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A Study of the Boundary Layer Transition Process

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SUMMARY From the results of a flow visualisation experiment, certain physical characteristics of a turbulent spot are suggested by the authors. The spot was artificially initiated at a point by a small intermittent wall jet. The authors also carried out experiments behind vibrating trip wires and observed the "signatures" or "footprints" of the Λ-shaped vortices seen by other workers. The fact that these "signatures" are also observed in a turbulent spot leads one to suspect that these spots consist essentially of an array of Λ-shaped vortices. The formation of the spot is subsequently described in terms of three dimensional disturbances of the cross-stream vortex filaments.

The basic structure of the turbulent spot proposed here is similar to the suggested structure of fully-developed turbulent boundary layers first put forward by Theodorson (1955) and more recently by Bandyopadhyay & Head (1979). Also the description of the spot appears to be consistent with the wave packet model suggested by Gaster (1978), Gaster and Grant (1975) and Wygnanski, Haritonidis and Kaplan (1979).

1 INTRODUCTION

The role which turbulent spots play in the transition process in boundary-layer shear flow has been of great interest since they were discovered by Emmons (1951). It has been suggested that turbulent spots in the laminar boundary layer (Emmons 1951; Schubauer & Klenbanoff 1956) might contain physical properties which are common with the structure in the fully developed turbulent boundary layer. This suggestion has motivated many people to study the "anatomy" of a turbulent spot.

Recently, Coles and Barker (1975); Wygnanski, Sokolov & Friedman (1976) and Cantwell, Coles & Daemotakis (1978) suggested that a turbulent spot consists essentially of one or two large coherent eddies. This interpretation of course, is correct only in the phase-averaged or ensemble-average sense and bears little relationship to the instantaneous patterns within the spot.

An experimental investigation was conducted by the authors using a boundary layer smoke tunnel similar in design to that of M.R. Head of Cambridge University. Some preliminary attempts were made to artificially stimulate the transition process from trip wires and from isolated points in the flow in a purely periodic way. By the use of stroboscopic light, which is synchronised with the disturbance, it was hoped to "freeze" the process in time in a similar manner as was done by Perry & Lim (1978) with coflowing jets and wakes. This "freezing" process was only partially successful. Nevertheless, some detailed features of the anatomy of a turbulent spot suggested themselves and are reported here. These proposed structures are similar to those fully developed turbulent boundary layer structures first suggested by Theodorsen (1955) and subsequently by many other workers. Bandyopadhyay & Hear (1979) showed very convincingly by a flow visualization technique that turbulent boundary layers consist of closely packed Λ-shaped† vortices which lean forward in the downstream direction.

† Some people refer to these as hair-pin vortices, horse-shoe vortices or vortex loops. For consistency the authors are using the Λ notation of Hama & Nutant (1963).

2 FLOW VISUALISATION

2.1 Trip Wire Experiments

The investigation of the three dimensional nature of boundary layer instability was conducted using a vibrating trip wire method. A stainless steel rod 4.15 mm in diameter was placed transverse to the flow with a gap of 3 mm between the rod and the wall, and 24 mm from the streamwise origin of the boundary layer. The boundary layer was approximately 1 cm thick at the trip-wire and the smoke layer was 2 mm thick. Figure 1 shows a typical pattern in the layer of smoke. The authors suspected that these patterns were the "signatures" or "foot-prints" of Λ-shaped vortices which were being stretched in the streamwise direction. Insufficient smoke was being entrained away from the boundary to make the Λ-shaped vortices visible. However, when the rod was submerged in the smoke at the wall level and the streamwise position of the rod was shifted to 96 cm from the origin of the layer the vortices were most visible. The boundary layer in this case was approximately 2 cm thick at the trip wire. These vortices were enhanced and made more orderly as seen in figure 2 by oscillating the rod as is commonly done for initiating a Tollmein-Schlichting type of instability. e.g. see Schubauer & Skramstad (1948), Klebanoff et al (1959, 1962) who used vibrating ribbons.

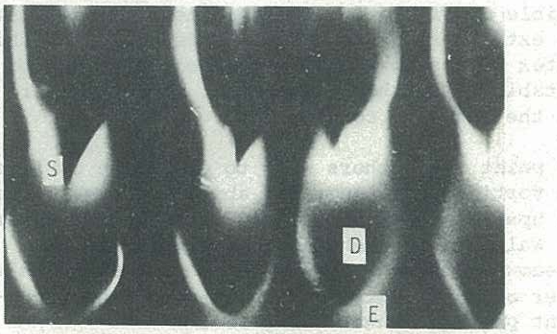


Figure 1 Typical smoke patterns showing the 'foot-prints' of the Λ-shaped vortices in their early stages. s, slit; D, depression; E, elevated smoke.

The photograph in figure 2 shows quite clearly that the vortex filaments have a strong tendency to develop a three dimensionality giving a longitudinal component of vorticity. These vortex filaments initially develop a triangular-like wave form like a lot of inter-connecting Λ's. These interconnecting Λ's possess both upstream and downstream apexes. Attempts were made to freeze these vortices by viewing them under stroboscopic light which was synchronized with the disturbing oscillation. The first four rows of vortices were frozen but further downstream randomness and disintergration of the structures made a detailed description difficult.

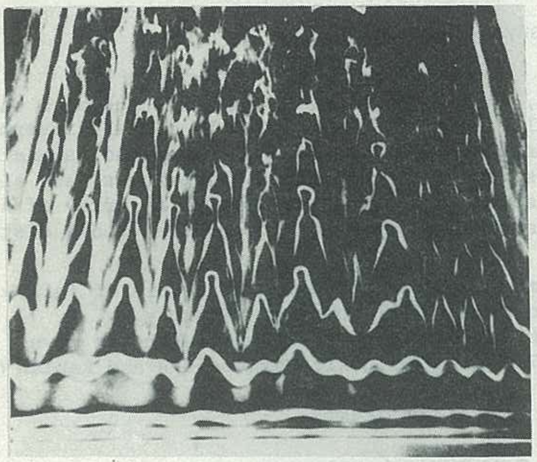


Figure 2 Typical smoke patterns of Λ-shaped vortices when the rod is submerged in the smoke. The rod is artificially oscillated (3Hz).

The spacing of these Λ's does not appear to depend on the flow velocity or the trip wire diameter. In fact it has been shown by Schubauer (1957), Klebanoff and Tidstrom (1959) that irregularities in the wind tunnel screen system determined this spacing. This was also found to be the case in these experiments. A cursory check was made by replacing the last screen with a finer mesh screen which did alter the vortex spanwise spacing.

As mentioned by Hama & Nutant (1963), these bent vortex filaments tend to convect themselves towards the wall at the upstream apex and convect themselves away from the wall at the downstream apex. Since the flow velocity is higher away from the wall, the Λ-shaped vortices stretch very rapidly in the streamwise direction. Klebanoff et al (1962) pointed out that it is sometimes unjustified to assume that concentration of vorticity corresponds with the higher concentration of smoke. However, a laser cross-section showed clearly that the smoke possesses a characteristic "scroll" indicating that it surrounds vortex filaments. The secondary Λ vortex which develops into an Ω shape as discussed by Klebanoff et al (1962), Kovasznay, Komada and Vasudeva (1962), Hama & Nutant (1963) is clearly visible in figure 2. These authors pointed out that the extra Ω shape at the downstream apex of the Λ vortex breaks down into a more complex form of instability further downstream. This however, is not the authors' concern here.

The point the authors wish to emphasise is that when the vortices are generated above the smoke interface the upstream apex of the Λ's is convected towards the wall, is stretched longitudinally in the streamwise direction and becomes submerged in the layer of smoke, giving the characteristic footprint pattern shown in figure 1.

A crude explanation of these patterns or "folds" in the layer of smoke can be formulated from a simple mathematical model consisting of a trailing vortex pair with images. This was used to represent the downstream apex region. Assuming that the distance x upstream is "time like", the deformation of the smoke surface was calculated and is shown plotted out in figure 3 giving a folded surface which resembles the patterns shown in figure 1. These folds are characterised by smoke being elevated from the wall. A depression occurs downstream of this elevated smoke. This depression tapers to a slit which occurs at the top of the elevated smoke. These slits are shown quite clearly in figure 1 and the various features have been labelled for clarification.

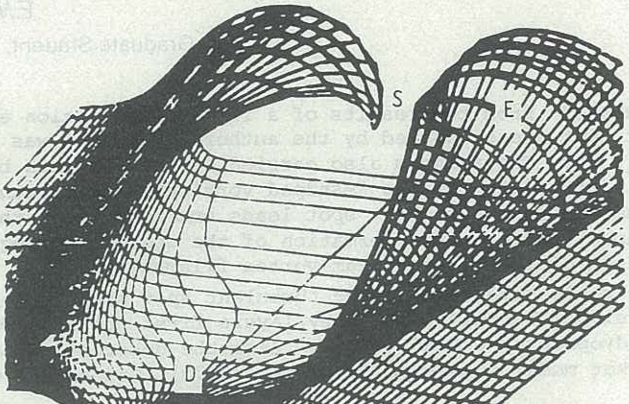


Figure 3 Computer plot of air-smoke interface. Isometric view. Distorted grid shown was originally a rectangular grid drawn on the smoke interface. S, slit; D, depression, E, elevated smoke.

2.2 Turbulent Spots

The trip wire in the tunnel was removed and a turbulent spot was initiated by a short pulse of air from a hole in the tunnel floor 88 cm from the layer origin. This formed a jet normal to the floor. The most striking feature of the spot was that it possessed an array of folds on the wall which were very similar to those shown in figure 1. This led the authors to suspect that a turbulent spot consists of an array of Λ-shaped voritces. In fact, using this idea one can explain five very important features of a turbulent spot, namely

1) the folds.

2) the staggered arrangement of these folds.

3) the long tapered tails which trail behind the spot.

4) the appearance of "mushrooms" after a sufficient development and

5) the characteristic heart-like shape of the spot.

Figures 4 (a-c) show schematic diagrams of the sequence of events which lead to the formation of a turbulent spot in terms of vortex filaments. The relationship of these filaments with the folds is also shown.

Consider figure 4(a). Here the jet has released a pulse and has caused the vortex filament to develop a V shape. The authors conjecture that this disturbance causes waviness in the vortex filament to propagate laterally in the spanwise direction as shown. In figure 4(b), this disturbance has been stretched and more undulations have formed in

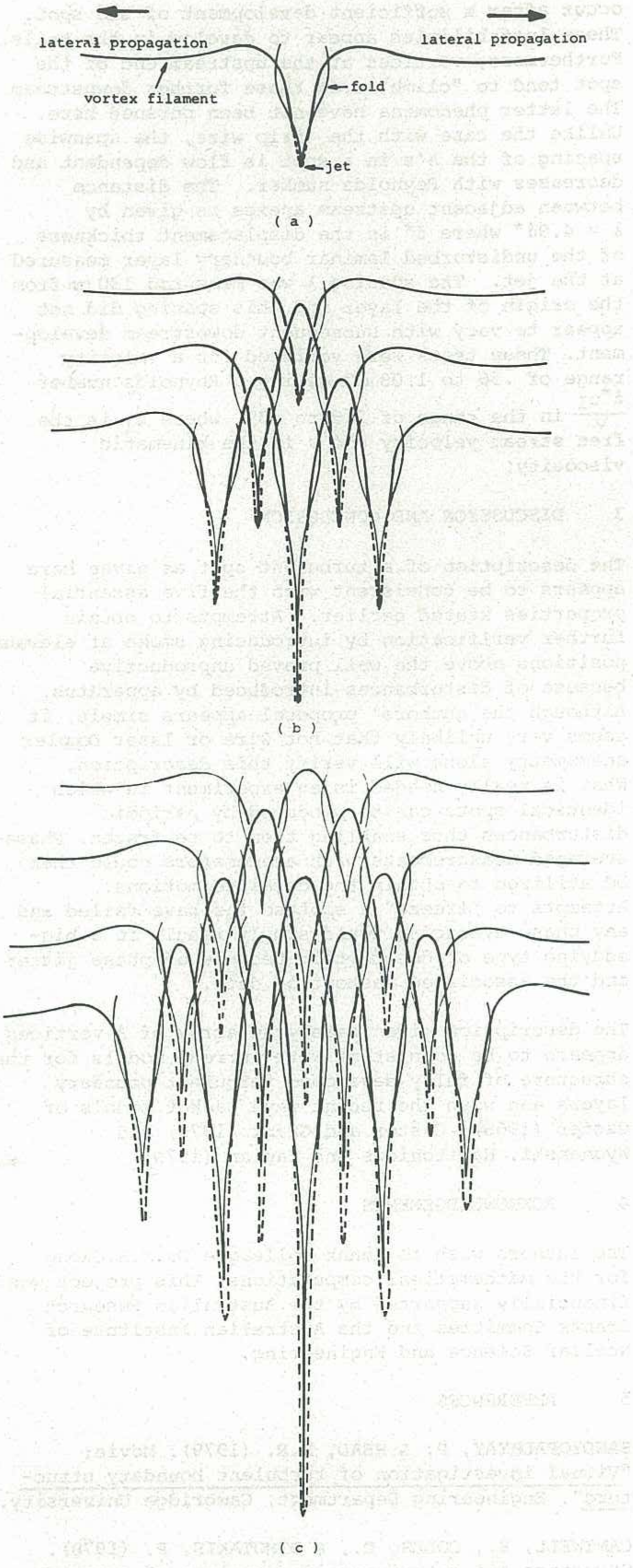


Figure 4 Schematic diagrams of the sequence of events leading to the formation of a turbulent spot in terms of vortex filaments.

(a) A jet initiated pulse caused the vortex filament to develop an undulation.

(b) The initially disturbed filament has been stretched and developed two more undulations laterally. The filament in front has started to induce disturbances in the filaments further downstream.

(c) The initially disturbed filament has developed two more undulations laterally.

the original filament. The undulations which point downstream induce a "back-flow" in velocity beneath them causing the undisturbed filament ahead (downstream) to develop waves which are distributed in the spanwise direction 180° out of phase with those upstream. In figure 4(c) the initially disturbed filament which has been stretched even more, has developed two more undulations laterally and the filament in front has started to induce in front of it disturbances in the filaments further downstream. Thus, the spot is propagating itself forward by a domino-like mechanism and is growing laterally at the same time. The characteristic heart-like shape and long tapered tails of a spot are seen in figure 4(c). Figure 5 shows diagramatially the "foot-prints" corresponding to figure 4(c). As mentioned in the discussion regarding trip-wire patterns, there is a depression downstream of each fold with the characteristic slit and these are shown shaded in figure 5.

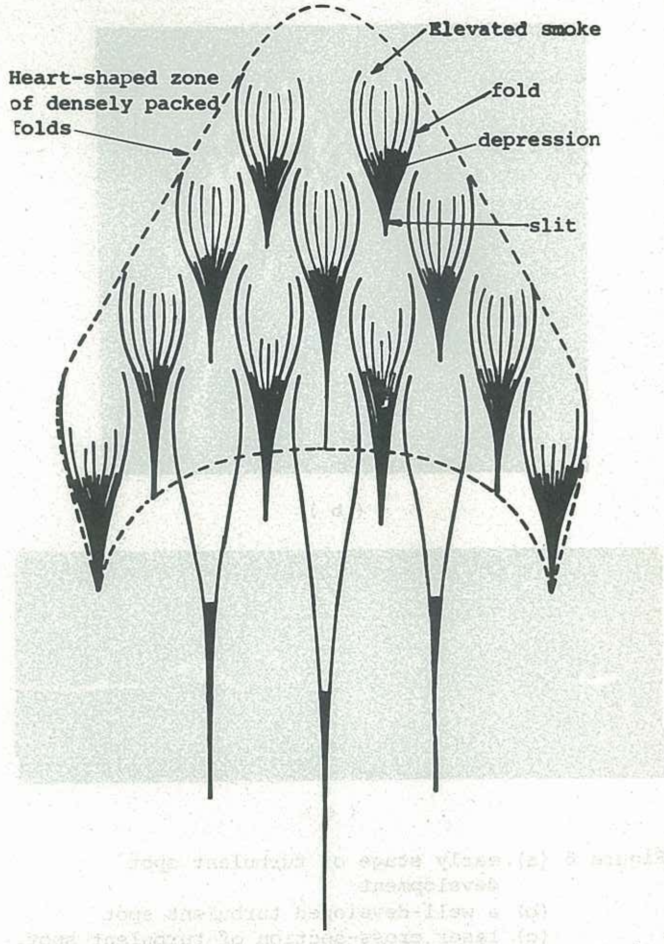
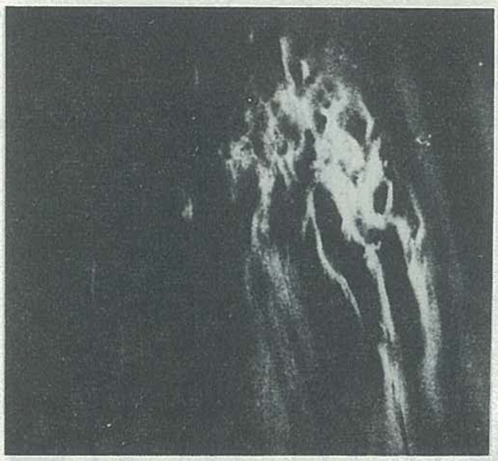


Figure 5 Arrangement of "foot prints" corresponding to the arrangement of folds in figure 4(c). The depressions, folds and slits are shown to be arranged in a checker-board fashion inside a heart-like shaped area with long tapered tails.

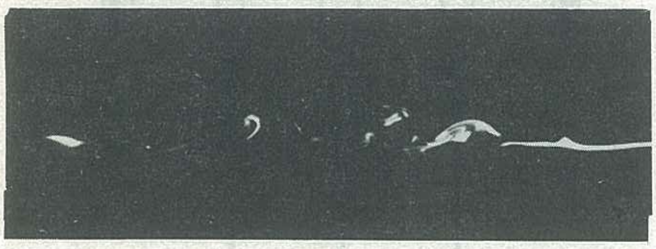
Figure 6(a) shows a typical photograph of the signatures produced in the surface of the smoke. The depressions, folds and slits can be seen and are arranged in a checker-board fashion inside a triangular or heart-like shaped area. The staggered nature of the arrangement of Λ vortices is absent behind trip wires as can be seen in figures 1 and 2.

Figure 6(b) shows a more developed spot. Here sufficient entrainment of smoke from the wall has occurred and shows up as "mushrooms". These "mushrooms" are actually quite complex because of the more intricate instabilities which occur at the apex of the Λ's as noted by Hama and Nutant (1963).

(a)



(b)



(c)

Figure 6 (a) early stage of turbulent spot development
(b) a well-developed turbulent spot
(c) laser cross-section of turbulent spot.

Figure 6 (c) shows a typical laser cross section of a turbulent spot at an early stage of development. The patterns shown in figures 4 and 5 are of course very orderly, neat and simple. The rear case is usually more messy.

As indicated in figure 5, the authors believe that the tails of the turbulent spot are nothing more than the folds at the upstream end of the spot being stretched out over long streamwise distances. The folds at the centre are stretched more than those at the sides since they had formed earlier. This causes the triangular region of densely packed folds to appear heart shaped.

The authors believe that the description given here, although simplified, gives the essential properties of a turbulent spot. However, other instabilities occur after a sufficient development of the spot. These instabilities appear to develop in the tails. Furthermore, vortices at the upstream end of the spot tend to "climb" over those further downstream. The latter phenomena have not been pursued here. Unlike the case with the trip wire, the spanwise spacing of the Λ's in a spot is flow dependent and decreases with Reynolds number. The distance between adjacent upstream apexes is given by $\lambda \simeq 4.9\delta^*$ where δ^* is the displacement thickness of the undisturbed laminar boundary layer measured at the jet. The spacing λ was measured 130 cm from the origin of the layer and this spacing did not appear to vary with subsequent downstream development. These tests were verified for a velocity range of .56 to 1.08 m/s giving a Reynolds number $\frac{\delta^* u_1}{\nu}$ in the range of 316 to 439, where u_1 is the free stream velocity and ν is the kinematic viscosity.

3 DISCUSSION AND CONCLUSION

The description of a turbulent spot as given here appears to be consistent with the five essential properties stated earlier. Attempts to obtain further verification by introducing smoke at elevated positions above the wall proved unproductive because of disturbances introduced by apparatus. Although the authors' proposal appears simple, it seems very unlikely that hot wire or laser Doppler anemometry alone will verify this description. What is really needed is an experiment in which identical spots can be produced by periodic disturbances thus enabling them to be frozen. Phase-averaged measurements with anemometers could then be utilized to obtain the detailed motions. Attempts to "freeze" a spot so far have failed and any phase averaging would simply result in a big-eddying type of description because of phase jitter and the associated washout of data.

The description given namely an array of Λ vortices appears to be consistent with current models for the structure of fully developed turbulent boundary layers and with the recent wave packet models of Gaster (1968), Gaster and Grant (1975) and Wygnanski, Haritonidis and Kaplan (1979).

4 ACKNOWLEDGEMENTS

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