully turbulent boundary layer up to 1 in. from the trip at M = 2.5. At M = 4.5 transition onset was only obtained up to 2 in. from the trip at the highest tunnel pressure.

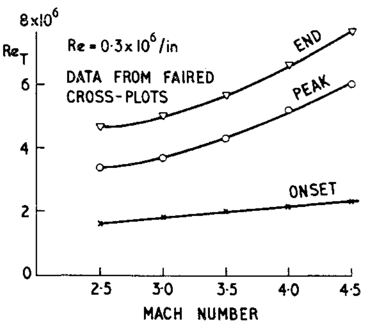

Fig. 8 Variation of transition Reynolds number with Mach number.

The rapid increase in roughness Reynolds number required to fix transition at the higher Mach numbers is shown in Fig. 10 for the 8 in. and 14.5 in. gage positions. Figure 10 shows the fairly wide Re_k range over which the boundary layer is transitional. However, this variation is much less at the 8 in. position indicating that the length of transition is greatly reduced as the transition front approaches the trip position.

Tripped and natural transition data are compared in Figs. 11 and 12 for the 14.5 in. gage position. Both sets of curves show the marked decrease in the length of the transition region in the tripped case. A decrease in peak rms signal in the tripped boundary layer is also apparent. This difference between the two peaks decreases with increasing Mach number.

The delayed rise in rms signal at the beginning of transition for the tripped boundary layer as the Mach number increases is particularly significant. This could be interpreted as an increase in the length of laminar flow as noted in the transient calorimetry heat-transfer tests of Holloway and Sterrett[13] for a Mach number of 6.0 when the surface roughness was less than the boundary-layer thickness. However, in the present case, the roughness height was always

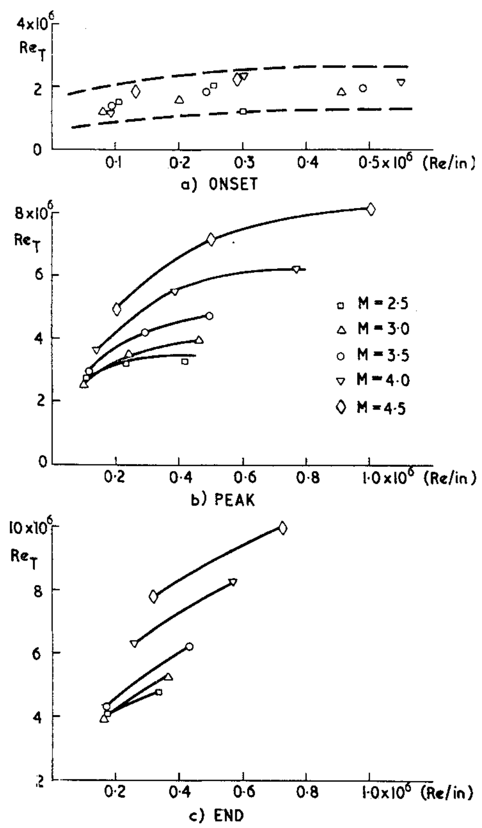

Fig. 7 Uncontrolled transition data.

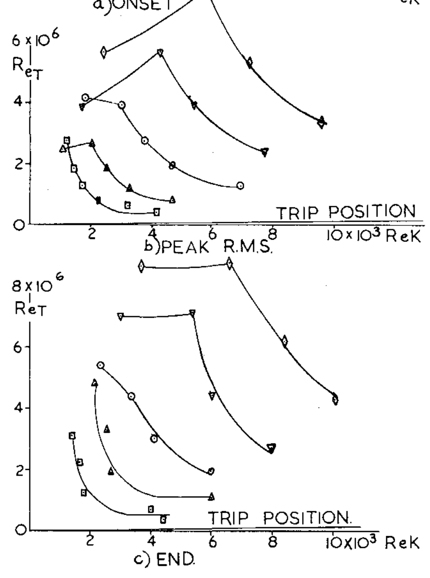

Fig. 9 Controlled transition data.

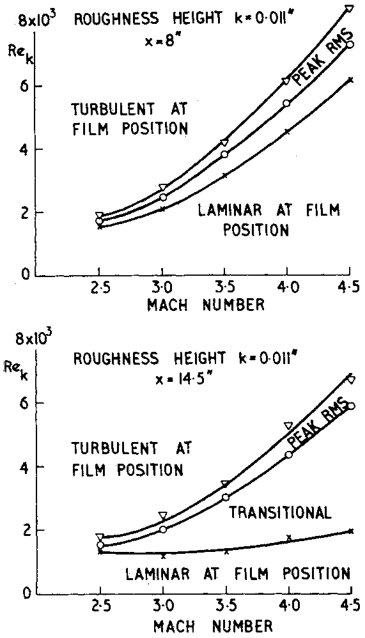

Fig. 10 Variation of critical roughness Reynolds number with Mach number.

greater than the calculated boundary-layer velocity thickness at the trip position.

The reasons for this initial delay are not fully understood although several possible causes present themselves. In Ref. 13, it was suggested that the roughness increases the effective leading edge bluntness thus producing a lower unit Reynolds number and Mach number at the edge of the boundary layer. Since the shock strength increases with Mach number this would explain the more pronounced delay at the higher Mach numbers. Another possibility is that the roughness elements cause the flow to separate ahead of the elements with an upstream restraint at the leading edge of the plate thus causing the flow to undergo a wedge-type compression. A less obvious reason is contained in the results of Ref. 14, where it is indicated that the stability of a separated laminar mixing layer increases with Mach number more rapidly than the stability of an attached laminar boundary layer. This has led to the speculation that the laminar separation that exists downstream of the roughness elements is partially responsible for delaying transition at high Mach numbers.

The fact that the fluctuation level in the turbulent boundary layer resulting from forced transition does not approach that of the natural turbulent boundary layer until sometime after complete transition suggests that boundary-layer measurements should only be made in a region well away from the roughness elements if it is desired to simulate turbulent flow

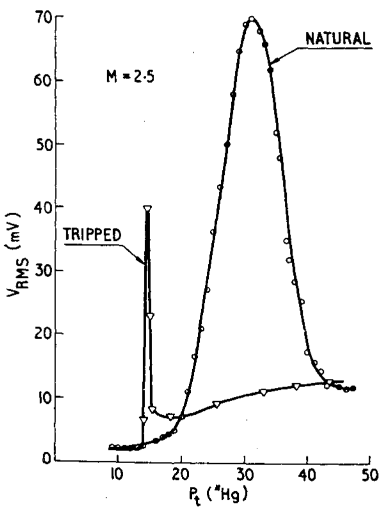

Fig. 11 Comparison of natural and controlled transition at $M = 2.5$.

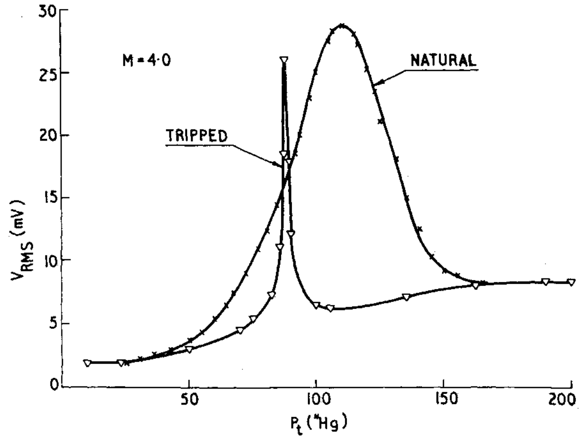

Fig. 12 Comparison of natural and controlled transition at $M = 4.0$.

due to natural transition. However, since both fluctuation levels are the same well downstream, it would appear that, in the wall region, no additional disturbances were introduced by the trip although this will not necessarily be the case for the greater roughness heights which would be required to bring transition close to the trip position.

Comparison of Hot Film and Surface Pitot Data

The surface hot film and surface Pitot tube readings are compared in Fig. 13 for the tripped boundary-layer case. Although there is good agreement between the two peak locations, close inspection shows that in all cases the peak rms signal occurs before the peak surface Pitot pressure. It is thought that this is due to the delay in the change in mean velocity profile at the onset of transition as noted previously in the subsonic tests.

The corresponding data for natural transition are compared in Fig. 14. These data clearly show the superiority of the hot film for transition detection especially at high Mach numbers.

Interpretation of Peak Fluctuation Level

Perhaps the most striking feature of the voltage fluctuation diagrams is the well-defined peak towards the end of transi-

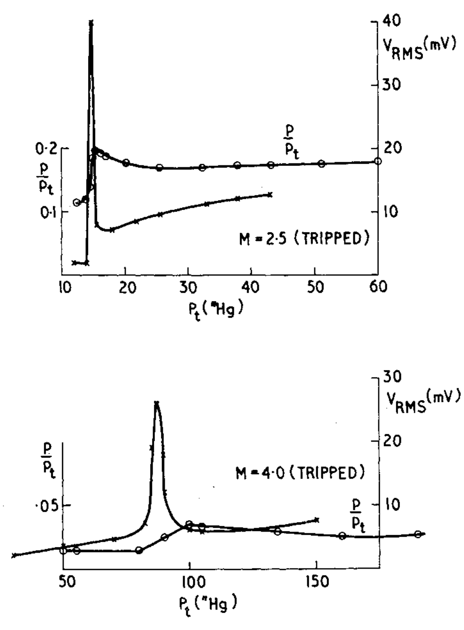

Fig. 13 Comparison of surface Pitot and thin film gage.

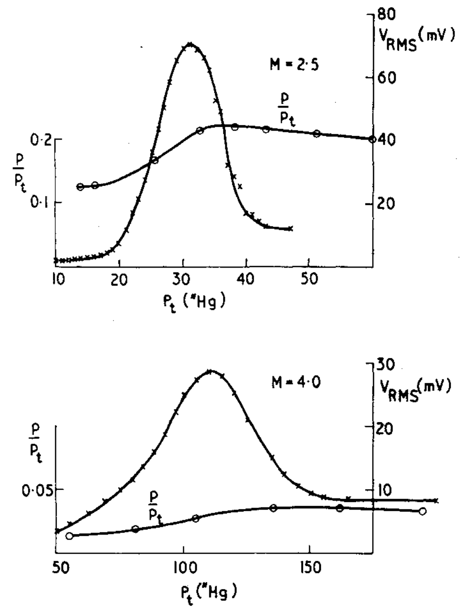

Fig. 14 Comparison of surface Pitot and thin film gage.

tion. This may be explained by considering the separate components of the fluctuating voltage, namely 1) the voltage fluctuation (V'_T) due to the turbulent flow associated with spot passage; and 2) the voltage fluctuation (V'_{LT}) caused by changes in mean voltage across the film from the laminar to the turbulent levels. Hence the total voltage fluctuation (V') at any point in the transition region may be written as

$$V' = f(\gamma V'_T, nV'_{LT})$$

where γ is the intermittency factor and n is the burst frequency.

A plot of turbulent burst frequency variation through the transition region of a subsonic boundary layer is shown in Fig. 15. It can be seen that the combination of this curve with the intermittency curve of Fig. 2 gives the familiar shape of the fluctuation diagram. Since $V'_{LT} > V'_T$ the peak fluctuation level must be close to the point of maximum burst frequency.

IV. Conclusions

The principal results of the experiments are summarized below.

1) Heated thin film gages operated at constant temperature provide a ready means of detecting the onset and length of transition in subsonic and supersonic flows, thus enabling the effects of Mach number and unit Reynolds number on transition "point" data to be more accurately determined.

2) Experiments with tripped boundary layers have also shown the importance of defining a consistent transition "point." The results show the rapid increase in roughness Reynolds number required to fix transition as the Mach number increases. The results also suggest that the transition front cannot reach the roughness.

3) The well-defined peak voltage fluctuation towards the end of transition, close to the positions of maximum surface temperature and peak surface Pitot pressure, coincides with the point where the turbulent burst frequency is a maximum.

4) A comparison of the hot film and surface Pitot tube techniques for detecting boundary-layer transition has shown that the peak voltage fluctuation and the peak surface Pitot pressure are in good agreement. However, these data clearly show the superiority of the hot film for transition detection especially at high Mach numbers.

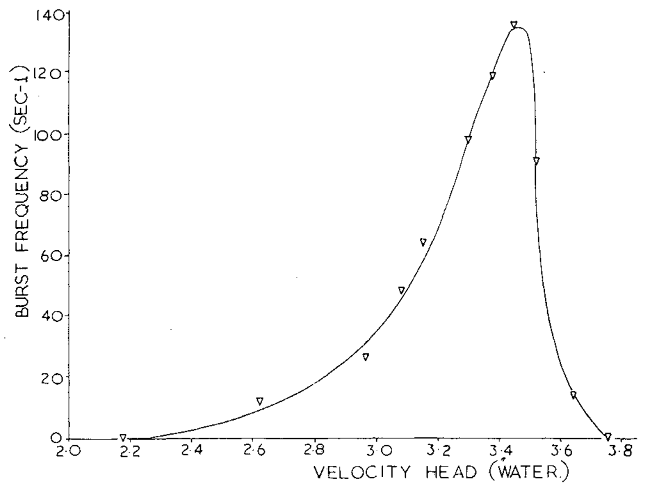

Fig. 15 Turbulent burst frequency variation.

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