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Investigations on the Closure of Laminar Separation Bubbles

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Abstract

Laminar separation was investigated experimentally on a flat plate under a strongly diffusing self-similar pressure distribution. This gave a long and thin laminar separation bubble. Boundary layer velocity traverses were performed at numerous longitudinal stations. An array of microphones was used to give instantaneous contours of pressure perturbation. Reattachment was caused by transition of the separated shear layer. Intermittency values for the flow in the reattachment region are well represented by the Narasimha intermittency distribution, supporting the use of intermittency-based predictions in calculating the closure of separation bubbles.

Introduction

Flows undergoing laminar separation, and possible reattachment, take many different forms. There are various classifications of laminar separation bubbles, an important one being the distinction between long and short bubbles [13]. Furthermore there are different candidates for the physical mechanism of the transition leading to bubble closure. Flows with incipient laminar separation will inherit the tendency to viscous instability, especially under the amplifying influence of an adverse pressure gradient and the viscous mechanisms of Tollmien-Schlichting (T-S) waves, which break down into turbulent spots. For thin laminar separation bubbles it may be anticipated that this mechanism will predominate. For thicker bubbles the inflectional influences resulting in Kelvin-Helmholtz (K-H) instability will become the more aggressive mode and this will result in transition and bubble closure. Furthermore the receptivity to external influences and by-pass mechanisms may intervene, resulting in an earlier and often relatively sudden transition. In the context of a separated flow this may result in the sudden collapse of a laminar separation bubble [5]. All of these mechanisms are, of course, strongly Reynolds number dependent so that a wide range of candidate scenarios is available.

In 1957 Narasimha [11] introduced the concept of intermittency as a basis for the phenomenological description of transition to turbulence in attached shear layers. Four decades later he suggested [12] that the intermittency approach might also be of value in predicting laminar separation bubble closure.

Under the strong adverse pressure gradients conducive to laminar separation the shape of the turbulent spot is quite far removed from the characteristic 'arrow-head' shape of the zero pressure gradient spot [2]. The universal intermittency distribution is still satisfied over the complete range of adverse pressure gradients for attached laminar flows and also over a wide range of free stream turbulence levels. Furthermore the use of intermittency has made it possible to produce transition length correlations that are robust in application for design purposes and computational fluid dynamics procedures [15].

The physical mechanism of boundary layer transition [18] varies according to the level of adverse pressure gradient sustained. Whereas under zero pressure gradient conditions the behaviour is quite stochastic, with random external influences largely determining the transition phenomenon and transition occurring in 'sets' or packets of T-S waves, under a strong adverse pressure gradient each wave participates in its own local transition process. This results in a transition region much shorter in length than under a zero pressure gradient but one which, nevertheless, is still very well represented by the universal intermittency distribution.

The broad context of this investigation was the large scale simulation of transition phenomena occurring in turbomachines, providing evidence on similarities between turbomachinery and wind tunnel flows [4]. Flows over blades are particularly dependent on the transition modes occurring on the suction surface of the blade. For Reynolds numbers below a million, characteristic of aircraft cruise conditions, laminar flow is present over a significant portion of the blade surface and the general nature of the flow is both unsteady and transitional. A triggered turbulent spot harbours an attendant calmed region [3] and the very similar interactions of blade wakes sweeping over blade boundary layers result in a very strong calmed region. This phenomenon is in use in aircraft engines to significantly reduce cost and weight.

The periodic passage of wakes from upstream blade rows also affects transition and could cause the boundary layer to undergo transition ahead of any laminar separation. Studies such as those of Halstead *et al.* [6] and Mayle [10] have documented this. In some meticulous work Hughes and Walker [8] used wavelet conditioning to identify instability phenomena in periodic transitional flows on compressor blades. In these flows the transition process was found to be mainly of the natural growth type, rather than of the bypass type.

The purpose of the present experiments was to establish a parameter space in which more than one of the routes to transition and bubble closure could be investigated. An experiment was set up in which different transition mechanisms could be compared directly. These included natural transition of a separation bubble in an undisturbed boundary layer, early natural transition resulting from a wake interaction, and by-pass transition from a different and more turbulent wake.

The work described here was limited to investigating the applicability of intermittency-based approaches to the closure of undisturbed laminar separation bubbles. The method of Solomon *et al.* [15] had predicted transition length under varying pressure gradients, based on spot formation rates and spreading angles. That model is based on intermittency to describe the transition process and thus addresses Narasimha's hypothesis concerning the application of intermittency to separated flows. Intermittency had given a robust basis for predicting the length of attached flow transition and it was a logical extension to enquire whether this approach could be extended to predict separated flow transition and bubble closure.

Experimental Arrangement

The experiments were performed in the $1.00\text{m} \times 1.15\text{m}$ working section of the University of Leicester low-speed research wind tunnel, shown in figure 1. The Reynolds number, based on the flat plate length of 2.41m, was constant at 1.4×10^6. The free stream velocity was around 9m/s and the turbulence level less than 0.2%.

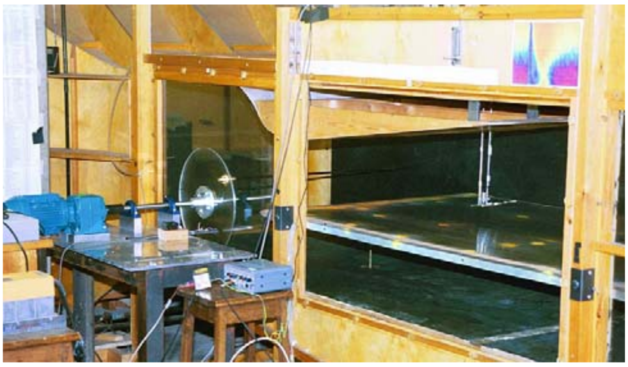

Figure 1. Flat plate installation with fairing, hot wire traverse and upstream wake generator

The top wall of the test section was contoured to provide the desired strong adverse pressure gradient with a similarity distribution having a Hartree parameter β of -0.221. This induced laminar separation in the form of a long laminar separation bubble which was sufficiently thin to barely influence the pressure distribution.

The tunnel had the capability to produce wakes generated by rotating a tapered spanwise rod upstream of the working section. The rod was cantilevered from a disc and was mounted at a radius of 270mm. The disc was rotated at 60 rpm, resulting in the introduction of two dissimilar wakes each second. The influence of these wakes is the subject of ongoing study and does not relate directly to the present work.

Hot Wire Data

Hot wire data were acquired continuously using a single wire probe mounted on a computer-controlled traverse mechanism. Centreline phase-averaged velocity traces were determined at 27 x locations along the plate and y distances up to 50mm normal to the flat plate surface. A photodiode, mounted near the wake generator, acted as a triggering mechanism for the purposes of activation of data acquisition routines, continuous signal discretization and processes such as phase averaging.

Phase averaging was performed over 128 repetitions, each record consisting of one full rotation of the wake generator producing two individual wakes. The spacing between these was sufficient that large portions of data were generated under steady conditions and these are reported in the current work as time-averaged data.

Microphone Data

Using a single hot wire it is not possible to track individual instabilities as they convect downstream. In most of this and the previous work a combination of individual traces, phase averaging and time averaging has been used. It was, however, found useful to instal an array of microphones to investigate the time dependent features of the undisturbed boundary layer and its separation bubble. These were mounted internal to the flat plate, as shown in figure 2.

The microphones were dynamically calibrated and a blind microphone was used for vibration compensation. Individual voltage traces have been acquired and a typical record is shown in figure 3. This covers x values from 0.675m to 0.850m in steps of 0.025m. The disturbances are depicted in contour form over a broader streamwise range in the $x \sim t$ diagram of figure 4.

The most prominent feature is the clear detection of developing instabilities through the transition region. The fundamental frequency was found to be 91Hz and the traces, which have been amplified by the adverse pressure gradient, are clearly strongest at transition inception and through transition. Once the coherence is lost, in a turbulent layer, the amplitude is diminished.

Walker [17] produced an equation that has allowed the prediction of the most likely T-S frequencies:

$$\frac{\omega \upsilon}{U_\infty^2} = 3.2 \mathrm{Re}_{\delta^*}^{-1.5} \qquad (1)$$

Estimated values using this approach closely match the measured frequencies for instability occurrence observed in the data. The 91Hz frequency corresponds to an x of 0.325m and it is hypothesized that this is the location of inception of the instabilities. Figure 4, along with the finer resolution data of figure 3, should relate quite directly to the Walker model of breakdown [17]. Although it does provide evidence that each T-S wave participates in its own breakdown process there is also some randomness in the inception location. The evidence tends to broadly confirm the Walker model, but with a degree of scatter. The data of figures 3 and 4 have also produced valuable information on the propagation rates of the T-S disturbances and these will be the subject of a future report.

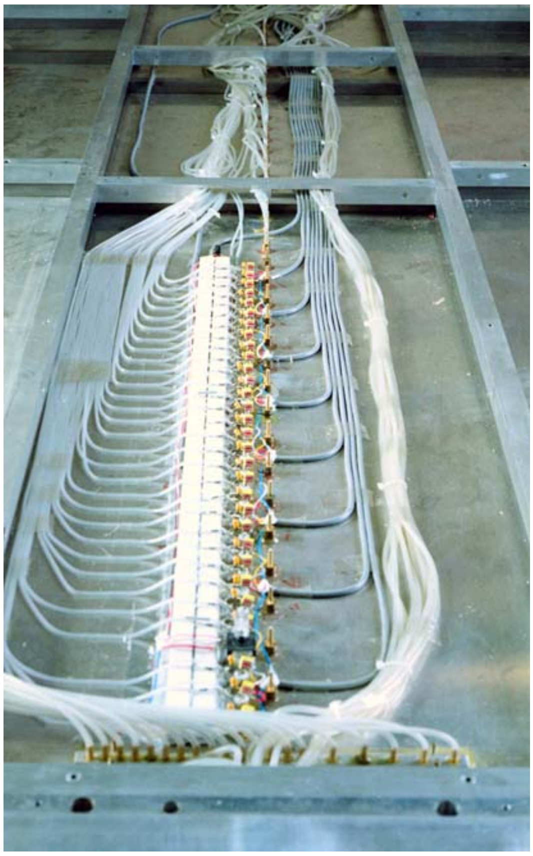

Figure 2. Microphone installation inside flat plate.

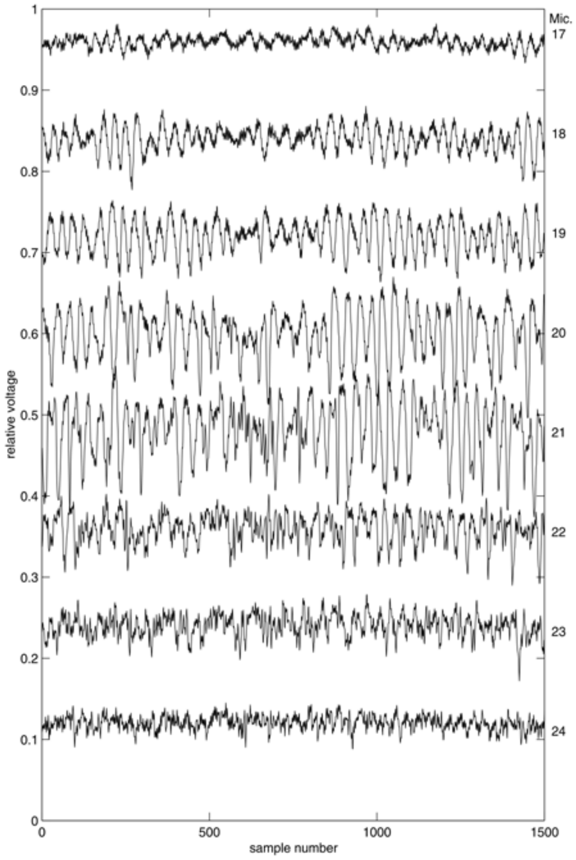

Figure 3. Simultaneous microphone voltage traces for streamwise locations x = 675-850mm.

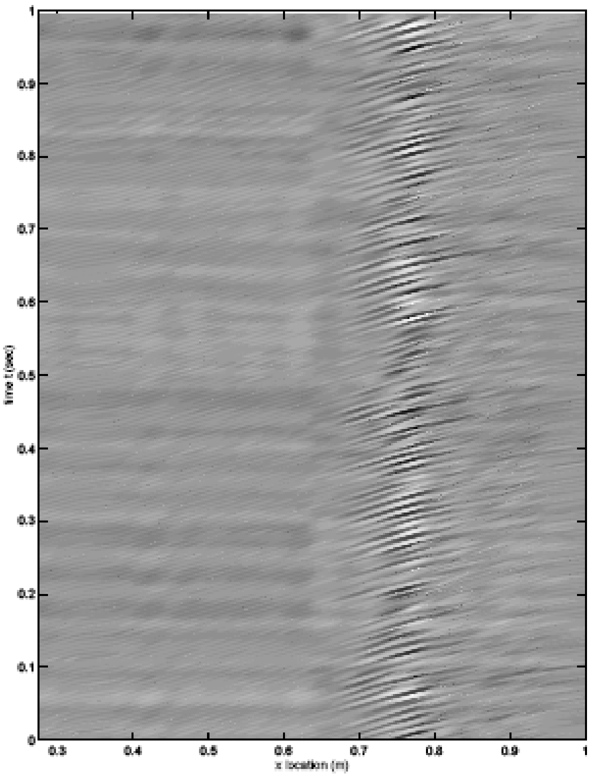

Figure 4. Microphone amplitude contour plot.

Intermittency

In earlier work on intermittency detection in transition and turbulent spots the TERA routine of Falco and Grendrich [1], based on $(u \times \partial u/\partial t)$ as a discriminant, has proved to be versatile and robust. However in the present investigation it failed to accurately discriminate the calmed region following each turbulent patch. This is due to the high velocities with steep gradients that exist at the beginning of the particularly strong calmed regions following a wake before they rapidly subside towards their undisturbed values. Accordingly, for these experiments on wakes, with particularly strong velocity gradients in stable flows, the temporal velocity gradient alone, $(\partial u/\partial t)$, was used to promote detection of high gradients only. The calmed region itself has a high gradient, but very little velocity fluctuation; a high pass filter was therefore applied to the data, retaining the high frequency content of the turbulent regions whilst reducing the aggressive gradient inherent in the relaxation process. A moving average smoothing with an eight-sample window was introduced to improve the continuity of the detected regions. Calibration was performed by visual selection of turbulent regions from velocity traces to derive the correct threshold.

In order to establish an appropriate y value for sampling intermittency the variation of intermittency with height was determined (figure 5). Although a constant value of y/δ would have been preferred, in practice it was determined that a constant y of 2mm would well represent the peak intermittency for a wide streamwise extent.

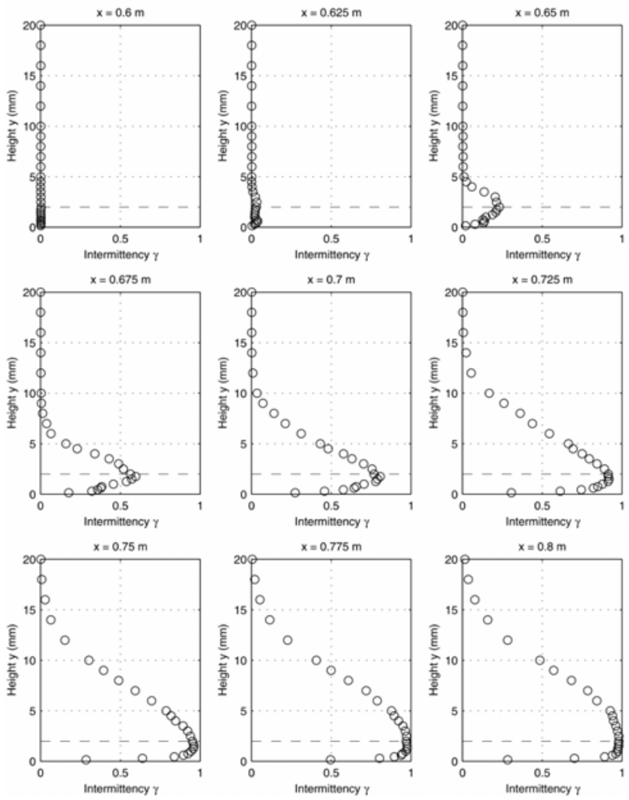

Figure 5. Time-averaged intermittency profiles for y = 2mm and increasing streamwise locations.

The Narasimha [11] universal intermittency distribution has proved to be a robust basis for predicting transition. Figure 6 shows the time-averaged intermittency for the undisturbed transition region. The test data show good agreement with Narasimha's intermittency (γ) distribution:

$$\gamma = 1 - \exp(-0.412\xi^2)\,, \qquad (2)$$

where $\xi = (x - x_t)/\lambda$

The value for x_t is determined from the values of intermittency plotted as

$$F(\gamma) = [-\ln(1-\gamma)]^{0.5} \qquad (3)$$

against x and equating the left hand side of a straight line fit to zero to find the x axis intercept. λ is the distance between the x locations for $\gamma = 0.25$ and $\gamma = 0.75$.

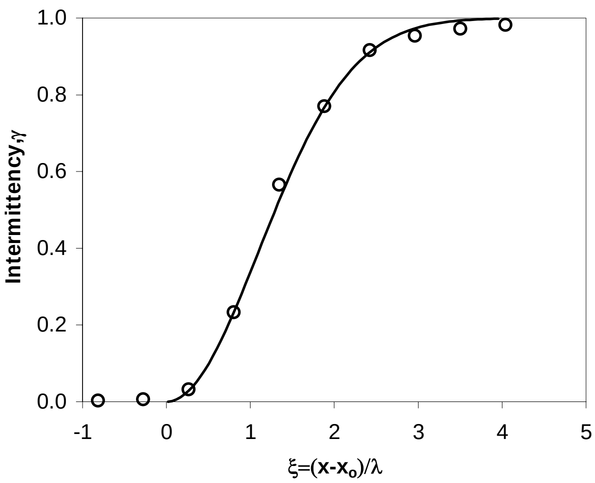

Figure 6. Time-averaged intermittency distribution for the reattachment region at y = 2mm.

This finding confirms the earlier findings of Malkiel and Mayle [9] and of Volino and Hultgren [16], who also observed agreement with the universal intermittency distribution in the reattachment region of a laminar separation bubble. It also justifies the extension of intermittency-based transition region prediction procedures such as those of Solomon *et al.* [4] to flows having laminar separation bubbles. Good examples of such a practice are given in the work of Sanz and Platzer [14] and Hobson and Weber [7].

Conclusions

The adverse pressure gradient causes strong amplification of instabilities detected far upstream of the separation point. Driven at a particular frequency, matching those of the predicted T-S waves, these instabilities grow into turbulent spots that develop in the shear layer of the separation bubble. This ultimately progresses into fully three-dimensional turbulence. The traces indicate that the undisturbed flow experiences a natural transition. At this low free-stream turbulence level, transition inception is predicted best by stability methods developed for natural growth transition.

The universal intermittency distribution for predicting the development of transition in a boundary layer has proven to accurately represent the transition process closing a laminar separation bubble. This relationship provides support for the use of intermittency-based predictive routines, such as the approach of Solomon *et al.* [15] even in flows involving separation bubbles.

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