Closure of a laminar separation bubble by natural and wake-induced transition

Thesis submitted for the degree of
Doctor of Philosophy
at the University of Leicester

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September 2004
Abstract

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Experiments have been conducted relating to the interaction of imposed freestream wakes upon a flat plate laminar separation bubble under an adverse pressure gradient.

Controlled wakes, representative of those seen in turbomachinery environments, were used to investigate unsteadiness effects upon a separating boundary layer that undergoes natural transition in the separated shear layer under steady conditions.

The concentrated use of one-dimensional hot-wire anemometry has shown leading edge boundary layer disturbances induced under each passing wake, which grow steadily via by-pass and natural transition methods into turbulent strips that convect with the flow. These disturbances are of such strength that the separated region is resisted and effectively swept away by the passing turbulence, momentarily giving rise to a wholly attached laminar boundary layer across the entire flat plate surface.

Propagation rates have shown leading edge speeds in excess of freestream values, a combination of boundary layer destabilisation and the negative jet effect of each wake. Trailing edge values are of typically 50% freestream.

Controlling the chordwise proximity of neighbouring wakes allowed for the investigation of the effect and extent of the calmed region behind each induced turbulent strip. Measurements have shown that although there is no slowing of the advancing turbulence by the calmed flow, a strong suppression of velocity fluctuations is seen, related to the proximity of the turbulent strips. Turbulence level reductions of up to 40% have been demonstrated as wake spacing is reduced.

The use of microphones to measure surface pressure fluctuations revealed the amplification of instabilities in the separated shear layer. These have been shown to be viscous Tollmien-Schlichting vortices, originating from fluctuations in the attached laminar boundary layer, and are responsible for the natural development of turbulent flow between wakes.
Acknowledgements

The greatest appreciation belongs to my supervisor, Prof. J. P. Gostelow, who’s tireless support and unwavering confidence in my abilities has been an invaluable motivation.

Of course, the work performed throughout the three years at the University of Leicester could never have been achieved without the efforts of each and every person involved. I was fortunate to have Dr. Alberto D’Ovidio as my co-supervisor during my first year, who has remained a good friend throughout.

Recognition of his valuable experience and sound judgement earns Mr. Paul Williams my gratitude, not only for his expert knowledge of the Department of Engineering’s large scale wind tunnel and advice on microphones, but also for his support and the friendly conversations.

Both Ian and Barry from the workshop receive my appreciation for their efforts to see the construction work performed on time, and their controlled temperance during those many arduous moments.

An appreciation of the efforts of my colleague John Starkey cannot go unrecognised, for his help designing and building everything electronic was invaluable.

Also, one can never forget the need to relax and unwind away from the office, for which I am entirely indebted to all my friends and colleagues; including Steve, Kwok, Hannah, John T. & Josie, Saikat (USA), Anita, Liz & Rich, Rod & Anna for the many missed Friday afternoons, and to Mark, Jon A., Paul and Andrew for the daily ‘coffee-break’ conversations that mean so much.

A huge thank you must go out to my partner Michelle for ‘Don’t Dwell, Focus!’, plus her endless support and unwavering faith in my ability to complete the work, and also to my parents for their support — literal and financial — throughout the many ups and downs of this research.

Additionally, this page would end incomplete without an acknowledgement to Prof. Howard Hodson for his much appreciated patience, and also Vasu, for the various enlightening discussions.
Statement of originality

This thesis is submitted for the degree of Doctor of Philosophy in the Department of Engineering at the University of Leicester.

The research reported herein was carried out, unless otherwise stated, by the author in the Thermofluids Group of the Department of Engineering at the University of Leicester, between September 2000 and September 2003 under the supervision of Prof. J. P. Gostelow.

No part of this thesis has been submitted for a degree to any other University or educational establishment.

Part of this work has been presented in the following publications:


Richard Thomas,
September 2004.
Nomenclature

Designated Symbols

- $c$ speed of sound (m/s)  
- $C_U$ Lange Durst coefficient of correction  
- $C_p$ Coefficient of pressure  
- $E$ hot-wire reading (V)  
- $f$ general frequency (Hz)  
- $f'$ (also $f''$, $f'''$) boundary layer equation derivatives  
- $f_c$ filter cutoff frequency (Hz)  
- $f_R$ resonant frequency (Hz)  
- $H$ shape factor  
- $L_T$ length of transition region, $L_T = x_T - x_t$ (m)  
- $p$ local static pressure (Pa)  
- $P_o$ working section total pressure (Pa)  
- $Re_x$ Reynolds number based on chord distance  
- $St$ Strouhal number  
- $t$ time (s)  
- $T$ temperature (°C)  
- $T_w$ hot-wire element temperature (°C)  
- $T_h$ intermittency threshold value (0.110)  
- $Tu$ turbulence intensity (%)  
- $u$ streamwise velocity component $(x, y, t)$ (m/s)  
- $U_{∞}$ local freestream velocity (m/s)  
- $U_T$ skin friction velocity (m/s)  
- $U^+$ normalised velocity $\bar{u}/U_T$  
- $x$ chordwise/downstream coordinate (m)  
- $x_r$ reattachment location (m)  
- $x_s$ separation location (m)  
- $x_t$ transition onset location (m)  
- $x_T$ transition completion location (m)  
- $y$ perpendicular coordinate (m)
\( Y^+ \) normalised perpendicular distance \( yU_\tau/\nu \) page 41
\( \alpha \) secondary rod displacement, polar coordinates (rad) page 32
\( \beta \) Falkner-Skan pressure gradient parameter page 77
\( \gamma \) intermittency parameter
\( \delta \) boundary layer height
\( \delta^* \) displacement thickness
\( \Delta E \) hot-wire aging compensation
\( \eta \) non-dimensional similarity variable page 77
\( \theta \) momentum thickness
\( \kappa \) relaxation parameter page 55
\( \xi = (x - x_t)/\lambda \) Narasimha non-dimensional distance page 54
\( \rho \) density (kg/m\(^3\))
\( \tau_w \) surface/wall shear stress (N/m\(^2\))
\( \lambda \) Narasimha transition length/Thwaites parameter.
\( \nu \) kinematic viscosity (m\(^2\)s\(^{-1}\))
\( \psi \) non-dimensional strip separation page 162
\( \omega \) wake generator rotational speed (rad/s) page 32

**Superscripts**

\( \cdot \) Root-Mean-Square
\( C \) beginning of calmed region
\( E \) end of calmed region
\( W \) beginning of turbulent strip

**Subscripts**

\( a \) ambient (temperature, pressure etc.)
\( c \) value at time of calibration
\( P \) primary rod
\( S \) secondary rod
\( t \) start of transition
\( T \) end of transition
Special Symbols

- \( \overline{\text{overbar}} \) time-averaged value
- \( \langle \rangle \) ensemble-averaged value
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Chapter 1

Introduction

1.1 Aims and objectives

It is always in the interests of an aerodynamicist to be able to understand and predict the behaviour of conceptual aerofoil designs as accurately as possible before the commissioning of expensive prototype tests. Successful estimation of the performance requires an understanding of the unsteady flow characteristics and their implementation within axial multi-stage engines.

Research into the complexities of boundary layer flow has always been, and shall be for a good many years, a constantly progressing field of study. In more recent decades, the focus of much research has migrated towards the importance of understanding unsteady, or time-varying, flows. One of the most important is the propagation of turbulent wakes from the trailing edges of upstream blade-rows. Much inaccuracy in past and current predictive methods can be attributed to a neglect of these aspects inherent in all multistage turbomachines.
1.2 The importance of understanding wake interaction

As stated by Cumpsty (1989), "It is a common factor with all compressors that when several stages are used together in series there is a serious problem of matching the stages so that the outlet flow from one stage is acceptable to the next." Although perhaps referring strictly to flow angles and other steady properties, this statement demonstrates the difficulties inherent to the design of precision axial turbomachines, and clearly the increasingly significant problem of understanding the interaction between trailing edge wake flows and succeeding blade boundary layers is yet to be fully clarified.

Briefly, it is currently known that interacting wakes promote the development of turbulent spots, or patches, in the boundary layer. These patches can develop into regions of local turbulence that have the effect of precipitating transition at a location upstream of, and thereby preventing, separation. Or they may develop in the separated shear layer in the form of vortices that grow to influence existing transition regions. A zone of highly stable flow may trail the travelling turbulence, a phenomenon known as the calmed region, temporarily preventing the reinstatement of the naturally turbulent surface boundary layer.

It is these complex behaviours that present difficulties for an aerodynamicist. Steady state predictions are entirely inadequate, and a definitive understanding of the time-varying properties is yet to be developed.

Gostelow (1984, pg. 196) states that a prime objective of controlling boundary layer flow is to delay separation in order to achieve high loading, which can be momentarily achieved via early surface transition from the interaction of upstream wakes. Armed with a knowledge of highly unsteady boundary layer behaviour, an aerodynamicist may be able to improve the performance of their designs by beneficially manipulating these propagating wakes. The forced onset of transition before the steady state separation point can prevent the development of a bubble. Intelligent application of successive wakes can therefore lead to the continual avoidance of separation from the perpetual precipitation of transition.
In axial compressors, wake interactions are seen to increase the flow incidence and local velocity, tending to cause a greater risk of separation and stall. Compared with turbine stages, compressors usually have a lower operating mass flow range (a smaller range between stall and choke), therefore it is all the more vital to understand the effects of these unsteady influences.

Walker (2003) expresses the importance of balancing the proportions of a boundary layer that are laminar and turbulent to gain the optimum lift to drag ratio. The unsteadiness associated with wakes keeps the aerofoil boundary layer in a state of flux, with a cyclic period equal to that of the shed wakes, a condition known as multi-mode transition. This has strong effects on these proportions of laminar to turbulent surface flow, and hence the lift to drag ratio.

As part of a larger research program investigating the details of boundary layer flows, the author's contributions provide information on the effects of impinging wakes upon transition across a laminar separation bubble.

Using large-scale low-speed wind tunnel experimentation, investigations were performed on a flat plate with an imposed adverse pressure gradient designed to induce laminar separation. Transition development in the separated shear layer, followed by turbulent flow reattachment, produces a region of recirculation — a laminar separation bubble. Both individual and paired wakes were introduced to the upstream flow to investigate the effects upon the boundary layer, and also upon one another when closely distributed.

The present work has been performed with the hope of elucidating and perhaps even quantifying the influences and behaviours of both impinging wakes and the becalmed region.

1.3 Thesis plan

A review of published research achievements to-date is reported in Chapter 2, including a brief description of compressor and turbine flows, current understanding of unsteady inflows, a summary of the latest computational schemes and a brief analysis of the experimental unsteady wake flows used in
this research and the fidelity of the wakes to those typical of turbomachinery.

An in-depth description of the experimental aspects of the work, plus the analytical and statistical techniques adopted, is reported in Chapter 3.

Chapter 4 covers the standard preliminary details of the steady boundary layer without wake impingement, including the global flow condition and studies of the developing transition region and separation bubble.

Chapters 5 and 6 group the results into two categories having progressive levels of wake impingement. The first reports the effects of isolated wakes directed into the flow to gain knowledge of their individual contributions; the second describes the different effects when multiple wakes are juxtaposed.

The final chapter finishes the thesis with an account of the conclusions drawn throughout the duration of the research, plus a summary of recommended future work as a continuation of the current.
Chapter 2

Theory on Separated Flow
Transition

2.1 Boundary layers in turbomachinery

A turbulent boundary layer has a natural resistance against flow separation, and is therefore the ideal design condition for the optimal performance of a compressor suction surface as this allows the flow to decelerate without suffering major separation (Cumpsty 1989, pg. 176). However, under design operating conditions, such as cruise, where the Reynolds number and freestream turbulence levels are at their lowest, laminar flow can dominate the first part of the profile, transition can be delayed, separation can ensue, and the boundary layer can exhibit significant additional losses.

With the ever increasing demands by industry to create even greater pressure gradients and achieve more lift from turbomachinery blades, the risk of separated boundary layers becomes a growing threat to the overall performance. Modern profile shapes are tending to push back the suction peak to a more rearward location, creating a longer region of unstable laminar flow followed by a greater adverse pressure gradient (Hughes & Walker 2001). An extended transitional region will increase the possibility of the boundary layer succumbing to separation before a turbulent profile is established, and with the separation point further from the leading edge, less
profile surface remains in which to restore attached flow, increasing the risk of bubble bursting coupled with an increase in flow losses. This is also described by Halstead et al. (1995a).

It is therefore becoming increasingly important to understand the behaviour and response of unsteady boundary layer separation regions, to learn how to predict and control them and investigate the possible techniques available to achieve this.

2.1.1 Separation bubbles

The advent of a separation bubble is usually the result of a combination of geometry and flow-field characteristics, such as high surface curvature or a strong adverse pressure gradient, and usually results in significant changes to the flow. These changes are not always detrimental to the performance of the aerofoil, in fact a separation bubble can be evident for a large proportion of an aerofoil’s working life. Small leading edge separation bubbles are sometimes encouraged in order to trip turbulent boundary layers ahead of the potential separation point. More resistant to separation, the turbulent profile then remains attached throughout diffusion.

However, under the more extreme operating conditions, separation can have a catastrophic effect. For the lowest Reynolds number flows laminar separation can fail to reattach before the trailing edge of the surface, and dramatic increases in the losses are seen as the flow mixes out into the wake (Lou & Hourmouziadis 2000). This bubble bursting effect can lead to stage failure.

Rhoden (1952) reported the strong losses evident under low operating Reynolds numbers due to the development of a separation bubble on the suction surface of a C4 blade profile in cascade. For the lowest Reynolds number case ($\text{Re}_x = 0.3 \times 10^5$) separation without reattachment caused heavy increases in blade performance loss and exit flow deviation. Other factors include a deficit to the stall margin and pressure rise capabilities of the aerofoil (Halstead et al. 1995a). This adds weight to the need for better understanding of separated flow behaviour.
Empirical separation bubble models

On the ability to predict laminar separation bubbles and the transition onset location, van Ingen (1974) presented additions to work by Chang (1970), Young (1966) and Gaster (1966). Expanding principally on the laminar boundary layer profile predictions of Thwaites (1949), van Ingen included a variation to the chordwise velocity gradient parameter that accounted for adverse pressure gradient effects to improve the ability to calculate a separation point. Although requiring a constant to be determined from the particular experimental arrangement, new predictions showed a remarkable improvement over existing models for determining separation and reattachment loci. The ability to predict transition in the bubble for ‘quiet’ flows was also remarked upon.

2.2 Transition

Transition has long been established as the process of flow development from laminar to turbulent. This process can manifest itself in a variety of ways, but ultimately concludes as a coalescence of numerous turbulent spots into fully turbulent flow.

Natural transition, described in §2.2.2 has undoubtedly been the subject of countless investigations, and has more recently been recognised as a significant player in the role of transition within turbomachines (Dong & Cumpsty 1990b, Solomon & Walker 1995 and Hughes et al. 1999). Previous concepts argued that typical compressor freestream turbulence levels were too great to allow the development of the small Tollmien-Schlichting instabilities required for natural transition. This was partly because the low amplitude T-S waves were difficult to detect in the disturbed turbomachinery environment, and so attention was focused on ‘by-pass’ transition methods. However, natural transition mechanisms have been seen to dominate, at low Reynolds cruise conditions, between the wake-induced transition zones as part of the ‘multi-mode’ transition mechanism identified by Mayle (1992), described later.
More recent flow predictions by Solomon et al. (1999) suggested that the natural transition process is more dominant than bypass transition methods in strongly decelerating axial compressor flows, and research from Hughes & Walker (2001) presents the undeniable existence of developing instabilities on the surface of a compressor blade, going so far as to controversially conclude no that evidence was seen for any by-pass mode of transition.

This concept of natural transition is discussed in more detail throughout this report as it has strong connections with the types of transition seen in the results.

### 2.2.1 Freestream turbulence

It was once accepted that beyond a critical freestream turbulence level, $T_u_{\text{crit}} \approx 2.5\%$, separation bubbles were prevented from appearing due to turbulent boundary layers developing from, or close to, the leading edge (Shepherd 1956 and Cumptsy 1989). This hypothesis was desirable in the sense that it allowed designers to simplify their predictive models to use the assumption that turbulent boundary layers predominated throughout the flow.

However, experiments by Boiko et al. (1994) have identified boundary layer instabilities capable of existing in turbomachinery flows with freestream turbulence levels as high as $T_u = 1.5\%$, representative of those encountered in axial gas turbines.

Indeed it is certainly the case that high levels of freestream turbulence can induce early transition and hence help to prevent the separation of the boundary layer, but with the recent identification of natural transition behaviour between wake-induced transition regions it is important that these mechanisms, and the switching between the differing modes, are fully understood.

### 2.2.2 Natural transition

Natural transition can be identified as a progress of events categorised as follows:
• **Instabilities.** The growth of small Tollmien-Schlichting instabilities in the early laminar boundary layer.

• **Vortices.** Development of the 3-Dimensionality of the instabilities into vortical structures including vortex loops.

• **Spots.** A breakdown of the vortical structures to create islands of turbulence known as ‘spots’.

• **Transition.** A region in which the spots grow and merge to ultimately form a continuous fully three-dimensional turbulent boundary layer.

**Turbulent spots**

The growth of small instabilities in the freestream flow, detectable as a wave-like motion periodic in both space and time, heralds the eventual onset of transition in the boundary layer flow. A particular narrow band of frequencies undergo the strongest amplification and growth to develop into turbulent spots. Much interest has been focused onto the behaviour of turbulent spots and their role in the development of transition, both in attached and separated boundary layers (Gostelow & Blunden 1992, Shaikh 1997, Westin et al. 1998a, D'Ovidio 2001a).

The breakdown of the laminar instabilities initiates turbulent spots which are small regions, or ‘islands’, of turbulent flow. In zero pressure gradient flows these spots tend to develop in groups distributed in a spanwise direction at a particular chordwise location, as shown in Figure (2.1a), known as the ‘transition onset location’, \( x_t \). Spots developing at this location are not necessarily created with such periodic predictability, but more likely behave with a degree of randomness (Walker 1989). Flow regions unoccupied by any turbulence remain laminar whilst the surrounding turbulent spots grow and encroach upon them until no laminar regions remain. At this point, where the flow is entirely turbulent in the spanwise direction, no more laminar flow exists and transition is complete. This latter point marks the ‘end of transition’, \( x_T \), the distance between these two locations representing the ‘transition length’, \( L_T = x_T - x_t \).
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However, with an increasing adverse pressure gradient, the laminar regions between sets of turbulent spots diminish until the spots are no longer seen to develop in periodic groups but rather continuously in time across the transition onset location, \( x_t \), as shown progressively in Figures (2.1b-c). As a result, the location of the point at which the spots are fully merged and no more laminar flow exists, \( x_T \), is precipitated sharply to the effect of reducing the transition length, \( L_T \).

This behaviour was seen by Knapp & Roache (1968) in their experiments on an ogive nose cylinder under varying pressure gradients, and was adopted by Walker (1989) in his derivation of a minimum transition length model which compared well to experimental transition length data published by Dhawan & Narasimha (1958). Of course, Walker’s minimum transition length model underestimates the true transition length, especially for flows under zero pressure gradient, but forms the basis for the derivation of a more general correlation as later published in Solomon et al. (1996b).

Of course, unlike Figures (2.1a-c), the spots do not necessarily develop with an equal time distribution, whether in sets or continuously, but may develop at slightly more unpredictable, or random, temporal locations. This idea is represented in Figure (2.1d), based upon Figure 4 of Pfeil et al. (1983), where it can be seen that the time periods between the onset of each spot are non-constant.

**Pressure gradient effects**

Early work, including that of Schubauer & Klebanoff (1955) and Gutmark & Blackwelder (1987), provided excellent details of zero pressure gradient turbulent spot generation, typical shape, growth rates, entrainment properties and proximity behaviour. These well established rules for turbulent spots were then challenged with regard to those generated in adverse pressure gradients, as experienced in the rearward diffusion section of a compressor blade suction surface. Gostelow (1993) performed hot-wire investigations for artificially generated turbulent spots in a moderate adverse pressure gradient and found strong variations from traditionally understood spot formation and behaviours.
The spots tended to spread more span-wise in response to the decelerating freestream velocity, therefore exhibiting lower celerity rates, and hence creating a spreading angle of up to 60°, much larger than the norm of 20°. The resultant shape was far from the typical arrow-head formation, showing a more complex and non-uniform structure. Subsequent works by Gostelow et al. (1995) presented greater detail with a review of spot celerities and spreading angles for various pressure gradients.

Propagation rates

Further to the work of Gostelow, D'Ovidio et al. (2001a-b) performed experiments on spots generated in adverse pressure gradients. It was found that the propagation rates for the instabilities were significantly lower and followed an exponential decline in proportion to an increasing adverse pressure gradient, with the spots alternatively growing in a spanwise direction. The existing inclusion angle equation represented the new data well, and a modified equation for the spot propagation parameter was presented that more accurately represented the effects of a changing pressure gradient.

Gutmark & Blackwelder (1987) performed experiments to investigate the interactive effects of pairs of artificially generated turbulent spots, briefly discussing the effects of two juxtaposed spots, and the effect of the trailing calmed region on their propagation rates. It was seen that those spots in the calmed regions of downstream spots had reduced propagation rates by as much as 20% when the second spot leading edge was closer than a spots length to the initial spot (i.e. well within the calmed region). Possible connotations of this could be that arrays of turbulent spots existing in the transitional region can begin to interact and effectively retard their own leading edge propagation rates by encroaching upon downstream spots. This could ultimately lead to a delay in their coalescence into fully developed turbulent flow.
2.2.3 By-pass transition

So called due the mechanics of directly transferring energy from a turbulent source, such as high freestream turbulence levels or a passing wake, into the laminar boundary layer, this development of turbulence effectively 'bypasses' the standard natural mechanism. There is no requirement for the amplification of boundary layer instabilities or the coalescence of growing turbulent spots as these induced regions are essentially fully developed three-dimensional turbulence.

2.2.4 Separated flow transition

A reducing Reynolds number causes the boundary layer separation point to move upstream which can lead to flow separation prior to any transition, which can then occur in the separated shear layer. Two scenarios are then possible; either the separated turbulent flow reattaches, creating a laminar separation bubble, or the separated shear flow fails to reattach before the trailing edge of the aerofoil and 'bubble bursting' occurs. This latter scenario results in severe losses as the wake mixes out into the freestream flow.

Separated flow transition, one of the least understood modes of transition, was the subject of research by Stieger (2002) into measurements on the suction surface of a cascade of T106 turbine blades with impinging freestream wakes. The interaction of the wake with the separation bubble was seen to amplify existing Kelvin-Helmholtz roll-up vortices in the shear layer, which then collapsed into the wake-induced transition.

Indeed, both Tollmien-Schlichting and Kelvin-Helmholtz instabilities can exist, even simultaneously, in a separated shear layer. A long and thin type separation bubble, as in the current research, presents difficulties to the development of K-H waves as the bubble height restricts the growth of the vortices. Therefore the T-S waves can be seen to convect from the laminar attached boundary layer downstream into the separated flow, where they receive strong amplification and dominate over K-H waves to be the responsible perturbation in the development of transition.
Hatman & Wang (1998a-c) expand on the possible varieties of separated flow transition. They discuss the potential for three different modes to exist: a laminar separation short mode, a laminar separation long mode and a transitional separation mode. In the latter, transition occurs before the separation location via the amplification of T-S waves. These T-S waves may or may not exist prior to the development of K-H instabilities in the laminar separation short/long mode. In either case, K-H instabilities develop in the shear layer to a degree dependant upon the bubble conditions. For short bubbles, under a milder adverse pressure gradient, the T-S waves of the transitional separation mode are sufficient to cause reattachment of the separation bubble. However, for long separation bubbles under strong adverse pressure gradients, transition fails to reattach the shear layer.

2.2.5 Periodic unsteady transition

Also known as ‘multi-mode transition’, or less accurately ‘wake-induced’ transition.

The propagation of wakes from the trailing edge of upstream stages is a major factor in the transition modes occurring within turbomachinery. The unsteadiness associated with the passing of a wake introduces freestream velocity and turbulence intensity fluctuations. A detailed study of these changes is presented in §2.6. In the path of these wakes ‘by-pass’ transition forces the underlying boundary layer to be turbulent.

The complete picture of unsteady wake-induced turbulence embedded within a steady natural transition have been studied by many authors including Mayle (1992), but the most detailed research was perhaps performed by Halstead et al. (1995a-d). Through the comprehensive use of $s \sim t^*$ schematics used to identify the various regions of flow transition throughout a multi-mode transition blade surface, Halstead et al. meticulously cover a broad range of operating conditions and study the surface boundary layer for both compressors and turbines.

Of particular interest, a test was conducted upon a compressor stage for

*A contour plot with both a space and a time axis.*
both baseline and reduced wake frequency conditions. The baseline conditions depict the standard multi-mode transition picture of wake-induced transition under the wake paths, with following calmed regions, and natural transition between the wakes. With one upstream blade removed, the transition mode between wakes became much more complex. The time between wakes is now sufficient to see separated flow transition developing after the effect of the calmed region has weakened. This transition length is now much shorter, reattaching further from the trailing edge than the transitional region behind the calmed regions.

In the author's work, wakes are studied in both individual and juxtaposed configurations. Although acquisition is not performed downstream of the calmed region as in the research of Halstead et al., similar features are seen, including the development of separated flow between wakes when the wake passing frequency is sufficiently low.

2.2.6 Semi-empirical transition correlations

Due to the plethora of instability sources in a true turbomachinery environment, which can all influence the onset of transition and the development of turbulence, a complete understanding of transition has yet to be confirmed. For this reason many correlations have been derived relating the transition onset location and transition length to boundary layer and freestream parameters such as local boundary layer thickness Reynolds number and turbulence intensity.

The transition length is simply the distance from transition onset to transition completion, hence onset must be exclusively determined before a transition length can be estimated. Several correlations for the onset of transition have been published, and mentioned here are the most popular works.

Transition onset

Linear stability theory shows us that a laminar boundary layer is susceptible to local disturbances at a critical boundary layer thickness Reynolds number.
Correlations relating the global and local boundary layer parameters to this transition onset location are presented by Abu-Ghannam & Shaw (1980), Mayle (1991) and Walker (1993) based on turbulence level and pressure gradient.

Abu-Ghannam & Shaw found in their correlations that the pressure gradient parameter became far less significant for high freestream turbulence levels at influencing the transition onset location. Mayle (1991) argued that the correlation of Abu-Ghannam & Shaw was forced for low turbulence levels, and derived his own zero pressure gradient correlation, stating that for turbulence levels above 3% his correlation was applicable to any pressure gradient environment. However, Walker (1993) disagreed with Mayle's assumption that linear stability theory and its remaining governing parameters were not applicable to the estimation of transition length in by-pass transition modes.

Transition length

Narasimha (1985) was the first to predict transition length using statistical approaches. He developed a non-dimensional spot formation rate parameter, which he proved to be constant for zero pressure gradient environments. Later, Gostelow Blunden & Walker (1992) showed experimentally that this non-dimensional parameter is dependant upon pressure gradient and turbulence intensity, demonstrating that spot formation reduces with increasing turbulence intensity yet increases rapidly with an increasingly adverse pressure gradient. They presented a new correlation based on their findings.

Subsequently, Gostelow Melwani & Walker (1995) discovered that spot propagation velocity and spreading angle were not constant under changing pressure gradients, which had strong consequences on the minimum transition length model. They presented new correlations relating the spot spreading angle and propagation rate to pressure gradient parameter. Solomon Walker & Gostelow (1996a) used these correlations with Narasimha's concentrated breakdown hypothesis to produce new transition length correlations, which D'Ovidio, Harkins & Gostelow (2001a-b) later extended to include a greater range of adverse pressure gradient.
2.3 Calmed regions

The calmed region has been recognised for many years as a prevalent phenomenon in the trailing flow behind a convecting turbulent spot or patch. A calmed region exists primarily due to the contrast in propagation rates between turbulent flow and laminar instabilities. The trailing edge of an entraining turbulent spot travels at a greater rate than the head of a developing laminar instability, and hence the expanding clearance created between the retreating features remains void of any turbulent activity. The flow here is stable and very much laminar in nature, yet retains the resistance to flow separation exhibited by its turbulent parentage.

Other works that exhibit the calmed region and its defiance towards turbulent flow include Halstead et al. (1995a) who describe the calmed region as 'effective in suppressing flow separation and delaying transition in the non-wake path'.

Works by D'Ovidio et al. (2001a, b) presented information on the restraining influence on local boundary layer instabilities presented by these calmed regions, and their contribution to the boundary layer properties upon passing a laminar separation bubble. Using the boundary layer shape factor parameter $H$ as the visual format, strong calming effects were seen to suppress the bubble and transition regions to a more laminar-like flow for a length of time comparable with that of the passing turbulent spot, before sharply returning to their natural steady state.

2.4 Unsteady inflow

For a true understanding of turbomachinery blade surface boundary layers one must certainly advance beyond steady time-averaged measurements and models into the realm of unsteady time-dependency. Only here can the full picture of a boundary layer's behaviour be studied and comprehended.

In cascaded simulations of turbomachines, upstream stages are modelled using a range of techniques, but the most popular and successful is the passing of bars across the blade span. Using bars or rods to simulate wakes from
upstream blades is a technique devised as far back as the late 1960's. W. H. Gibson (see Dzung 1970) performed pioneering experiments investigating the variation of cascade performance loss with rod passing frequency.

2.4.1 Unsteadiness sources

Time variation of the boundary layer does not necessarily have to come from outside influences such as incoming wakes or a turbulent freestream. Separation bubbles are themselves inherently unsteady. The separation and reattachment locations of a separation bubble are not a constant and usually oscillate about a mean separation point. These fluctuations in time are the result of the developing instabilities in the boundary layer and free shear layer.

However, the strongest causes for unsteadiness in true turbomachinery environments are inarguably the passing of freestream wakes from upstream stages. Strong boundary layer influences are created by these highly turbulent events, including the precipitation of the transition point to a location far upstream of that of the steady state. Notably, strong calmed regions develop in the trail of each wake induced transitional and turbulent path, a feature resistant to flow separation and the development of further transition. All these issues affect the overall performance of a blade’s boundary layer and need to be fully investigated to understand the bigger picture of how turbomachines behave in unsteady environments.

2.5 Computational Fluid Dynamics (CFD)

This short section summarises the capabilities of current CFD codes as reported in recent publications, and outlines briefly those areas showing the greatest promise for generating commercially reliable transition region predictions.
The challenge

Undoubtedly one of the biggest obstacles facing the field of CFD lies with the true physical simulation of the mechanics involved in the process of boundary layer transition. Historically, CFD engineers have avoided the complex task of correctly predicting aerofoil transition and instead resorted to experimental results and other semi-empirical correlations to determine a transition location appropriate for the specific model. Although fairly reliable for the more common scenarios, these techniques proved less accurate under the more extreme environments of today's modern blade profiles.

2.5.1 The Navier-Stokes equations

Deficiencies in the accurate understanding and ability to predict the physics behind complex unsteady boundary layer transition are the result of an inherent difficulty in solving the Navier-Stokes equations, for which many methods have been proposed. RANS codes (Reynolds-Averaging Navier-Stokes) are one of many approaches to solve the Navier-Stokes equations by modification to a time-average solution. These techniques also require closure modelling to determine the time-dependant features lost in the time averaged solution, for which there are also many approaches (Cant 2002).

Large-Eddy Simulation (LES)

An emerging technique known as Large-Eddy Simulation (LES) has earned more attention in recent years due to the availability of ever-growing computational power. Continuous efforts to improve the technique have developed LES into an impressive approach to solving large-scale flow features. Advantages over RANS are the inherent ability to time resolve the larger features, with a closure model again used to represent the lost small-scale features.

Direct Numerical Simulation (DNS)

A widely respected technique is that of Direct Numerical Simulation (DNS), which implements an explicit solution of the Navier-Stokes equations, sim-
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Calculating without models all features of physical flow. The influence of DNS solutions has had a tremendous impact in the development of CFD, using the highly resolved data to calibrate existing turbulence models and help understand established flow phenomena (Cant 2002).

However, this ultimate manifestation of CFD comes with the heavy price of requiring the most powerful of high-performance computing (HPC), and is restricted to limited geometries and flow complexities due to the immense computational time required for solution convergence. Modern achievements in DNS are consistently bounded by the limitations of existing HPC, and shall be for many years to come. Consequently, DNS solutions to large geometries and complex scenarios are unlikely to be seen in the near future.

2.5.2 Separation

Many works have been published on the numerical simulation of separation bubbles, with each differing approach helping to determine various characteristics, from the ability to influence flow separation and separated shear layer transition, to the study of laminar boundary layer instabilities using DNS.

As an example, the studies of Papanicolaou & Rodi (1997) used a hybrid of the popular $k-\varepsilon$ technique combined with a Norris-Reynolds one-equation model to solve geometries of a leading edge separation bubble and a backward facing step. By incorporating an expanded version of the intermittency model of Chen & Tyson (1971) and using some experimental measurements for correlation purposes, predictions of separation and transition regions compared well with the corresponding experimentation.

Suzen et al. (2001) adopt an intermittency transport method to determine intermittency levels throughout the boundary layer and generate an estimate for the subsequent separated transition inception point for low-pressure turbines. Validation of the code was against the experiments of Hultgren & Volino (2000), and proved to be considerably successful, generating realistic stream-wise and cross-wise intermittency profile variations, with good predictions for the separation point and transition inception lo-
Yang & Voke (2001) performed LES computations for a flat plate with a semi-circular leading edge having a separation bubble. Comparisons with experimental data are presented and the results are relatively good, showing the development of Kelvin-Helmholtz instabilities in the shear layer, then breakdown three-dimensionally due to spanwise fluctuations, creating reattachment via the development of turbulence. It is also noted that the 'instantaneous reattachment' location varies by up to 50% of the reattachment length due to the shear layer vortex shedding, highlighting the inherent unsteadiness of separated flows.

Early DNS works by Spalart & Coleman (1997) demonstrated that, although under-developed, DNS had the potential to reveal interesting facts about the flow features, however limited computer resources at the time restricted their performance to low Reynolds number and hence small bubble sizes. Three years later, and with greater computing resources, Spalart & Strelets (2000) simulated flat-plate surface flow deceleration and achieved a laminar separation bubble with turbulent reattachment using pure DNS methods. Analysis of the transition region revealed the development of Kelvin-Helmholtz vortices after a 'wavering' of the shear layer, caused by the amplification of the upstream instabilities. The background turbulence levels were kept below 0.1% to prevent by-pass transition and ensure naturally developing transition mechanisms in the boundary layer. In contrast, Alam & Sandham (2000) performed similar DNS calculations, and detailed the shear layer transition mechanism as comprising oblique modes and Λ-vortex-induced breakdown. These promising results show strong potential for the eventual accurate analysis of transition phenomena that will surely provide a strong foundation for the advancement of existing $k-\varepsilon$ models.

2.5.3 Instabilities & turbulence

Johnson (2001) uses a finite differencing scheme to explicitly solve for the introduction of a slight perturbation to laminar flow as experimentally performed by Gostelow et al. (1995) to create particle streamline imagery show-
ing turbulent spot inception and development. Johnson states that local separation is required for the development of a spot, resulting in a circulation of fluid. This vortex pushes low momentum fluid from the surface upwards and high momentum fluid towards the surface. This sustains the local separation which then grows in the spanwise direction, encouraging development of the spot. Introducing an adverse pressure gradient causes the spot to grow more in the spanwise direction, as seen by Gostelow et al. (1993), effected by the larger amount of high momentum fluid from the upper layer being entrained in order to accelerate the greater amount of low momentum fluid within the boundary layer. This saturates the horseshoe vortex, creating additional spanwise vortices which become saturated in a similar manner.

DNS research works by various authors such as Chong et al. (1998), Jacobs & Durbin (2001) and Na & Moin (1998) show excellent capabilities in the generation of turbulent spots and the analysis of their mechanisms. Jacobs & Durbin recreate bypass transition in a laminar boundary layer using varying degrees of freestream turbulence level, and find evidence of negative perturbations in the streamwise velocity field that accompany the appearance of turbulent spots. They go on to describe a method for deriving turbulent inflows from Orr-Sommerfeld continuous modes.

2.5.4 Wake passing

The simulation of passing freestream wakes adds a level of unsteady complexity to computations, hence recent investigations have been generally limited to RANS solutions (Thurso & Stoffel 2001) although DNS has been attempted (Wu et al. 1999).

Thurso & Stoffel (2001) performed RANS model simulations of experiments by Lou & Hourmouziadis (2000) designed to investigate laminar separation bubbles with unsteady main flow conditions. The effects of both the wake velocity deficit and the turbulent content were analysed independently, plus the accuracy of the separated and transition region estimations to the experimental. It was seen that the location of laminar separation
and bubble length were predicted with good accuracy, however temporal fluctuations to these statistics due to unsteady inflow were not so accurately determined. The effects of wake-induced transition were under-predicted, with an extended transition length and underdeveloped turbulent flow.

The DNS research of Wu et al. (1999) simulated the experiments of Liu & Rodi (1991) consisting of a rotating squirrel cage of rods upstream of a flat plate with initially laminar flow to emulate the effects of wake embedded freestream flows. Using top-of-the-range HPC equipment and an unprecedented fifty million domain grid points, they were able to perform a comprehensive investigation of the various mechanisms of wake-generated boundary layer turbulence with varying degrees of freestream disturbance intensity. The existence of streaky ‘puffs’ was noted prior to the development of turbulent spots, with an explanation for their amplification as due to a ‘forcing’ from an interaction with freestream wake eddies. This forcing, evident as a negative stream-wise velocity fluctuation behind the puff and hence implying an inflectional instability, amplifies the puff to an eventual turbulent breakdown. A positive stream-wise velocity fluctuation induced from freestream eddies effects a decay in the transformation of a puff into a young spot.

2.6 Simulated wake flow

Study of the velocity triangles for both rotors and stators in compressors and turbines reveals a substantial difference in the inlet flow characteristics for the region in the trailing edge shadow of an upstream blade. These wake regions have significantly reduced velocities and higher turbulent content than the surrounding freestream, yet arguments have been advanced for both the velocity defect and the increased turbulence level as having the greatest role in affecting the boundary layer flow.

Work by Orth (1993) into the effects of stationary and rotating wakes impinging onto a flat plate boundary layer have shown that transition occurs in the same place for both cases. This indicates the importance of considering the elevated wake turbulent content as opposed to the mean velocity
deficit.

Using examples of generic turbine blade velocity vectors for various degrees of reaction from Gostelow (1984), estimates for the velocity deficit of the wake path flow, and the resultant change in inflow conditions for a downstream blade, were calculated. Modification of the velocity triangles in the wake flow was determined from empirical values as reported by Reynolds et al. (1979), which revealed that, for a inter-stage clearance equivalent to that of the author's experimental arrangement, the typical velocity defect at the core of the wake flow upon arrival at the leading edge would be in the order of one quarter of the freestream flow. For these calculations, an axial wake flow deficit of 22% and a tangential wake flow deficit of 26% have therefore been used, as determined from the wake velocity profiles of Reynolds et al. (1979). Shepherd (1956) also briefly describes the exit flow deviation from the trailing edges of cascades as being variable with regard to tangential location, hence the need to account for both axial and tangential differences in the wake flow. The radial component of velocity has not been taken into consideration, and as such the analysis can be considered appropriate for mid-height velocity triangles.

Figure 2.2 shows velocity triangles for the steady wake-free flow as typically drawn in publications, for both a compressor and turbines of various degrees of reaction. Overlaid are the effective velocity triangles for the flow within the wake of the trailing edge of the upstream blade. For each case the effect of transferring from the absolute to the relative axes upon consideration of the succeeding blade row shows strong changes in the flow velocity and approach angle.

These estimated results ought to be taken qualitatively as their precisions are highly dependant upon parameters that are variable across compressor and turbine design with regard to their differing applications. Stage loading, flow turning, rotational speed, mass flow rate and degree of reaction are examples of parameters that can alter the properties of the freestream, and hence the wake flows; these cannot all be taken into account in this simple analysis.
Compressor flow

For a typical compressor rotor inlet, the changes are small. This estimation shows a slight, and most likely insignificant, increase in the freestream velocity of 3% within the wake retarded flow, which is caused by a reduction of the absolute tangential component of the flow after the trailing edge of the upstream stator. The incidence angle of the flow, increasing by as little as 7 degrees, is also very indifferent to the steady flow. Although in real turbomachinery environments a 7 degree change in inlet flow angle can be sufficient to induce separation and possibly even stall, in the current experimental setup the flow change has little bearing on the boundary layer properties.

The results from the study of the stator are almost identical to that of the rotor, since the designs of both rotor and stator are similar. There was again seen to be a small increase in freestream velocity in the wake path flow, around 5%, with an identical increase in incidence of near 7 degrees. Choosing identical axial and tangential wake velocity deficits reduces these changes to smaller values, and under the consideration of the generality of these velocity triangles it can be justifiably stated that the effects of the unsteady wake flows are minimal if at all significant with regard to the velocity defect alone.

Turbine flow

For a typical turbine stage, the unsteady nozzle flow wake path approaches the leading edge of a rotor with a presumably equivalent flow defect to that of the compressor. Under this assumption the same axial and tangential velocity retardation has been used.

For three varying levels of stage reaction (zero, 50% and 100%) the effect of the wake flow on the freestream velocity vectors has been estimated. Regarding the rotor inlet, with the wake flow from an upstream nozzle, much greater reductions in the freestream velocity are seen when compared to those of compressors. Here as much as 45% of the freestream velocity is retarded for a zero reaction, or impulse, turbine rotor, with an incidence
angle change of 11 degrees. With increasing stage reaction, the freestream velocity defect reduces to 42% and 22% for a 50% and 100% reaction turbine stage respectively. This is matched with increasingly greater incidence angles of 30 and 37 degrees, which imparts the wake flow onto the suction surface of the blade.

The turbine stators receive similar variations in inlet flow for the wake periods, but in a reverse sense with regard to stage reaction. Here the lower reaction stages promote low velocity defects and high incidence increments onto the suction surface of the stator, with an opposing trend to that above of high velocity defect and low incidence increments for the higher reaction stages.

**Wake generator**

Studies of the flow from the wake generator have shown properties most similar to those of a compressor stage, with a maximum wake flow deficit of 4% and an increase in incidence close to 11 degrees. Although the wake flow deficit for a compressor was shown to in fact increase the relative inlet flow speed, the error is less than 10%, and with closely matching angles of incidence this environment proves the closest match to ours.

In fact, returning to the velocity triangles of a compressor, but with a slightly greater axial velocity component, the wake flow velocity defect can be seen to have a similar effect to that of our wake generator producing a reduction of inflow speed to the succeeding stator. The effect of small changes such as this show the high dependency of the velocity triangles to the particular design parameters of the stage.

Turbines stages exhibit much greater changes in velocity and incidence which would be less accurately modelled by our wake generator.

**Turbulence intensity**

A plot of measured turbulence intensity across the span of the each wake is presented in Figure (2.3) and shows a maximum turbulence intensity increase of close to 20% for the near-wake, and 10% for the far-wake.
These values are very typical of those encountered within turbomachinery, as researched by Raj & Lakshminarayana (1973) and Gorton & Lakshminarayana (1976), where maximum values for turbulence intensity recorded in a wake from an upstream trailing edge were $T_{u_{\text{max}}}$ = 23\% and $T_{u_{\text{max}}}$ = 24\% for background levels of $T_u$ = 0.1\% and $T_u$ = 5\% respectively.

As will be demonstrated in later Chapters, this variation in turbulence intensity between the two wakes gives rise to a slightly different transition mechanism in the boundary layer.
Figure 2.1: The growth of a) spots in sets for zero pressure gradients, b) slight adverse pressure gradients, c) continuous spot production as seen for strongly adverse pressure gradients and d) continuous with non-constant temporal spot onset d).
Figure 2.2: Velocity triangles for a compressor and three turbines of varying stage reaction (zero, 50% and 100%). Velocity triangles with trailing edge wake deficit shown in red. Figure demonstrates the changing velocity vectors experienced within by downstream blades during the wake path.
Figure 2.3: Turbulence intensity levels, $Tu$, for the near- and far-wakes measured by the hot-wire in the freestream at $x = 0.15$ m. Figure demonstrates the differing levels of turbulence within the wake flows for the primary and the secondary wakes.
Chapter 3

Experimental Approach

This Chapter describes in detail the unique apparatus and the intensive experiments adopted to acquire the highly time and spatially resolved flow data, use and calibration of the hot-wire, the design, implementation and calibration details for the linear microphone array. The degree of data error and other problems associated with such a large experimental program are also addressed.

3.1 Low speed wind tunnel & laboratory apparatus

At the University of Leicester a low speed wind tunnel of closed construction has been prepared for investigating the interaction of upstream disturbances with a boundary layer in an adverse pressure gradient, Figure 3.1. Working section speeds are low (in the order of 10 ms$^{-1}$) with background turbulence levels of less than 0.20%. The wind tunnel has been used in recent years for the investigation of turbulent spot development in adverse pressure gradients (D’Ovidio et al. 2001a), the characteristics of propagating spots (D’Ovidio et al. 2001b), and other earlier boundary layer experiments.

The upper wall has been fitted with a contoured section to impose an adverse pressure gradient onto the flow, see Figure 3.2, specifically chosen to promote three conditions of boundary layer: an attached laminar layer,
an incipient laminar separation bubble and a sustained laminar separation bubble; each achievable under different flow Reynolds numbers. For the present experiments only a sustained laminar separation bubble has been investigated.

3.1.1 Flat plate

A large flat plate with dimensions 2.41 m long by 1.15 m wide, was mounted at zero incidence and spanning the full width of the test section. With the use of a pitot-static combination positioned towards the leading edge of the flat plate, precise freestream speeds can be selected and maintained to within ±0.1 m/s (±1.11%) for long periods, ensuring highly repetitive experimental conditions.

The flat plate was fitted with numerous surface static pressure tappings, some of which were additionally implemented during modification stages performed by the author (see §3.1.4) and were therefore not available during the earlier stages of experimentation. A series of 1 mm diameter static tappings exist with 50 mm spacings covering the entire chordwise centre-line of the flat upper surface. The curved leading edge has thirteen 0.5 mm diameter tappings across both the upper and lower surfaces, distributed short distances from the centre-line of the flat plate. A short series of spanwise-distributed ports, again 0.5 mm diameter, exist at chord location $x = 0.235$ m (9.4% chord), extending to 0.12 m either side of the centre-line with a minimum spacing of 10 mm between each. These spanwise tappings were used in previous experiments for the purposes of introducing small jets of air at different spanwise distances from the centreline in order to achieve a third spatial dimension in the acquired velocity data. This was necessary due to the limitations of the hot-wire traverse, as explained later.

During the implementation of the microphone array (see §3.1.4 for a description of the microphone array), an extra set of 1 mm diameter static tappings was created offset from, but parallel to, the chordwise centre-line by 20 mm, having an equivalent spacing to those of the microphones at 25 mm and covering a smaller range than the existing centre-line tappings.
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from 0.275 m to 1.025 m chord. These enabled a more accurate picture of the chordwise pressure gradient to be acquired in the region of the bubble, resolving the problem of wide spacing static tappings as encountered during previous research works (D'Ovidio & Gostelow 2000). The pressure distribution is presented and detailed in §4.1.1 Figure (4.1).

3.1.2 Wake generator

The mechanism by which the wake disturbances were produced was one which has been used successfully over many years by researchers who have required a periodic unsteady inflow, such as Pfeil & Herbst (1983), Orth (1993), Kyriakides et al. (1999), Funazaki & Kato (2002), Jeon et al. (2002), and those reported in Mayle & Dullenkopf (1990), namely Ashworth et al. (1985 & 1987), Doorly et al. (1985), La¨Graff et al. (1988), Wittig et al. (1988). All of these researchers have used rods or cylinders in their experiments to achieve turbulent, or wake-disturbed, inflows in order to investigate the unsteady effects of viscous flows.

Essentially, the wake generator simulates the trailing wakes of an upstream rotating blade row by periodically passing a cylinder, of average diameter 12 mm and length equivalent to the span of the working section, across the face of the flat plate leading edge, as shown by the cut-away diagram of the working section in Figure 3.2 and dimensionally in Figure 3.3. With a rotational speed of \( \omega = 2.0\pi \) rad/s, wakes were generated with a period of \( T = 1.0 \) s. With each complete rotation two wakes interact with the flat plate as the rod passes the horizontal plane at approximately \( \omega = 0.50\pi \) and \( \omega = 1.5\pi \) rad. These have been termed the primary and secondary wakes respectively.

The carbon fibre cylinders, or rods, have a slowly reducing diameter along their length to alter the frequency of shed wake vortices and hence minimise the development of a von Karman vortex street and also aid the reduction of cylinder vibration (Zdravkovich 1997).
Analysis of the wakes

Figure (3.4) shows a conceptual understanding of the wakes shed from the rod of the generator. Both a primary and a secondary wake have been sketched to show the differences in approach and content.

The effective width of an expanding wake is proportional to the square root of the distance from the cylinder $x^{1/2}$ (see Zdravkovich 1997), therefore at large distances from the cylinder, relative to the cylinder diameter, the wake's rate of expansion increasingly slows. From the experimental data it was seen that the wakes did not significantly increase in width throughout the acquisition range $0.15 < x < 0.80$ m, demonstrating that the wakes were already well developed before reaching the flat surface of the plate. This can be seen in Figure (3.4) by comparing the wake breadths from directly behind the rod to those far downstream; the rate of expansion slows to relatively zero before the flat plate horizontal surface is reached. This helps to demonstrate the fact that the wakes are well-developed and unlikely to contain any strong periodic vorticity.

Due to the low elevation of just $11^\circ$ for the primary wakes and $11^\circ$ for the secondary wakes, relative to the flat plate surface, the wakes are effectively elongated to a horizontal length of approximately 0.80 m, prolonging their interaction with each single chordwise location by a multiple of 5.

The small arrows do not represent the absolute velocity within the wakes, but depict the component of velocity attributable to the velocity of the rod. These arrows demonstrate that the lower portion of the primary wakes are imparting a 'surface-wards' velocity that both injects turbulent flow into the boundary layer and 'pushes' the edges of the induced turbulence outwards, creating an impression of a highly accelerative leading front (see Figure 3.5).

The secondary wakes, generated on the return cycle of the wake generator, have a vertical component in the opposite sense, i.e. 'freestream-wards'. This has the effect of drawing fluid from the boundary layer, and suppressing the development of the turbulence within the induced disturbances. This has the added effect of creating an impression of a retarded leading edge propagation rate, as is discussed in more detail in §5.2.3.
A second rod

To achieve a second wake, as required for the study of closely spaced wakes, an additional and identical rod was attached to the wake generator disc. To gain the greatest understanding of the behaviour of these two interacting wakes it was desirable to make available a variety of differing time delays between them, therefore it was necessary for the location of the secondary rod to have as many finite locations as possible. For a description of the method derived to estimate the likely pattern of wakes see Appendix A.3. A summary of this method is repeated below.

A second rod was constructed to the exact specifications of the first. Its disc locations were defined by a mathematical code loosely based on a Golomb ruler, designed to determine the optimum positions for the minimum number of locations that provide the desired range of arrival time delays.

A range of values for $\alpha$, the rotational distance in degrees between the two rods, between 30 and 80 degrees was required, preferably with a large number of evenly distributed positions, to cover the variety of scenarios with which we were interested. As a result, the following potential rod locations, in terms of their rotational distance from the primary rod, were determined: 45, 60, 95, 125 and 165 degrees. There are a total of 30 possible values for $\alpha$ when the angular distance between all the possible location pairings are considered, and out of those the important values are 15, 30, 35, 40, 45, 50, 60, 65, 70, 80, 95 and 105 degrees. See Figures (3.6) and (3.7) for schematics of the new secondary rod locations.

The rods are attached to the periphery of a circular disc cut from the sidewall of the working section. This disc is rotated at a constant speed using a Brook Hansen 1.1 kW motor through a 10:1 gearing system, powered through an ALSTOM Alspa MV500 speed controller permitting speed settings in steps of 3 rpm, or 0.3 rpm after gearing ratio, and accurate to within 0.02%.
3.1.3 Hot-wire traverse

Along the roof of the working section lies the traverse mechanism for the hot-wire anemometer consisting principally of a sturdy lead screw and probe carrier. The probe carrier is computer controlled to automate the aligning of the probe in a direction perpendicular to the flat plate surface. Motion in the direction normal to the plate is achieved with a stepper motor, powered using a controller unit that receives its commands from the computer. Displacement steps of 3.175 μm can be achieved, with a hysteresis of less than 10 μm. During runs the hot-wire is moved in only one direction, away from the surface of the plate, to aid elimination of any further possible hysteresis in the system.

Chordwise movement is manual, with an infinite number of positions achievable between a range of $x = 0.14$ to $0.81$ m chord.

The single wire hot wire is mounted forward facing, as can be seen in Figure 3.2, and at an oblique angle to reduce the interference effects caused by the probe body in the flow, a difficulty inherent in the use of hot-wire anemometry. For more on the hot-wire system see §3.2.1.

3.1.4 Microphone array

High quality pressure transducers are excellent devices for the high speed measurement of fluid pressures over extensive periods of time. Such devices are ideal for the detection of small scale instabilities present in boundary layer flow (as used by Hudy et al. 2002). However, for the gathering of information regarding the flow pressure properties across the entire region of interest, a large number of sensors would be needed positioned with a close proximity to one another down the centreline. The region of interest, from the beginning of the laminar shear layer, through the bubble and into the turbulent flow, extends to over 50 cm, and an estimated maximum distance of 2.5 cm between each microphone would be required to achieve satisfactory data resolution within the transition region, demanding a minimum of 20 sensors.
Unfortunately, the retail cost for this number of pressure transducers exceeded the budget limitations, hence an alternative method for the detection of the pressure fluctuations was investigated.

**Microphone arrays**

After successful experimentation into the use of electret microphones for the detection of turbulent properties in boundary layers (Cherry et al. 1984, Hudy et al. 2002, Snarski 2002), it was decided to investigate this novel technique. Sub-miniature microphones, mounted flush to the exposed surface, can detect pressure fluctuations in the fluid as they pass over the orifice.

Sub-miniature electret condenser microphones have a reasonable performance and relatively low cost and were an ideal choice for the role of sensing surface pressure disturbances.

As previously reported by Hudy et al. (2002) such microphones can be successfully used to detect the pressure fluctuations of a moving fluid. In those experiments, as performed by the aforementioned researchers, microphones were mounted with their surfaces flush, or very close, to the exposed surface of their model. However, the author felt it an undesirable step to make such radical modifications to the surface of the flat plate, hence it was proposed that the mounting should position the microphone directly beneath a small tapping, similar in design to a surface static pressure tapping. See Figure (3.9) for the microphone mount design.

**Microphone receptacle design**

A novel mounting technique was adopted here with the integration of a static pressure line into the microphone receptacle, Figure (3.10). This was to permit the analysis of the surface steady pressures and gain a more detailed understanding of the chord-wise pressure gradient than the previous pressure ports could provide.

A series of 31 microphone sensors were fitted to the underside of the plate, parallel to the centreline and offset by 20 mm to avoid the existing
line of static ports. For the microphone experimentation the line of the microphone array was subsequently viewed as the new centreline.

With a centre to centre distance of 2.5 cm, approximately 6% of the bubble length, between each microphone, the array was located as far upstream as was physically permissible by the internal construction of the flat plate, see Figure (3.11).

Receptacle design testing

The concept of including a static pressure line into the microphone receptacles lowered each microphone orifice to 9.8 mm below the flat plate surface, giving rise to concerns over problems that may have developed in the tapping, long enough to be technically considered a waveguide,* between the flat plate surface and the microphone.

Significant investigations were conducted with regard to this static tapping, and the consequent waveguide, to ensure that no undesirable effects were introduced. A miniature flat plate was constructed with a microphone installed into the prototype holder. Results showed that longitudinal and transverse pressure waves, that could have potentially developed in the waveguide, were not in evidence. Tests were also carried out to ensure that no stationary waves developed in the piping between the static tapping and the external pressure transducer. Calculations using stationary wave theory (see eqn. (3.1)) estimated possible waves in the region of 17 to 21 Hz, however none were detected in the tests.

\[ f_R = \frac{(2n - 1)c}{4L} \quad \text{where } n = 1, 2, 3\ldots \]  

(3.1)

Experimentation has shown that it is very unlikely that pipe resonance will occur in an air column of such narrow diameter due the existence of a stagnant layer of air about 1 mm thick next to the wall of the tube, which considerably dampens any vibrations (Richardson 1953, Stephens & Bate 1966).

*A device which constrains or guides waves along a path defined by its physical structure (Redwood 1960).
Differential pressure transducer

A relatively inexpensive differential pressure transducer was fitted amongst the microphone array to provide a calibration signal for the microphones. So as not to interrupt the microphones throughout the separated boundary layer region, the pressure transducer was positioned ahead of the separation point at the fourth port, \( x = 0.350 \) m (Figure (3.12)).

Unfortunately, despite the initial successful stage testing, the pressure transducer failed to detect the very low-amplitude instabilities in this laminar flow region and provided little information of use. Therefore, all microphone data are presented in voltages, as measured directly from the apparatus.

Other modifications

The inclusion of this extra internal apparatus required a modification to the rear of the plate chassis, where all the static port tubing and electrical cables were gathered together and drawn out. Figures (3.13–3.15) show the aperture designs that allow the cables and tubes to be channelled from the plate, which were bound together to form an ‘umbilical chord’ that extends to the laboratory acquisition systems.

As a precaution to maintain the quality of the boundary layer flow, attention was focused on the upper surface contact point between the leading edge profile and the beginning of the flat plate. No surface defects, such as steps or gaps, could exist here otherwise the introduction of small instabilities to the flow could have occurred. A workable filler was used to bond and seal the junction, which was progressively levelled and polished to give a smooth transition between the surfaces.

Electronic enclosure

A unit was designed and constructed for the purposes of providing power to the microphones and pressure transducer, and providing a solid chassis for the quick and easy connection of the various signals to the A/D card.
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To maintain the signal integrity, a D.C. battery supply was chosen as opposed to the use of A.C. mains. A rectified A.C. supply can always contain distortions that may contaminate signals with unwanted sinusoidal components, whereas a battery cell will provide a transient free D.C. supply. A 12 V, 7 Ah sealed lead acid battery was used to provide power to the electronics, which control the power distribution throughout the sensor array. The capacity is large enough to provide constant power for over 100 hours before charging is required.

For the purposes of battery cell charging, an A.C. mains powered charging unit was incorporated to provide a trickle charge to the battery under 'charge' mode. Although the charging circuitry can be active, the system was designed to permit charging only whilst the unit is not operational, to prevent the possibility of introducing any interference into the circuit.

Other measures were taken to ensure signal clarity. The enclosure has been earthed to the laboratory ground earth, independent of the single-phase mains, as well as through the A/D card's own ground connection. Twisted pair ribbon cable was used to reduce cross-talk between signal lines. The enclosure architecture finds the battery cell positioned between the charger unit and the signal carrying circuitry to reduce the chances of interference should the charger be left active during use.

3.2 Acquisition techniques

For each run, the atmospheric conditions dictated the operating speed of the wind tunnel in accordance with formulae derived to achieve a constant working section Reynolds number of Re = 1.4 × 10^6 based on flat plate length. The working section total pressure is measured using a pitot-static combination upstream of the leading edge, and converted into a freestream velocity. Calibrations for this allow for the estimation of a pitot-static pressure appropriate to the daily atmospheric conditions to create the desired working section Reynolds number.

Batches of experiments for the various wake combinations sometimes required several weeks of constant daily operation, and hence experienced
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significant changes in atmospheric pressure and temperature across this duration. In some cases, as a result of this, initial tests may have been operated at wind tunnel fan speeds much lower, or higher, than those towards the end. This was an unavoidable issue incurred as a result of long acquisition times and high spatial resolutions, but is not thought to create significant levels of error in the data (see §3.3.6 on error analysis).

3.2.1 Hot-wire anemometry (HWA)

A single wire hot-wire probe was implemented throughout all experimentation to determine accurate flow velocity data within the boundary layer. Although a X-wire probe may have provided useful information on the flow direction by measuring two flow vectors simultaneously, it would not have permitted close inspection of the boundary layer or separation bubble due to the proportionately larger tip dimensions. With a very thin boundary layer and separation bubble it was necessary to use a single probe hot-wire to achieve the large number of data points required for accurate determination of the boundary layer velocity distribution.

The probe used was a constant-temperature platinum plated tungsten element DANTEC 55P11 having a hot-wire length of 1.25 mm and a diameter of 5 μm, set to an overheat ratio of 0.8, connected to a DANTEC 90N10 frame driven by a 90C10 CTA module. The signal was fed into a Khronite 8-pole Butterworth filter set to low-pass at \( f_c = 1.4 \) kHz to remove any high-frequency noise, before finally being acquired at 3.2 kHz as a differential signal using the onboard 16 channel A/D card.

Hot-wire calibration

A reliable calibration technique was adopted to derive the voltage to velocity polynomial required for analysis of the hot-wire data. A pitot-static combination connected to a pressure transducer with a precision of 0.01 Pa was used to accurately determine flow speeds at the head of the hot-wire. This method was used due to difficulties experienced with the use of the usually adopted miniature hot-wire calibration tunnel, later discovered to
be the fault of a damaged cable, see §3.3.6. A four-coefficient polynomial curve was fitted to the data, as expressed in eqn. 3.2.

\[ u(t) = a_1 E^3 + a_2 E^2 + a_3 E + a_4, \text{ where } a_n \text{ are constants}. \quad (3.2) \]

**Near wall correction**

Among the collection of literature available on the subject of near-wall hot-wire signal correction, none is conclusive to the extent of providing a universal correction procedure applicable to all boundary layer flows. That of Wills (1961) is a frequently referenced routine based on precise experiments designed to investigate the radiative effects of a near-wall HWA. However, these experiments were restricted to laminar boundary layers and not turbulent flow, and the signal correction procedures were suggested to be overcorrective for turbulent flows. Wills suggested that half the full laminar correction should be used, however later studies showed that this method gives unsatisfactory results (Bruun 1995, p.270).

Lange *et al.* (1999) published works on simulated heat-flow losses from a circular cylinder and likened the data to represent the working method of constant temperature HWA techniques. With precise computational fluid dynamics (CFD) computations the effect of conductive walls near to a heated cylinder in a boundary layer flow was investigated, and the results compared to several other works including Hebbar (1960) and Krishnamoorthy *et al.* (1985). Later works by Durst *et al.* (2001) using highly accurate measurements of flow near to a highly heat-conducting wall helped to derive a correction factor, based on a simple bounded curve, that was applicable to hot-wire velocity measurements.

However the work was limited to simple laminar zero-pressure gradient scenarios, and at its essence relies upon knowledge of the surface shear stresses and on an assumption that the surface velocity profile follows closely that of a near-wall turbulent profile as described by the ‘law of the wall’ (Bruun 1995, p. 264).

The method, cited from Lange *et al.* (1999), uses normalised values for velocity \( u \) and perpendicular distance \( y \), \( U^+ = \bar{u}/U_\tau \) and \( Y^+ = yU_\tau/\nu \).
respectively, where $U_T = \sqrt{\tau_w/\rho}$ is the skin friction velocity, $\nu$ is the kinematic viscosity and $\rho$ is the density of the fluid. Using the 'law of the wall', briefly stated as three regions of a universal non-dimensional boundary layer profile, with the wall region described by,

$$Y^+ \leq 5 \quad U^+ = Y^+, \quad (3.3)$$

Lange et al. (1999) fitted a curve to data of $Y^+$ against $C_U = \bar{u}/u_{meas}$, where $C_U$ is the coefficient of correction, a ratio of the actual velocity $\bar{u}$ to the measured velocity $u_{meas}$. The curve follows the equation,

$$C_U = 1.0 - \exp\left[-0.4(Y^+)^2\right], \quad (3.4)$$

such that a correction for the velocity can be calculated from the non-dimensional height.

However, to calculate $C_U$ one requires knowledge of the surface shear stress $\tau_w$. This can be derived from its definition, $\tau = \mu(du/dy)_{y=0}$, but requires a prior knowledge of the correct flow velocities at the surface of the wall (achieved in the experiments of Lange et al. (1999) using surface Laser-Doppler Anemometry [LDA]).

Rearranging the formulae one can produce a recursive equation that iteratively approaches the corrected value for the near-wall flow velocity,

$$U_0(n + 1) = U_{meas} \left[1.0 - \exp\left(-0.4y_0U_0(n)\nu^{-1}\right)\right], \quad (3.5)$$

where $U_0$ is the flow at the lowest perpendicular height $y_0$ (theoretically on the surface, but values for the velocity gradient nearest to the wall have been taken). Beginning with inserting $U_0(0)$ as the uncorrected velocity from the hot-wire $U_{meas}$ one asymptotically reaches the value for the corrected near-wall velocity $U_0$ with each converging iteration. This corrected velocity can then be used to calculate the actual wall-shear stress $\tau_w$ for determining $Y^+$ in equation (3.3).

Comparison of the Lange method to Wills method provided predictable results (Figure 3.8) under the consideration that the former is derived for turbulent zero pressure gradient flows.
In the laminar flow regions up to station 6 (x = 0.400 m) the two corrective procedures compared reasonably well, with the variation between velocity correction parameters less than 19%. Beyond this point separation ensued and after x = 0.425 m the Lange corrective procedure was no longer applicable, furthermore at station 11 the Lange corrective procedure failed completely, presumably due to the lack of similarity between the separated velocity profile and the universal profile described by equation (3.3). However the Lange correction technique recovered before reattachment at station 16 (x = 0.650 m), and from here the Wills correction factor consistently exceeded that of Lange, but by no more than 18%.

That the Wills method over corrects for turbulent flows has already been stated, so it not surprising to find here the method of Lange suggesting a lower correction. In fact, adjustments as little as 0.04% are seen for the highly turbulent flow at station x = 0.800 m. However, with no true corrective method available for adverse pressure gradient flow, the Wills method has been incorporated here as it has shown itself to be reasonably accurate across the entire boundary layer.

**Deterioration compensation**

Bruun (1995) discusses the dramatic alteration of a hot-wire probe’s response due to the contamination of the probe element via the deposition of impurities from the flow, and the need for constant time-consuming recalibration of the system.

The vast number of experiments performed during the duration of the author’s work exposed the hot-wire to over 150 hours of operating speed air flow, and during this time a linear decline in the d.c. voltage response was detected. Compensation for this moderate ‘aging’ of the probe was necessary as, for the higher velocities especially, errors as great as an estimated 22% would have been incurred for those experiments performed towards the end of the hot-wire’s operating life.

A correction was implemented as a simple adjustment of the recorded voltage, via the addition of a small constant, $\Delta E$, proportional to the life of
the hot wire probe. This correction factor was determined from a linear least squares fit derived from recorded hot-wire values for a known flow velocity taken at different stages of the hot-wire’s working life.

\[ E_D = E + \Delta E. \] (3.6)

It was later seen that this aging of the hot-wire was responsible for large inconsistencies in the data, especially for the higher velocity regions in the freestream. For this reason, it was deemed necessary to perform pitot-static freestream velocity traverses to accurately determine the freestream velocity distributions for the tests, as described further in §4.1.2.

**Temperature compensation**

Due to varying atmospheric conditions between tests the air temperature can be different at the end of a set of experiments from its original value at the beginning. Temperature changes affect the signal from the hot-wire by altering the heat transfer properties around the element, and must therefore be taken into account in the calibration.

According to van Hest (1996) temperature effects can be compensated for with a knowledge of the fluid temperature at calibration, \(T_c\), the current ambient fluid temperature, \(T_a\), and the hot-wire element temperature, \(T_w\). The correction is applied to the hot-wire voltage signal using,

\[ E_T^2 = E^2 \cdot \left[ 1 - \frac{T_a - T_c}{T_w - T_c} \right]^{-1}, \] (3.7)

where \(E_T\) is the temperature corrected voltage from the hot-wire.

The hot-wire calibration techniques employed did not account for any temperature changes, so the effects of varying temperature were investigated to determine the extent to which the hot-wire readings were being affected.

Based on two recorded atmospheric extremities, the maximum temperature correction was estimated to be less than ±1.0%. This was seen as an acceptable error, and was not therefore considered to be significantly detrimental to the results. It is however recommended by the author that such considerations be implemented in future experimentations.
Errors in the hot-wire data

During the experimentation period questions arose regarding the accuracy of the hot-wire readings, arising from strong discontinuities in the freestream velocities between consecutive $x$ locations. These issues were initially discarded as unavoidable errors due to the varying operating speeds between sequences of tests caused by the daily varying atmospheric conditions.

It was later discovered, during the freestream velocity distribution tests of §4.1.2, that the hot-wire data were suffering from more than a simple freestream variation. There was in fact a problem with the connecting cable between the hot-wire and the Dantec acquisition unit that had been randomly creating a small yet significant D.C. offset throughout the data.

The problem laid undiscovered until the end of the experimental work, infecting every dataset in an unpredictable way. Translated into a velocity, estimations show that the maximum errors were in the region of 16% in the phase averaged data and, due to their random nature, cannot be reliably corrected.

However, this does not necessarily categorise the hot-wire data as insufficiently accurate for analysis purposes. Although the amplitude information may be slightly in error, time arrival information from the data can be accurately determined. Therefore accurate celerity rates and other temporal statistics can be reliably calculated. The most commonly presented information is that of velocity perturbation and root mean square disturbance level. These are normalised parameters and are therefore relatively unaffected by the systematic errors in the freestream.

Section(3.3.6) covers the error analysis of the hot-wire data and summarises the contribution of this problem.

No amount of testing, calibration and validation can declare a system free of potential error sources. Nevertheless, thorough pre-experimental testing is an obvious unconditional prerequisite to all forms of research work.
3.2.2 Microphone array

Calibration

During the construction phase of the project, it was shown that the frequency response for one microphone was negligibly different from that of another. However, possibly due to differences between each manufactured microphone or perhaps small geometrical variances between each waveguide, it was not the case that the amplitude response from each microphone was constant across the array. Therefore a calibration of the signals was necessary.

With the knowledge that the amplitude of the response from each microphone was independent of the frequency, a power response test was performed to determine a suitable calibration curve.

A 100 Hz source signal, equivalent to the detected Tollmien Schlichting instability frequency (see §4.2.3), was directed to each microphone through a small speaker positioned over the surface port, and the signals for a variety of source powers were recorded. Signals were acquired at 3.2 kHz for 1.0 second, and repeated for source peak-voltage values of 1, 2, 5, 10 and 20 mV.

From Figure (3.16a) it can be seen that the microphones have a varied range of response amplitudes to the 100 Hz signal, and proved remarkably sensitive to the quietest of source voltages.

A highly varying trend in response amplitude can be seen between each microphone, although this was seen to be consistent from test to test and therefore not down to a fault in the analysis technique. As can be seen microphone numbers 30 and 31, the final microphones of the array, appeared particularly weak in their response, and were consequently dismissed from the results.

From Figure (3.16b) it can be seen that the voltage of each microphone signal is directly proportional to the root of the power of the source, demonstrating a linear response to amplitude variations for each microphone. From this data a simple calibration vector was derived that successfully normalised the amplitude response of the microphone array for any given source ampli-
tude. With the array normalised in this way amplification rates for propa-
gating instabilities could be estimated.

Digital filtering

Spikes were detected in the frequency spectra that were the influence of
aliased high frequency components. Careful tests were performed to deter-
mine the extent of the interference within the signal. These tests involved
the acquisition of typical signals with and without the use of a single chan-
nel 8-pole low-pass Butterworth filter, each at a variety of sample rates,
followed by close scrutiny of the frequency spectra to determine if any extra
components, introduced via the effects of aliased noise, were at all present.

It was seen that the amplitude of any noise in the data was very low
in comparison to the microphone signal, and also that the high frequency
noise in the signal only appeared at two specific frequencies. Using a sample
rate of 3.2 kHz, identical to that used in the hot-wire acquisitions, caused
these two small interference components to appear at approximately 790 and
1394 Hz. The use of a digital low-pass filter set to \( f_c = 600 \) Hz, significantly
reduced these components.

To ensure that no interference existed below the cut-off frequency limit
of the digital filter, close scrutiny of the power spectra for analogue low-pass
filtered and unfiltered signals was performed. The power spectra for these
signals virtually overlap, see Figure (3.17), hence demonstrating the very
low levels of noise interference below the digital filter setting.

Advantages of a digital filter

Digital filtering has the advantage of knowing signal content ahead of time
and can actually provide better filtering techniques than analogue methods.
\texttt{filtfilt}\(^1\) is a simple to implement filtering technique that loops a signal
through a predefined filter in both directions, reversing the method for the
second pass. This has the advantage of helping to reverse the effects of

\(^1\)MatLab command (Pärtnander 1999).
phase distortion and also reduce any end-effects. The reduction of phase-distortion is a big advantage as an important element of the research is the requirement to determine the time arrival of flow features from the instantaneous appearance of signal frequencies.

**Noise cancellation**

Due to the construction of the wind tunnel, mild forced-vibration of the flat plate was induced from the downstream fan. The experiments were performed at a constant Reynolds number, requiring variable rotational speeds in the range 180–210 rpm, dependant on the atmospheric conditions, and therefore, for an eight bladed fan, vibrations were introduced into the structure at approximately 24–28 Hz. These interference components were more pronounced than expected, and needed to be removed from the microphone signals.

The use of a filter could not be approved as the fan interference frequency was close to the actual data content of the signal, and therefore a filter would be likely to remove some of the actual pressure fluctuation data.

The solution was to seal one microphone for the purpose of noise cancellation. Microphone 29 (chord location $x = 0.975$ m) was sealed up to prevent exposure to surface flow effects, and recorded in the same way as the exposed microphones during each acquisition. The signal content then contained purely the forced vibrations of the flat plate, and was used to remove these components from the other microphone signals. No phase lag was detected across the array, so a direct subtraction of the data, after high order low-pass filtering at $f_c = 60$ Hz, efficiently minimised these interference components in the microphone data.

Figure (3.18) shows an example of a microphone signal before and after interference cancellation using the signal from microphone 29. The loss of microphone 29 from the array was not detrimental to the experiment as microphones 30 and 31 were not responding strongly and had already been excluded from the acquisition procedures (See Calibration §3.2.2).
Final note about the microphone array

With the constant implementation of the cancellation microphone and the loss of another channel to accommodate the triggering signal, the maximum number of *useful* signals that could be simultaneously acquired was reduced to 14, however the experiments still only had to be performed in two runs in order to acquire from each half of the array, i.e. microphones 1–14 then 15–28.

Problems were experienced with microphones 8, 22 and 25 (x locations 0.450, 0.800 and 0.875 m respectively) concerning d.c. and low frequency signal components, and hence contouring of the data sometimes appears slightly 'flat' for these three x locations. This was later suspected to be a problem associated with the electronic enclosure designed to channel the signals to the A/D card.

3.2.3 Instrumentation

Wake generator

The wake generator was fitted with a reflective strip located rotationally before the first brass rod support. An infra-red emitter-receiver mounted to face the rotating disc to detect the passing of the reflective strip created intermittent 20 μs pulse signals once every complete rotation of the wake generator that were monitored and recorded by the computer acquisition system for accurate determination of wake passing. The recorded signal was used as an accurate means of discretising the continuous hot-wire and microphone signals into the required number of records, or bins, to await the post-processing techniques.

MKS pressure transducer

An MKS digital pressure transducer connected to a pitot-static configuration within the head of the working section allowed the accurate determination of freestream speeds. With a precision variation of less than ±0.01 Pa, freestream speed resolution within the order of 0.1 m/s was technically
achievable, however in practice the system was shown to vary by up to ±1 Pa during runs due to the various freestream disturbances interfering with the pitot-static device.

This pressure transducer apparatus was also implemented for the recording of surface static pressures to accurately calculate the chord-wise pressure gradients. The flat plate surface static ports were connected to a 49 channel Scanivalve unit automatically controlled by the computer software.

Software

Extensive programming was performed by the author to automate and improve the efficiency of the laboratory operations. Automatic data cataloguing and post-processing routines, coupled with tailored file exporting options created an efficient and error-free system for the acquisition and analysis of the data.

Routines were programmed in combinations of LabVIEW and MatLab codes, each chosen for their ease of access to hardware and mathematical processing techniques respectively.

3.3 Data analysis techniques

3.3.1 Standard statistical approaches

In this report, the data are statistically regarded as ‘samples’ from an infinite ‘population’ of possible values due to the subjective nature of the chosen number of acquired data samples, \( n \). The total number of samples is considered simply as a random ‘sample set’ of size \( n \) from a potentially infinite population of samples. Under these considerations, parameters for the entire population—or the global statistics—can be estimated from the sample set.

A more in-depth discussion of the statistical procedures can be found in the hot-wire publication of Bruun (1995).
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Time-mean and standard deviation

The population mean, $\mu$, and standard deviation, $\sigma_u$, are estimated from the 'sample' mean and standard deviation,

$$\mu \approx \bar{u}(x,y) = \frac{\sum_{i=1}^{n} u(x,y,i)}{n},$$

and

$$\sigma_u \approx u'(x,y) = \sqrt{\left[\left(\frac{1}{n-1}\right) \sum_{i=1}^{n} (u(x,y,i) - \bar{u}(x,y))^2\right]}.$$

Often scientists use the synonym root-mean-square (RMS) when referring to the standard deviation, although this would actually be represented as $\sqrt{\bar{u}^2}$. Hence, similarly, within this report any reference to the RMS value actually refers to the standard deviation.

Ensemble averaged mean

In addition to the time-mean, the mean of time-history data, an ensemble-average time-dependant mean can be attained by averaging across the phase-locked realisations, hence,

$$\langle u(x,y,t) \rangle = \frac{\sum_{i=1}^{r} u_i(x,y,t)}{r},$$

where $u_i(x,y,t)$ represents the instantaneous velocity at a particular location and time for realisation $i$ of total realisations $r$. Ensemble averaged data has the advantage of retaining time dependant features, such as the passing of wakes, whilst removing the random components associated with noise and jitter etc.

3.3.2 Integral parameters

Three commonly used integral parameters to represent the boundary layer are used in this thesis. They are boundary layer displacement thickness $\delta^*$, momentum thickness $\theta$ and shape factor $H$, defined as follows:

$$\delta^* = \int_{y=0}^{\delta} \left(1 - \frac{u}{U_\infty}\right) dy,$$

$$\theta = \int_{y=0}^{\delta} u^2 dy,$$

$$H = \int_{y=0}^{\delta} \frac{u^2}{U_\infty^2} dy.$$
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3.3.3 Intermittency parameter $\gamma$

The definition of intermittency can be described as ‘the probability of flow existing as turbulent at a given spatial and temporal location’, or ‘the fraction of time that the flow is turbulent’. The intermittency factor is most commonly determined from velocity information, where turbulent regions can be detected and isolated from the laminar regions.

A number of different methods have been published for the detection of turbulent content within a flow, such as those discussed by Walker & Wu (1991) and Walker & Solomon (1992), and many work using similar techniques. The basic steps are described as,

- Sensitisation
- Smoothing
- Detection

The first stage, sensitisation, manipulates the data signal to enhance the regions of turbulent behaviour. There are a variety of published techniques, each with different advantages, for this detection, varying from simple squares of velocity, $u^2$, to multiples of the velocity standard deviation by its temporal-gradient, $u'(\delta u/\delta t)$.

This sensitised signal usually requires some degree of smoothing to remove spikes and dips that would distract the routines, hence increasing the accuracy of the intermittency measurement. The simplest method is to smooth the data across the time domain using a defined window width, but a more accurate method is to implement a moving-average smooth that allows, for each individual data point, a local average to be determined based on the values enveloped within the window width surrounding the current

\[
\theta = \int_{y=0}^{\delta} \frac{u}{U_\infty} \left(1 - \frac{u}{U_\infty}\right) dy,
\]

(3.12)

\[
H = \frac{\delta^*}{\theta} .
\]

(3.13)
data point. Although more computationally intensive, this method results in a better time resolution of the intermittency detection.

The final stage takes the smoothed sensitised signal and applies a simple threshold level for the determination of regions of turbulence. This threshold level must be calculated by the user for reasonable detection results and it is a simple case of performing tests using varying threshold settings and choosing the more appropriate setting from visual inspection of the detected turbulence regions. A selected proportion of instantaneous velocity traces from a range of chordwise locations were inspected visually for regions of turbulent flow, allowing for the determination of the local intermittency rates. These values were then used as a calibration tool to determine the threshold setting for the ad-hoc method as described above.

Author's intermittency detection method

Various intermittency detection techniques were tested but none provided satisfactory results for accurate determination of regions of turbulence. Errors, or inaccuracies, were seen to occur in the regions of calmed flow following each passing wake due to the strong decelerations evident here whilst the flow relaxed from highly turbulent to pseudo-laminar.

Figure (3.19) shows an example of the regions of detected turbulence, using velocity data at the transitional station $x = 0.675$ m, with $|du/dt|$ as the sensitisation formula shown in blue, from where it can be seen that in the initial stages of calmed flow (from sample point 325 onwards), the velocities are decelerating, yet laminar in nature, and hence erroneously declared turbulent. A second popular method, using $u \cdot |du/dt|$ and shown in green, worsened the situation and enhanced detection of the calmed region by incorporating a velocity multiplication.

The author's solution was to implement high-pass filtering of the sensitised signal, set to a frequency of $f_c = 20$ Hz, one fifth of that of the fundamental instabilities, to remove the gradient inherent to the calmed regions. The resultant intermittency, shown in red, was much cleaner and tests showed a more consistent end to the detection of the trailing edge
of turbulent patches. This filtering method has been attempted before by Thomas (1973) as described in Bruun (1995) pg. 369.

Smoothing window widths were kept as short as possible, usually 8 points (2.5 ms), to prevent the loss of clarity for each arriving turbulent region, whose highly contrasting leading edges would otherwise be spread out in time and hence reduce the accuracy of their detection. The threshold value was set such that calculated intermittencies matched intermittencies determined from a visual inspection of the raw velocity traces. The value chosen was $T_h = 0.110$.

**Narasimha’s universal distribution**

Following the value for intermittency in a stream-wise direction, one would expect to see some increase from zero before transition has begun through to unity where the turbulence is dominant. The region in between is the transition region and has, for most cases, a predictable intermittency growth trend.

Building on the predictions of Emmons (1951) for turbulent spot development, Dhawan & Narasimha (1958) modified the method to consider a chordwise location before which no turbulent spots could develop, identifiable as the beginning of transition $x_t$. This method of ‘local’ or ‘concentrated’ breakdown led to the derivation of an intermittency distribution for the transitional region,

$$\gamma = 1 - e^{-0.412\xi^2}, \quad (3.14)$$

$$\xi = (x - x_t)/\lambda, \quad (3.15)$$

$$\lambda = \{x\}_{\gamma=0.75} - \{x\}_{\gamma=0.25}. \quad (3.16)$$

Equation (3.16) measures the distance in metres between the chordwise locations for boundary layer intermittencies of 0.75 and 0.25.

The determination of $x_t$ from experimental intermittency data is best obtained by plotting the function $F(\gamma) = [\ln(1 - \gamma)]^{1/2}$ and extrapolating to $F = 0$ from a straight line fit to the data (Narasimha 1983).
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The end of transition $x_T$ is marked by the point $\gamma = 0.99$, similar to boundary layer thickness theory, and hence the transition length $L_T = x_T - x_t$.

The calculated intermittency distributions matched very closely those of the experimental data available to Narasimha, and have since matched many other experimental intermittency measurements of boundary layer transition regions (Owen 1970, Malkiel & Mayle 1995). It must be noted that little experimentation had previously been performed with strong adverse pressure gradients, although it was briefly mentioned in the publication of Dhawan & Narasimha (1958) that the effect was seen to change the rate of development of turbulent spots and hence alter the shape of the curve in the region close to transition onset. This effect can be seen in the work of Gostelow et al. (1992) where the universal intermittency curve deviates slightly from the experimental intermittency values near to the transition onset location. This concept has been coined 'sub-transition' and is addressed in more detail in more recent publications by Narasimha.

### 3.3.4 Relaxation parameter $\kappa$

Relaxation, defined as the ‘probability of the flow existing in a relaxing or calmed state following a turbulent spot or patch’, is a good discriminator between calmed regions following turbulent regions and ordinary laminar flow. This allows for its use as a good representation of the temporal extent to which a calmed region extends in the boundary layer.

Relaxed flow can be simply identified as intervals of continuously decelerating velocity following regions of unity intermittency. The relaxation value is then built up in exactly the same way as the intermittency parameter, by taking the mean across all the realisations at each sample point. Again, as with the intermittency detection, a smoothing of the data helps to maintain better continuity throughout the routine. A value of 1.0 represents a guarantee of relaxing flow at that location, likewise a zero represents no relaxing flow at any time.

The determination of relaxation parameter $\kappa$ is described in Gostelow et
al. (1997), as regions of negative $d\tau/dt$ after falling-from-unity intermittencies, where $\tau$ is a quasi-shear-stress. As no shear stresses are recorded in this current research work the relaxation parameter was determined directly from the instantaneous velocities as regions of negative $du/dt$ after each falling-from-unity intermittency region. As with intermittency, a qualifying region is tagged with 1, everywhere else 0. Averaging over all ensembles gives a picture of highly relaxed regions (close to unity), and non-relaxed regions (close to zero). Note that the routine was applied only to regions directly behind wake-induced turbulence within the boundary layer to help prevent incorrect detection in regions of naturally laminar flow.

3.3.5 Celerity rates

Celerity rates are a comparison between local propagation speed and the freestream velocity. This ratio, usually expressed as a fraction but sometimes a percentage, is a simple indicator of the speed of a feature. Values greater than 1.0 represent features travelling faster than the local freestream velocity.

Various techniques have been adopted for the calculation of the celerity rates for the various flow features, each with certain advantages and disadvantages that will be discussed at the point of implementation. The author's own intermittency technique has proven to provide very 'clean' results that are ideal for the determination of celerity rates based upon turbulent regions. Also, the RMS of velocity $u'$ has been shown to be a versatile parameter for the analysis of the turbulent strips, as well as the use of the relaxation parameter $\kappa$ for the calmed region.

The techniques adopt a similar process to each other, first preparing the data, whether it be intermittency or RMS of velocity, then applying a threshold setting followed by an edge detection for the determination of 'faces' which represent the feature's leading edge or trailing edge. In cases where this is performed repeatedly for each individual record, a mean location with a standard deviation is calculated, whereas for those cases where the ensemble average data is under scrutiny, only a single location can be
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determined.

3.3.6 Error analysis

An unavoidable part of experimentally sampled data is error accumulation, manifesting itself in various forms including noise, voltage drift and human error. It is therefore important to understand the accuracy of the recorded data to be able to fully interpret any extracted results. This section examines the errors inherent in every aspect of the data acquisition, using the 'standard error' of each parameter to describe the typical variation, defined as,

\[
\text{Standard Error } S = \frac{\sigma}{\sqrt{n}},
\]  

(3.17)

where \(\sigma^2\) is the variance and \(n\) equals the number of samples.

Unavoidable incursions

As previously explained, the wind tunnel operating speed is dictated by the need for a constant working section Reynolds number, which is entirely dependant upon the particular atmospheric conditions of each day. As a result, a non-constant working section freestream velocity is seen across each series of experiments.

The standard error for the freestream velocity is not a simple characteristic to calculate, due to the existence of other errors in the hot-wire setup, as described in previous sections and repeated in the next few paragraphs. The accumulated error for the hot-wire data is expressed in the following section.

Other unavoidable errors inherent to the experimentation include those from the equipment due to limitations on their accuracy, such as discretisation errors from the A/D card and low signal to noise ratios in the analogue filter. However, the errors incurred from these apparatus are of several magnitudes lower than the errors described in the following section.
Hot-wire errors

Errors in the hot-wire anemometry can be estimated from both the acquired data and a knowledge of the precisions of the laboratory apparatus. These can be superimposed to determine an estimate for the typical standard error of the velocities, and their respective statistics.

The largest error evident in the hot-wire data was caused by a problematic signal cable that laid undiscovered until after all the experimental runs were complete. Post-processing of the results showed a moderate d.c. offset in the voltage from the equipment, seemingly random, creating significant inaccuracies throughout all the recorded velocities up to a maximum of 5.0% error.

Other errors created through the usual channels of interference, noise, discretisation, calibration drift and general human error are all amalgamated into the final recorded signal. Comparing the data to the know freestream velocities, as calculated from §4.1.2, show a standard error, after correction for repairable issues such as calibration drift, of $S = 0.602 \text{ ms}^{-1}$ (⇌ 7.21% of the free-steam velocity).

These errors are not insignificant. They show that there is some uncertainty in the velocity data, however, regardless of these errors, the information in the data was only partially compromised. Phase averaging techniques aid in the elimination of these errors, and furthermore, fluctuations in the signal $u'$ are not affected as greatly as the absolute velocity $u$, as a d.c. offset to the recorded voltage does not affect these fluctuations.

Other parameters, such as intermittency and celerity rate, are not affected by these errors. Intermittency is calculated by comparing turbulent to non-turbulent signals, a procedure unaffected by minor amplitude errors. Celerity rates are determined from time-arrival information only, an aspect of the data unaffected by potential amplitude errors in the data. These statistics are the most commonly referred results in this report, and can be entirely relied upon.
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Figure 3.1: Plan view of Closed-Circuit Wind Tunnel showing Flat Plate and Wake Generator.

Figure 3.2: Cut away view of working section, showing flat plate, wake generator, contoured ceiling and the hot-wire with traverse.
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Figure 3.3: Dimensioned view of the working section showing wake generator sidewall disc with one rod, flat plate, hot-wire with traverse and contoured ceiling. Diagram to scale.

Figure 3.4: Conceptual sketch of the two wakes from the wake generator under normal operating conditions.
Figure 3.5: Hypothetical boundary layer reaction to wake velocity components in (a) primary and (b) secondary wakes. Figure not to scale, increasing time from upper to lower, freestream direction from left to right.
Figure 3.6: Locations for the second rod on the wake generator disc

Figure 3.7: Design template for rod brass holder.
Figure 3.8: Velocity profiles for undisturbed boundary layer at all $x$ stations. (+) Uncorrected velocities, (×) Wills corrected velocities and (○) Lange corrected velocities.
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Figure 3.9: Microphone brass receptacle design 2

Figure 3.10: Cross sectional view of microphone receptacle mounted underneath the flat plate, with a fitted microphone and static tapping tube.
Figure 3.11: Microphone array fixed to underside of flat plate with electronics and pressure lines attached.
Figure 3.12: Pressure transducer mounted in the flat plate.
Figure 3.13: Flat plate chassis modifications. The rear chassis support that houses the apertures for the extraction of cables and pressure lines.

Figure 3.14: Flat Plate Chassis Modifications. Design for the passage of the nine sensor power and signal cables.
Figure 3.15: Flat plate chassis modifications. Design for the passage of the static pressure lines. Each tube is a length of 1.65 mm diameter hypodermic needle.
Figure 3.16: Microphone response characteristics to varying source peak voltages. (a) Varying response across array. From top of plot, source voltage peak values are 20, 10, 5, 2 and 1 mV. (b) Demonstrating the linear response of each microphone.
Figure 3.17: Power spectra of signals with (black) and without (red) an anti-aliasing filter.
Figure 3.18: Examples of a microphone signal before and after interference cancellation.
Figure 3.19: Comparison of different intermittency detection routines for velocity data of a wake induced turbulent patch. Regions of colour indicate detected turbulence, author's method in red, $|du/dt|$ in blue, $u \cdot |du/dt|$ in green. Sample rate $f = 3200$ Hz.
Chapter 4

Undisturbed Flow

This chapter describes the natural boundary layer state without the influence of upstream wakes. As stated in §3.1 in these investigations, it is possible to induce three principal types of surface boundary layer, each dependant on the strength of the imposed adverse pressure gradient and the freestream Reynolds number. For the present experiments, the conditions were focused on investigating the single condition of laminar separation with turbulent reattachment.

4.1 Global properties

4.1.1 Pressure distribution

The contoured ceiling of the working section was designed to create a pressure field similar to that of a compressor blade suction surface. Chordwise pressure distributions were measured using the surface static ports from the apex of the leading edge to a distance far downstream of the hot-wire traverse system.

The static pressure coefficient, $C_p$, has been calculated using the usual definition,

$$C_p = \frac{p - p_{\text{ref}}}{\frac{1}{2} \rho U_{\text{ref}}^2},$$  (4.1)
which, since \( P_0 = p_{\text{ref}} + \frac{1}{2} \rho U_{\text{ref}}^2 \), can be re-written in the form,

\[
C_p = \frac{p - p_{\text{ref}}}{P_0 - p_{\text{ref}}},
\]

where \( p \) represents the local static pressure, \( p_{\text{ref}} \) the static pressure at the chosen reference location and \( P_0 \) the total pressure, constant throughout the working section. The denominator of eqn. (4.2) was measured using a pitot static combination, with the pitot positioned at the inlet to the working section. For comparability the chosen reference static location was identical with previous experiments, using the port at chord location \( x = 0.260 \) m.

**Differences between measured \( C_p \) values**

The isolated disturbance work of Chapter 5 was performed prior to the implementation of the microphone array and other wind tunnel modifications, as discussed in §3.1.4. Therefore the resolution of the initial pressure distribution measurement was restricted to the existing coarsely spaced surface pressure tappings, resulting in a pressure gradient chart with less than adequate information in the region of the separation bubble, see Figure (4.1a).

After the implementation of the microphone array, acquisition of a more highly resolved pressure distribution using the closely spaced microphone surface tappings became possible, showing greater clarity in the region of the bubble, Figure (4.1b).

Differences between the measured surface pressures are evident in the results. It is hard to locate the separation region visually due to the appearance of a large anomaly in the microphone signal data between \( 0.75 \leq x \leq 1.0 \) m. The bubble, as represented by the slight plateauing of the value for \( C_p \), exists between \( 0.525 \leq x \leq 0.75 \) m, however, an unidentified feature is apparent immediately following reattachment.

Surface flow visualisations published in D’Ovidio & Gostelow (2000) confirm the bubble extent but fail to elucidate the feature following reattachment. It is conceivably an anomaly accidentally introduced by the implementation of the microphone array system, perhaps fortunately downstream of the turbulent reattachment region.
D’Ovidio & Gostelow (2000) noted the discontinuity in the pressure gradient at a chordwise location coincident with the leading edge blend location \( x = 0.147 \) m. This was due to curvature discontinuities between the super-elliptic leading edge shape and the flat plate, and was not seen to interfere with or affect the quality of the downstream flow.

### 4.1.2 Freestream velocity distribution

The freestream velocity was recorded by means of the hot-wire anemometer and a temporarily mounted pitot-static combination positioned close to the element of the hot-wire. Both were simultaneously traversed above the boundary layer at a height of \( y = 50 \) mm covering the full chordwise extent of the traverse mechanism. Hysteresis effects were checked by traversing from \( x = 0.80 \) m to \( x = 0.20 \) m then returning to \( x = 0.80 \) m, and repeated for three wind tunnel fan operating speeds of 189, 194 and 199 rpm, covering the typical operating range experienced during experimental testing.

Steady flow data were acquired at a sample rate of 3.2 kHz for a period of 10 seconds at each location. Surface-pressure data were acquired at the start and end of each hot-wire traverse, i.e. while the hot-wire was at locations \( x = 0.80 \) and \( x = 0.20 \) m. The results are presented in Figure (4.2).

From the hot-wire data, three freestream velocity distributions were acquired for each variation of wind tunnel speed. From this data an algorithm was developed to permit the estimation of the freestream velocity dependant upon chord location and wind tunnel fan speed.

The accuracy of this freestream velocity distribution information was of utmost importance to the calculation of reliable feature celerity rates. As explained by the error analysis of §3.3.6, the use of the hot-wire velocity data from the experimentation was not entirely reliable and would have resulted in small errors in any celerity estimates.

**Traverse interference**

The pitot-static velocity tests with the hot-wire holder stationed in the far upstream location \( x = 0.20 \) m have been plotted with the symbols + □
and *. For each, common differences can be seen when compared to the pitot-static data taken with the hot-wire holder in the downstream location ($x = 0.80$ m), plotted with symbols o * and ◊.

At $x = 0.30$ m, there is an increase in the local value for $U_\infty$ of 0.06 ($\approx 0.7\%$) when the hot-wire holder is upstream, consistently evident for each operating speed. Also, within the flow region $0.40 \leq x \leq 0.75$ m, $U_\infty$ values are consistently lower. This perhaps demonstrates that the separation bubble is not evident whilst the hot-wire holder is upstream, due to the wake of the hot-wire holder enforcing a premature turbulent boundary layer and suppressing separation.

If this is the case, then this information can aid in the determination of the extent of the boundary layer separation bubble. It can be proposed that profile inflexion begins near to station $x = 0.425$ m, separation perhaps at $x = 0.575$ m, and then reattachment near to station $x = 0.75$ m, concurring with the values from the previous section. This is shown later to be consistent with velocity profile information and other statistical parameters useful for the determination of the separation bubble.

### 4.2 Boundary layer

Full boundary layer traverses were performed using the hot-wire anemometer and the microphone array simultaneously. For the hot-wire, the full extent of the stream-wise traverse was accommodated to gather as much information as possible on the boundary layer, over a streamwise extent of $0.15 \leq x \leq 0.80$ m. Transverse movement was extended far out into the freestream to ensure full velocity profiles were acquired, giving a height range of $0.15 \leq y \leq 50.00$ mm, with a sensible concentration of locations in the near-wall region.

Microphone array acquisition was performed in two blocks covering the regions $0.275 \leq x \leq 0.625$ and $0.65 \leq x \leq 1.00$ m. The data are then concatenated to leave a full array-length data matrix with a slight discontinuity at the join (i.e. between $x = 0.625$ and $x = 0.65$ m).
4.2.1 Velocity distribution

The surface boundary layer commences at the very leading edge of the flat plate and progressively thickens with chordwise travel. Data readings were physically restricted to an upstream location limit $x = 0.150$ m, and hence boundary layer properties were not known for regions upstream of this point, although it is quite reasonable to presume it to be laminar in nature.

Time-averaged steady flow velocity profiles for all the chord locations have been presented in Figures (4.3, 4.4), showing the early laminar boundary layer, the development of inflexion under deceleration, separation, transition, and turbulent reattachment. Streamlines are included in the final overlay to help visualise the mean bubble location and the variation of boundary layer height as determined from the velocity profiles.

Self-similar Falkner-Skan profiles

**Theory** From the principle of self-similar profiles in steady two-dimensional boundary layer flows, Blasius (1908) developed the popular flat-plate flow equation,

$$f'''' + ff'' = 0, \quad (4.3)$$

related to the conventional Cartesian domain through the following relationships,

$$f'(\eta) = \frac{u}{U_\infty}, \quad \eta = y \sqrt{\frac{U_\infty}{2\nu x}}. \quad (4.4)$$

Falkner & Skan (1931) later developed the Blasius equation to allow for the determination of more complex boundary layers, including wedge flows of constant diffusivity. Similar to equation (4.3), the Falkner-Skan equation incorporates the pressure gradient parameter $\beta$,

$$f'''' + ff'' + \beta(1 - f'^2) = 0. \quad (4.5)$$

Using several boundary layer conditions, Hartree (1937) calculated analytical solutions to eqn. (4.5), for varying degrees of pressure gradient $\beta$, more commonly termed the ‘Hartree pressure gradient parameter’.
The theory adopts a simple pressure gradient principle that does not qualitatively apply to realistic profile pressure distributions, using a chordwise distance proportionality relationship such as,

\[ \frac{U}{U_\infty} = K \left[ (2 - \beta) \frac{x}{L} \right]^{\frac{\beta}{2-\beta}}, \]  

that creates an ordinate tending to infinity as the chord location approaches the leading edge. As such, no single value for \( \beta \) can represent the entire pressure distribution of the current experimentation.

Using a computational code to solve the Blasius equation from DeLullo (2003), which incorporates a second-order Runge-Kutta method, modifications were implemented to expand the solution for the Falkner-Skan equation with adaptations incorporated to include dynamic \( \beta \) variation to account for the non-self-similarity of the profiles with chord location.

**Calculated Profiles** The Falkner-Skan profiles for each \( x \) location are included in Figures (4.3, 4.4) for the extent of laminar flow, showing a reasonable match to the experimental data throughout. Due to the rectification of the reverse flow in the hot-wire velocity profile, the code does not accurately determine suitable Falkner-Skan profiles for separated regions as it unavoidably attempts to accommodate both consistently positive near-wall velocities with a strong inflexion point. Therefore as separation is approached the Falkner-Skan profiles regress away from the separation value of \( \beta = -0.1988 \) at approximately \( x = 0.55 \) m. As a result, in the separated region the computed profiles do not match the data as accurately as the upstream attached profiles. Turbulent profiles are not establishable.

**Overall picture**

The final inset of Figure (4.4) shows a composite of the various velocity profiles, with estimated streamlines for the separation bubble and boundary layer thickness \( \delta \), as based on the various conclusions from this Chapter.

The separation bubble is very thin in comparison with the boundary layer thickness, and terminates near to transition completion \( x_T \). The coincidence of these locations is believed to result from the influence of the turbulent shear layer enforcing reattachment and resisting further separation.
4.2.2 Integral parameters

Separated flow can be characterised by the shape factor distribution $H = \delta^*/\theta$ across the surface. Figure (4.5) shows the development of the three common boundary layer integral parameters with chordwise location as derived from the experimental velocity profiles and the Falkner-Skan profiles.

According to White (1991), the shape factor for flat plate boundary layers rises above $H \approx 3.5$ at the separation point, and similarly the point of reattachment is also associated with the return of the curve past $H \approx 3.5$ (Cumpsty 1989). Using these criteria, the separation bubble can be estimated to exist between $0.465 \leq x \leq 0.660$ m. This is a little earlier than the estimates from the previous sections where reattachment occurs as late as $x = 0.775$ m.

A quick estimate by the Thwaites method (White 1991) produced a different result. Based on eqn. (4.7) and expecting separation to occur at $\lambda \approx -0.09$, the Thwaites method estimates a separation location of $x = 0.58$ m, but does not work for transitional flows and cannot estimate a reattachment point.

$$\lambda = \frac{\theta^2 U'}{\nu} \quad \text{where} \quad U' = \frac{\partial U}{\partial x}. \quad (4.7)$$

It is unusual to see only moderate variances in the shape factor, however one must recall that the separation bubble encountered in this research is of a long and thin type, with little reverse flow. This creates only small differences in integral parameters calculated from the velocity profiles, such as the shape factor $H$, which may explain the disagreement over the estimated reattachment point.

4.2.3 Laminar instabilities

Due to the nature of hot-wire anemometry acquisition with a single hot-wire it is not possible to track individual instabilities as they convect downstream, therefore pressure field information was acquired for the surface flow using the microphone array system to investigate the time dependant features of the natural boundary layer and its separation bubble.
Acquired in two halves, Figure (4.6) shows contours of pressure data from the microphones for a single record.

The most prominent feature is the clear detection of developing instabilities across the transition region. Absolute amplitude levels for these disturbances were not calculable, although from hot-wire data it was seen that the local streamwise velocity perturbations were as great as 7% of the freestream velocity, rising to as much as 80% of $U_\infty$ as each spot breaks down, downstream of $x = 0.70$ m.

The fundamental frequency of these instabilities is 91 Hz, as can be seen from the power spectra in Figure (4.7). These acoustic traces of the instabilities, which have been amplified by the adverse pressure gradient, are clearly strongest at transition inception and through the transition. Once the coherence is lost in a turbulent layer the amplitude of the instabilities is diminished.

Walker (1989) developed eqn. (4.8) during work on turbulent spot predictions to estimate Tollmien-Schlichting disturbance frequencies undergoing the most amplification in naturally developing boundary layers,

$$\frac{\omega \nu}{U^2} = 3.2 \text{Re}^{-3/2}. \quad (4.8)$$

The distribution of predicted dominant disturbances is presented in Figure (4.8), and shows that the location at which the 91 Hz frequency undergoes the strongest amplification rate is near to $x = 0.325$ m, and it can therefore be proposed that the instabilities present in the transition region begin here.

A similar trend of constant instability frequency was also seen by Stieger (2002) in his boundary layer studies across a flat plate. The growing instabilities observed across the separation bubble are noted to match the estimated dominant frequency associated with a location far upstream of the separation point.
Breakdown

As transition develops, the breakdown rates accelerate and the spots develop higher frequency components, thus becoming less visible in the contour plots due to the lack of spatial resolution. At this point the data can be visualised more clearly from the actual traces of each microphone, see Figure (4.9).

Referring back to §2.2.2 on wave breakdown behaviours under adverse pressure gradients, as described by Walker (1989), one might expect to see a continuous breakdown of the instabilities at a single chord location due to the severity of the pressure gradient. Inspecting the contours of Figure (4.6) shows that breakdown near the wall does indeed occur in a random yet consistent manner at a constant chord location, with no evidence of set behaviour or grouping of spots.

This can be verified by studying the signal traces of microphones 17 and 18 (x locations 0.675 and 0.70 m) as shown in Figure (4.9). No evidence of laminar regions exists between the spots, amplification occurring uniformly across the time-trace, which demonstrates continuous spot production with time.

However, examining the hot-wire velocity traces in this region, but further towards the boundary layer edge, shows evidence of breakdown in sets, as reproduced in Figure (4.10). For a short distance from $x = 0.70$ m, there exist regions of laminar instability interspersed with turbulent spots, showing that the instabilities break down in a grouped formation. In describing measurements of intermittency, it will be shown that the transition length is $L_T = 0.15$ m; this is a substantial distance for the coalescence of turbulent spots. It would therefore be appropriate to propose that instability breakdown occurs randomly in sets after the transition onset location, $x_t$.

Propagation rates

The temporal distribution of these disturbances can be measured to determine their convective rates through the transition region. Initially, hand-calculated values were determined from plots similar to that of Figure (4.6). This was backed up by the application of a computer code that successfully
determined the velocities of 234 wave packets from 17 arbitrarily selected records. The routines had their tolerances set to conservative levels to prevent the inclusion of features that would have been deemed inappropriate. An example of the detected wave packets from record 14 can be seen in Figure (4.11).

The average velocity of the 234 detected disturbances was calculated to be 3.380 ms\(^{-1}\), with a standard deviation of just 0.147 ms\(^{-1}\). This value is approximately 44\% of the freestream velocity at \(x = 0.750\) m. DNS work by Na & Moin (1998) reports wall-pressure fluctuations in a reattaching turbulent boundary layer to have celerity rates in this range, and also as low as 33\%. As one might expect, the celerity rates are seen to decrease with downstream location, showing a deceleration of the pressure fluctuations as the shear layer separates.

### 4.3 Natural transition

Referring back to §2.2.2, it was determined that under strong adverse pressure gradients turbulent spots were developing randomly, or in sets, after the transition onset location, \(x_t\). This behaviour leads to a protraction of the transition length, \(L_T\), as complete merging of the turbulent spots takes considerable surface travel before a fully turbulent boundary layer is ultimately achieved.

#### 4.3.1 Intermittency

The exact development of the transitional region is best monitored using the intermittency parameter \(\gamma\), which can be calculated from the hot-wire velocity information.

Intermittency profiles, showing the development of turbulent flow with boundary layer height, show the distribution of the intermittency parameter. These have been plotted in Figure (4.12) for all regions demonstrating an intermittency greater than zero. From this information a constant height for the calculation of temporal intermittency was determined, partly using
the $\delta$ criteria of Walker & Wu (1991), as $y = 2.00$ mm. Using this height for $x \sim t$ plane contour plots gives the clearest representation of turbulent development, as used in the following chapter to demonstrate the influence of turbulent wakes on the natural boundary layer.

Narasimha universal intermittency distribution

For the stable boundary layer state of this chapter, a simple time-averaged chordwise distribution of the intermittency will suffice, showing the development of $\gamma$ as the turbulent spots grow and merge (see Figure 4.13). The distribution is accurately represented by the Narasimha universal intermittency distribution, as previously described in section §3.3.3.

At the commencement of this research work, little had been published on the intermittency distribution of transitional regions across separation bubbles under an adverse pressure gradient, therefore the result of this intermittency analysis was included in Thomas et al. (2002) as some of the first evidence to confirm the accuracy of the Narasimha universal intermittency distribution for such conditions.

Using the universal intermittency distribution, the transition onset and completion locations can be determined from $\xi = 0$ and $\gamma = 99\%$, which results in chord locations $x_t = 0.612$ m and $x_T = 0.767$ m, with a transition length of $L_T = x_T - x_t = 0.155$ m.

4.4 Discussion

This chapter has described in detail the reliable creation of a separation bubble in laminar flat plate boundary layer flow under an adverse pressure gradient and the development of natural transition to turbulence.

Matching Falkner-Skan velocity profiles have been generated to show the boundary layer trend towards inflection, and used as an aid to the calculation of the boundary layer integral parameters, $\delta$, $\theta$ and $H$, and the location of the separation point.
The steady-state separation bubble is estimated to begin at $x_s = 0.56 \pm 0.03$ m and terminate in near coincidence with the end of transition at $x_r = 0.75 \pm 0.01$ m. This results in a long and thin laminar separation bubble, of length $0.19 \pm 0.02$ m and height approximately $0.75$ mm, that has little influence on the surface pressure distribution.

Transition has been detected using reliable intermittency techniques, and shown, with the aid of Narasimha's universal intermittency distribution, to begin at $x_t = 0.612$ m and complete with $\gamma = 99\%$ at $x_T = 0.767$ m. Transition length $L_T = 0.155$ m.

The amplification of natural freestream instabilities in the boundary layer, of the Tollmien-Schlichting variety, leads to vortex breakdown and the development of turbulent spots. The amplification of these spots is seen to be highly accelerated in the unstable separated shear layer and transition to turbulence quickly progresses, causing shear layer reattachment responsible for the closure of the reverse flow region.
Figure 4.1: Flat plate pressure distribution $C_p$, as measured before and after implementation of the flat plate and wind tunnel modifications. (b) shows the existence of an anomaly between $0.75 \leq x \leq 1.00$ m.
Figure 4.2: Measured freestream velocities using a pitot-static combination and hot-wire anemometry. Hot-wire data is compensated for voltage drift.
Figure 4.3: (c) Normalised velocity profiles for chord locations $0.15 \leq x \leq 0.525$ m, (—) Falkner-Skan profile approximations.
Figure 4.4: (○) Normalised velocity profiles for chord locations $0.55 \leq x \leq 0.80$ m, (—) Falkner-Skan profile approximations. Final insert: $x \sim y$ plot of normalised profiles with locus of separation bubble and of boundary layer thickness $\delta$. 
Figure 4.5: Boundary layer integral parameters, displacement thickness $\delta^*$ (□), momentum thickness $\theta$ (◇) and shape factor $H$ (○), with equivalent Falkner-Skan profile parameters (•).
Figure 4.6: Microphone signal contour plot for single record 14. Data has been calibrated, filtered, and contour corrected.
Figure 4.7: Power spectra for record 14, microphones 17–24 (x locations 0.675 to 0.850 m in steps of 0.025 m).
Figure 4.8: Estimated dominant instability frequency against streamwise distance calculated using theory of Walker (1989). Both experimental and analytical data presented.
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Figure 4.9: Traces from record 14 for microphones 17–24 ($x$ locations 0.675 to 0.850 m in steps of 0.025 m). Data has been calibrated and filtered. Sample rate $f = 3200$ Hz.
Figure 4.10: Hot-wire velocity trace at $x = 0.70$ m $y = 2.00$ mm, showing the development of spots in groups, or sets, qualifying as an intermittently turbulent region.
Figure 4.11: Traces for microphones 17–21 from record 14. Data has been calibrated, filtered and contour corrected. (o) detected peaks, (---) identified related peaks, (—) calculation of propagation velocity.
Figure 4.12: Time-averaged intermittency profiles for the steady state boundary layer. (- -) at $y = 2.00$ mm indicates nominal height used for boundary layer analysis.
Figure 4.13: Time-averaged intermittency distribution for the steady state boundary layer. (—) shows the Narasimha Universal Intermittency Distribution.
Chapter 5

Single Wakes

This chapter describes the series of experiments performed using a single rod on the wake generator to impart individual wakes into the freestream flow. The interaction between a turbulent wake and the boundary layer, the resultant development of early transitional flow before the separation point, and the consequences of this turbulent flow upon the laminar separated shear layer are all discussed.

5.1 Wake properties

5.1.1 Velocity content

Each rod of the wake generator imparts changes to the freestream flow in the form of a wake. The impact on the freestream velocity is shown in Figure (5.1) as a variation of the normalised hot-wire velocity. The primary wakes (those generated closest to the flat plate leading edge) have a peak velocity deficit of approximately 3.9%, and a temporal width of approximately 0.10 s. The secondary wakes (generated on the cyclic return and further upstream) have further to travel before reaching the flat plate and therefore have slightly weaker, more dissipated, characteristics; showing a lower velocity deficit of approximately 3.0% and a greater temporal width of 0.11 s.
Also, one can see short oscillatory behaviour at the edges of each wake, perhaps evidence of vortical structures in and around the wake. Therefore, although steps were taken to prevent their development (see §5.1.4), some degree of vortical behaviour may be prevalent in the wakes.

5.1.2 Turbulence content

According to Zdravkovich (1997), with a cylinder Reynolds number $Re_D \approx 3600$, similar to that for the rod of the wake generator, the state of the shed wake ought to be transitional in the shear layer directly behind the cylinder, and therefore turbulent a short distance downstream.

This information is useful in establishing the state of the wake before it carries to the boundary layer, and becomes especially important when one considers that the turbulent content of the wakes is most likely to be the influencing factor in the development of boundary layer instabilities on the flat plate.

The typical intermittency $\gamma$ distributions for early primary and secondary wakes are shown in Figure (5.2). Although the velocity characteristics for the two different wakes are not largely dissimilar, it is immediately obvious that the turbulent content differs greatly. Primary wakes (created closest to the leading edge of the flat plate) contain a higher degree of turbulence than the secondary wakes, peaking at $\gamma_P = 0.7$ and $\gamma_S = 0.1$ respectively. This difference can perhaps be explained as the result of dissipation of the secondary wakes which occurs in the additional 42 cm streamwise distance necessarily covered as a consequence of their greater upstream origin.

The author presents here a simple check to this hypothesis: It can be seen that the travelling from $x = 0.15 \text{ m}$ to $x = 0.80 \text{ m}$ and taking approximately 0.08 s, decreases its peak intermittency from $\gamma_P = 0.7$ to $\gamma_P = 0.1$. The distance between the two origins for both wakes is equivalent to the diameter of the wake generator disc, 42 cm, with an approximate freestream flow speed of 6 ms$^{-1}$ in this region. Therefore the time taken to span this gap is approximately 0.07 s. The similarity of these two time periods infers a similar dissipation of turbulent flow, and indeed the secondary wake in-
termittency value does begin at $\gamma_5 = 0.1$. This basic hypothesis could help to justify the large variation in intermittency seen between the two wakes.

5.1.3 Approach angles

Another difference between the two types of wake is the opposition of approach angle created by their opposing vertical velocity components. The primary wakes incorporate a deficit in *downward* velocity, towards the boundary layer, whereas the secondary wakes, generated on the return journey of the rod around the wake generator, incorporate a deficit in *upward* velocity, away from the boundary layer and into the freestream. This is demonstrated in Figure (3.4) showing the effective wake pattern as seen from the flat plate surface. In this diagram the small directional arrows depict the 'internal' velocity of the wake, showing primary wakes to have a downward, and secondary upward, vertical velocity component within themselves. This is later related to the jet effect seen within passing wakes.

Also, the primary wakes, effectively approaching the boundary layer from the outer freestream, propagate across the surface with a 'forward' lean, with an average elevation angle of approximately 11 deg. The secondary wakes, approaching the boundary layer from below the leading edge, show a 'backward' lean, with an opposite elevation angle of $-11$ deg.

Dong & Cumpsty (1990b) performed wake interaction experiments upon supercritical profile cascaded compressor blades. They consider the turbulence intensity to be the important issue influencing suction surface boundary layers, and do not put so much emphasis on the variation of velocity deficit within the wakes. In the author's works, turbulence intensity is the greater variant between the primary and secondary wakes.

5.1.4 Frequency content

A non-constant vortex shedding frequency ($f = StU/D$), manipulated through the use of a reducing rod diameter with increasing span, suppresses the development of von Kármán vortex streets in the wake, which could other-
wise impart constant-frequency effects into the boundary layer through the growth of stable vortices (Schlichting 1968).

As this research is aimed at determining the effects of wakes as shed from upstream stages, it was felt important to minimise systematic vortical content from the wakes to permit the investigation of wake velocity deficit and turbulence effects only. However, as described in §5.1.1, a small amount of vortical behaviour is evident in the hot-wire velocity data of the wakes in the freestream.

## 5.2 Wake induced disturbances

The passing of each wake above the early flat plate laminar boundary layer causes the generation of patches of turbulence within the layer directly beneath the footprint of the wake. Two different mechanisms for the generation of these patches of turbulence have been detected, each mechanism related to the strength of the passing wake.

**Primary wakes (Figures 5.3–5.6)**

For the primary wakes the intermittency is as high as $\gamma_p = 0.7$, and regions of turbulence are present within the boundary layer directly under the wake path. Analysis shows that the intermittency is not unity at the first measurement location, and hence the boundary layer turbulence is still developing, with further transition process remaining. It is conceivable that the passing wake induces transition under its path at the very leading edge of the flat plate, such that the strip grows into a strongly turbulent one as it carries towards $x = 0.20$ m. For this reason the mechanism has been categorised in this work as that of ‘by-pass’ transition, whereby the turbulent spots are initiated directly without having to undergo the natural process of instability amplification.

Figures (5.3–5.4) show $t \sim y$ contours of the RMS of velocity $u'$ at various chord locations and demonstrate the initiation and growth of the induced turbulence within the boundary layer (note the change of scale between
the figures). Low values of \( u' \) represent laminar flow, and similarly high \( u' \) values are regions of perturbation and therefore most likely turbulent flow. The patches of turbulence are newborn spots that propagate with the flow, whilst continuously evolving and expanding.

The interaction of the turbulence with the separation bubble and transitional region, as can be seen in Figure (5.4) and Figure (5.6), is described in detail in §5.3.

**Secondary wakes (Figures 5.7-5.11)**

The secondary wakes are less effective at inducing boundary layer turbulence. It is thought the presence of the secondary wake above the attached laminar boundary layer on the flat plate encourages the amplification of laminar instabilities, perhaps already present in the boundary layer, that develop into individual turbulent spots from a natural growth process.

Indications for this come from inspection of individual velocity traces from within the boundary layer showing evidence of strong short wavelength perturbations. These perturbations increase the local RMS of velocity but, due to their laminar nature, do not influence the intermittency to any strong degree, see Figure (5.7). Figures (5.8-5.9) show RMS contours for the induced disturbance of the secondary wake. Relating the contours of \( u' \) at the location \( x = 0.15 \) m to the intermittency, as represented in Figure (5.10), shows the high magnitude of the perturbation within the boundary layer with low levels of turbulence, signifying a strongly laminar disturbance.

Induced in this way, the boundary layer disturbance is merely transitional and requires a period of surface travel for development before it achieves strong characteristics similar to those created beneath the footprint of the earlier primary wake. These clear differences in induced turbulence levels allow for a good comparison of wake induced turbulence versus wake induced transition.

These results agree with work by Orth (1993), who used a similar experimental arrangement and showed that the boundary layer turbulence
induced by passing wakes was proportionate to the strength of the passing wake turbulence intensity.

**Growth & development trends**

The initial disturbances generated from both wakes resemble newly formed turbulent spots, somewhat circular in cross-section and highly turbulent at their centre. Although individual turbulent spots are truly three-dimensional, each wake creates a spanwise row of disturbances, or tightly juxtaposed spots, creating an essentially two-dimensional turbulent strip along the width of the flat plate (See Chp. 4 of van Hest 1996).

These images compare excellently to those of artificially generated spots investigated by Gostelow *et al.* (1990); an example of which has been copied to Figure (5.12) for the RMS of velocity along the central vertical plane of such a spot.

With the progression of each turbulent strip follows a change in the structure, or internal distribution of kinetic energy, within them, as seen in the ensemble averaged hot-wire velocity data (Figures 5.3–5.4, 5.8–5.9). The strip splits into two visible regions: the leading downstream portion, which remains highly turbulent and fast-travelling, referred to here as the *core*; and the remaining two thirds of the strip, which diminishes into what appears to be a series of smaller entraining turbulent spots, referred to here as the *tail*. See Figure (5.13) for a schematic of these regions, also study $x = 0.30$ m in Figure (5.3) to see the initiation of these regions in those disturbances induced by primary wakes, and $x = 0.45$ m in Figure (5.8) for those of the secondary wake (this metamorphosis occurs further downstream due to their weaker origins).

Similarly, Gostelow *et al.* (1997) observes this relationship between the 'age' of the turbulence and the value for $u'$. In his studies of artificially generated turbulent spots, values for $u'$ differ between the turbulent spot and the natural turbulence of the surrounding boundary layer. To quote, "Paradoxically, the triggered turbulent spot has a lower disturbance level than the surrounding boundary layer. This may be because the triggered
spot is composed of older turbulence while the natural boundary layer has not yet completed its transition process.” This ability to identify the two zones of turbulent flow aids in the differentiation of the turbulent strips from the surrounding boundary layer.

Jitter considerations were investigated, see Appendix (A.2), but were not shown to be significantly responsible for the features seen in the $u'$ data.

The trailing spots in the tail generate a lower RMS of velocity, $u'$, than the core, yet retain their high intermittency $\gamma$. This behaviour is more evident in the disturbances created by the secondary wake by inspecting the growth from $x = 0.40$ m to $x = 0.50$ m in Figure (5.8). In this short distance, the front of the spot grows upwards into the freestream whilst the trailing edge suppresses itself into a much lower value of $u'$.

Before speculating on the apparent causes for this redistribution of RMS of velocity, studies of the flow intermittency $\gamma$ will be visited in the following section.

5.2.1 Intermittency

RMS of velocity $u'$ is not the clearest parameter for the representation of turbulent energy, whereas intermittency, $\gamma$, is a direct representation of the turbulent content. Figures (5.5–5.6, 5.10–5.11) show the intermittency parameter for the same experimental data as the $u'$ contour plots in Figures (5.3–5.4, 5.8–5.9).

The strength of the wakes is easily seen from these plots by inspecting the upper freestream regions, confirming peak values of $\gamma_P = 0.7$ and $\gamma_S = 0.1$ for the primary and secondary wakes respectively.

Unlike the $u'$ contour plots, the intermittency $\gamma$ does not show any redistribution of the turbulence levels within the developing spots. The tendency to produce core and tail features, as described earlier in the RMS, is not visible in the intermittency contours, showing only uniform levels of turbulence throughout each disturbance.

The author presents here his interpretation of this dissimilarity between the RMS of velocity $u'$ and the intermittency $\gamma$. 
One can acknowledge that RMS of velocity does not accurately represent the turbulent content of ensemble averaged velocity data, whereas intermittency is a more specific indicator for the presence of turbulence. As described earlier, a region of high RMS of velocity having low intermittency indicates the presence of instabilities, or local perturbations, of a laminar nature. However, regions of low RMS of velocity with close-to-unity intermittency must be fully turbulent without having strong variations to the mean flow velocity.

Recalling that turbulent spot breakdown increases the band of detectable frequencies, one can envisage that a hot-wire signal trace itself may become more 'noisy', with less of one fundamental frequency standing out from the developing harmonics. The result of this would be a reduced statistical variance, and hence RMS, as the superposition of the numerous frequencies reduces the variation to the mean. Additionally, some of the highest frequencies are eliminated from the signal due to anti-aliasing filters. In terms of the recorded data, this would translate into a reduction of the RMS of velocity as the clusters of spots continue to break down. Throughout all this the flow remains or becomes increasingly turbulent, generating very high intermittency values.

Therefore it may be that these trailing spots within the tail contain older, more mature, turbulence due to the lower $u'$ values; and the contrasting leading edge core is a region of constantly replenished, and hence perpetually new, turbulence, with a consequently higher value for RMS of velocity than the tail.

The implications for this are that the wake continuously replenishes the leading edge of the turbulent strip with fresh sources of turbulence, whilst the trailing turbulent spots in the tail convect and develop naturally in a predictable manner. This also dictates that the propagation rates for the leading edge of the turbulent strips must be equal to, if not greater than, those of their respective wakes. Addison & Hodson (1990a-b) mention the predilection of a wake to promote turbulence under its leading edge, ahead of previously induced turbulence travelling slower than itself, which could hence create the effect of apparently greater-than-freestream velocity
disturbances. This is discussed further in §5.2.3.

Only after sufficient travel to the naturally developing turbulence of the boundary layer at $x = 0.70$ m do the levels of turbulence within the developed strips seem to change, and in an equivalent manner for both the primary and secondary. Inspecting the final location, $x = 0.80$ m, where the boundary layer has already re-attached and the effect is most marked, one can see that intermittency at the very centre of the turbulent strip drops slightly to $\gamma = 0.8$, particularly in the regions close to the surface, whereas the outer regions remain highly turbulent.

This is perhaps due to the data acquisition losses in terms of insufficient sampling rates, resulting from an inadequate temporal resolution as required to detect the highest frequencies in the fully developed turbulence.

**Intermittency distribution**

It has been argued that the secondary wake generated turbulent strips are ordinary spots artificially encouraged by the passing of the wake, and for this reason they ought to behave and react in a similar manner to any other naturally induced spot, i.e. one created from instability amplification. Narasimha's universal intermittency distribution, as previously mentioned in §3.3.3, should therefore describe fairly well the turbulent growth rate of these wake induced spots as they propagate downstream.*

Figure (5.14) shows values of intermittency taken from within the boundary layer, at a constant height of $y = 2.00$ mm, for time steps coincident with the centre of the passing turbulent strip. The distribution of the intermittency shows here that the rate at which the strips develop is well predicted by Narasimha's universal growth curve.

This good general agreement between the strip intermittency distribution and that for natural transition demonstrates their highly predictable nature and confirms their growth history to be that of a natural mode. The

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*Those of the primary wake, being born from a by-pass form of transition, are almost immediately fully turbulent and therefore have little growth distribution to analyse.
spots are initiated at a point upstream of the hot-wire's range, so an extrapolation of the curve has been performed, estimating this chordwise location to be approximately $x_t \approx 0.10 \pm 0.02$ m, which is a point that lies on the curvature of the leading edge.

It ought to be noted here that due to the varying atmospheric conditions between tests which therefore affected the tunnel operating speed that was set to maintain a constant flow Reynolds number, non-constant transition onset locations $x_t$ were evident when calculated from the entire experimental data-set. Hence it can be seen that the data extrapolations in Figure (5.14a) for the location of $x_t$ do not converge for all cases. The abscissa scale should, of course, be drawn to the $\xi = (x - x_t)/\lambda$ scale, as demonstrated in Figure (5.14b) where the data fits certainly collapse onto an identical curve and onset begins at ($\xi = 0$) but does not demonstrate the variation of transition onset location between experiments.

5.2.2 Velocity profiles

Figure (5.15) demonstrates the various profile shapes that the boundary layer becomes during the passing of a turbulent strip and its trailing calmed region. This plot is comparable to Figure 6 from Gostelow et al. (1997), showing the same velocity profiles for a passing turbulent spot. The same change in profile shape is seen in each plot, with the boundary layer switching from laminar to turbulent at the moment of spot/strip arrival, remaining full yet without perturbation in the calmed flow, before finally slowly returning to the natural laminar state again.

5.2.3 Celerity rates

**Determination methods**

Measurement of the leading and trailing edges of each wake induced disturbance is complicated by the constant growth of the disturbances as they propagate in the boundary layer, and also by the non-constant freestream velocity.
The detection of leading and trailing edges can be estimated from both the RMS of velocity $u'$ and the intermittency data $\gamma$; but before the various techniques are explained, it is wise to discuss the basic methodology.

For the RMS data, a threshold value has to be chosen to decide at which point the data changes from laminar flow into that of a turbulent flow disturbance. Once determined and gathered, depending on the technique used, edge locations or contour lines are produced on $x \sim t$ plots from which an estimation of the propagation velocities can be calculated. In the case of discrete points, polynomial curve fits were applied to the data points to attempt to determine the accelerative nature of the edges, but the information is subjective and therefore only the trend is noted.

The leading edges of all the wake induced disturbances encounter the natural transition region and cannot therefore be tracked beyond $x \approx 0.60$ m. For the secondary wakes, whose transitional disturbances only develop sufficiently to be tracked after $x \approx 0.3$ m, this leaves only a few spatial locations for the analysis, which leads to difficulties in the determination of accurate propagation rates.

Three different techniques for the estimation of the celerity rates in the data were developed, each designed to determine the same thing: the exact arrival times for the leading and trailing edges of instantaneous or ensemble averaged turbulent strips. Where the distribution with height was considered a mean location has been presented, with a plus-or-minus variation range.

1. The first technique is the most reliable. It is automated in the sense that it is given the intermittency data for an entire experimental configuration plus a set of constraints, and it returns a series of plots representing the celerity rates for each of the leading and trailing edges detected in the data. Standard contour lines are drawn to three-dimensionally smoothed intermittency data at a range of threshold settings. The disturbances are identified and their leading and trailing edge velocities and celerity rates calculated, based on local freestream values.

Being automated, this technique is not open to subjective human influences, although it has the downside of producing the occasional peculiar
plot where more edges are detected than necessary. Aside from this, the information is very useful.

The remaining techniques all require human intervention to determine those locations along which to generate least-squares and polynomial fits, and could perhaps therefore be considered to be subjective:

2. This technique is applied to the RMS of velocity, $u'$, and estimates the time arrival of each ensemble averaged turbulent strip at each spatial coordinate $(x, y)$. The $u'$ data is low-pass filtered and tolerance matched to determine the outer edges of regions of high perturbation. From this, a picture can be built up of each turbulent strip path and, more importantly, estimates for the local velocities and celerity rates can be determined. In most cases, a linear fit to the locations is sufficient, however, second-order curve fits are also attempted to help determine any acceleration or deceleration trends.

3. The third technique incorporates the relaxation parameter $\kappa$, which is itself derived from the instantaneous hot-wire velocity data, to estimate the location of the trailing edge of the calmed region. The results from this analysis are open to question as $\kappa$ incorporates strong data smoothing and filtering, which in turn decreases the resolution of the information.

**Turbulent strip leading edges**

The leading edges of the boundary layer disturbances induced by both the primary and the secondary wakes were detected using techniques 1 and 2, as described above.

The intermittency contour technique, 1, provided a lot of reliable celerity information on the wake induced turbulent strip. The technique is most effective for long chordwise edges, therefore it performs better on the primary wakes than the secondary due to the stronger imposed disturbances.

Figures (5.16–5.17) shows the contour lines and their respective celerity rates side-by-side for the primary and secondary wake intermittency data at four threshold levels. Focusing on leading edge results, one can see that the primary wake celerities have been calculated from the most upstream
location \( x = 0.2 \) m through to the point where natural transition begins near \( x \approx 0.60 \) m. The secondary wake values only begin at \( x = 0.35 \) m and therefore exhibit less chordwise range along which to measure their respective velocities.

The averages are shown in Figure (5.18). The primary wake induced turbulence strips show leading edge celerities greater than 100\% of the freestream velocity, beginning with an average celerity rate near 170\% at \( x = 0.20 \) m, slowly decelerating down to approximately 120\%. These values take into account the varying local freestream velocity imposed by the adverse pressure gradient. We shall ponder over these extraordinarily high celerity rates later in this section.

The leading edge trend is a lot harder to see for the secondary wake induced turbulent strips due to the unavoidable relatively short length of chord over which the edges and celerities have been calculated. Sensible values lie in the narrow range \( 0.4 \leq x \leq 0.5 \) m and show celerity rates to be fairly constant, averaging to around 120\% freestream. Again, the trailing edge celerities are discussed later.

Figure (5.19) shows typical plots from the analysis of primary turbulent patches at various heights within the boundary layer as calculated using technique 2. The second-order curve fits show a common trend for chordwise deceleration, concurring with technique 1, as one might expect with the reducing freestream velocity distribution. Also, again, the interesting feature that one might not expect is the magnitude of these velocities. Turbulent strips generated by the primary wake tended to propagate at leading edge speeds greater than the freestream velocity. Table (5.1 - following page) catalogues the velocities and celerity rates as determined from the linear fits of technique 2, with celerity rates this time based only on the maximum freestream velocity \( U_{\infty_{\text{max}}} \). One can clearly see that primary wake turbulent strips, on average, travel approximately 26\% faster than the wake.
CHAPTER 5. SINGLE WAKES

<table>
<thead>
<tr>
<th></th>
<th>PRIMARY</th>
<th></th>
<th>SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leading</td>
<td>Trailing</td>
<td>Leading</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>10.52 ± 0.19</td>
<td>4.69 ± 0.16</td>
<td>8.61 ± 0.39</td>
</tr>
<tr>
<td>Celerity Rate (%)</td>
<td>126 ± 2.3</td>
<td>57 ± 1.9</td>
<td>103 ± 4.7</td>
</tr>
</tbody>
</table>

Table 5.1: Table of calculated leading and trailing edge propagation and celerity rates for the primary and secondary turbulent patches using technique 2 with a closest linear fit to detected \( u' \) faces and maximum velocity \( U_{\text{omax}} \).

Jet effect

One explanation for this would be that of the so called 'jet effect'. Figure (5.20) demonstrates the effect of the velocity deficit within a propagating wake as it encounters the boundary layer of a downstream cascaded blade. The velocity deficit within the wakes create a negative jet effect on the suction surface, which tends to inject flow into the boundary layer. Similarly, as described in §3.1.2 and Figures (3.4–3.5), the vertical velocity component of the primary wakes are of a downwards trend towards the surface, and can theoretically create this accelerated velocity effect at the leading edge of the induced turbulent strips. The injection of turbulent fluid from the wake into the boundary layer causes the leading edge to be pushed forward, i.e. downstream, giving the appearance of an accelerated velocity.

Another possible theory, primarily applicable to the geometrical particulars of this wind tunnel investigation rather than general turbomachinery, concerns the shallow angle of elevation that the wake demonstrates with respect to the flat plate surface. Within contour plots such as Figure (5.3) the wake appears to travel downstream with an almost vertical attitude, it must be noted that these axes demonstrate a distorted view of the scene due to a far-from-unity ratio between spatial axes. The wake elevation angle actually is as low as 11 degrees from the horizontal (see Figure 3.4). This can mean that as the boundary layer thickens with chord, more of the leading edge of the wake becomes associated with the turbulent strip, and since the wake
TABLE 5.2: A compilation of measured turbulent spot/strip edge celerity rates. Where two values are reported, they relate to that author’s equivalent of ‘primary’ and ‘secondary’ wakes respectively.

<table>
<thead>
<tr>
<th>Source</th>
<th>Leading Edge</th>
<th>Trailing Edge</th>
<th>Disturbance Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schubauer &amp; Klebanoff (1955)</td>
<td>0.88</td>
<td>0.5</td>
<td>Spark</td>
</tr>
<tr>
<td>Wygnanski et al. (1976)</td>
<td>0.89</td>
<td>0.5</td>
<td>Spark</td>
</tr>
<tr>
<td>Cantwell et al. (1978)</td>
<td>0.87</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Antonia et al. (1981)</td>
<td>0.74</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Wygnanski et al. (1982)</td>
<td>0.89</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Gutmark &amp; Blackwelder (1987)</td>
<td>0.88</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>Obremski &amp; Fejer (1967)</td>
<td>0.88</td>
<td>0.58</td>
<td>Freestream perturbation</td>
</tr>
<tr>
<td>Houdeville et al. (1977)</td>
<td>0.89</td>
<td>0.48</td>
<td>Freestream perturbation</td>
</tr>
<tr>
<td>Pfeil et al. (1983)</td>
<td>0.75</td>
<td>0.54</td>
<td>Wake generator</td>
</tr>
<tr>
<td>Jeon et al. (2002)</td>
<td>0.89/0.83</td>
<td>0.47/0.40</td>
<td>Wake generator</td>
</tr>
<tr>
<td>Present Measurements</td>
<td>1.26/1.03</td>
<td>0.57/0.57</td>
<td>Wake generator</td>
</tr>
</tbody>
</table>

Heavily leans forward the strip therefore interacts with sections of wake further downstream of itself, promoting new boundary layer turbulence ahead of itself. This encourages the strip to progress and develop faster than the wake (which travels at the freestream velocity), and would fit in with the similar hypothesis of Addison & Hodson (1990a-b), as described in §5.2.1.

This accelerated leading edge was not seen for the disturbances induced by secondary wakes (see Figure 5.21), which tended to propagate at the same rate as the wake in the freestream. Here, as in the pressure surface of Figure (5.20), a positive jet effect is seen, with the passing wake expelling flow away from the boundary layer out into the freestream.

### Similar published work

These celerity rates for both the primary and secondary strips are much greater than those seen in published data on artificially generated turbulent
spots, however, as the disturbances in this work are generated by a passing wake, rather than an excitation, one can expect the resulting behaviours to differ. A short compilation of published results is presented in Table (5.2). Freestream pressure gradients have not been taken into account.

Addison & Hodson (1990a-b) remark upon a similar celerity feature noted in their measurements of wake-induced turbulence on an axial flow turbine suction surface. From $x \sim t$ plots of random unsteadiness as acquired from hot-films, the propagation rates for ensemble-averaged wake-induced turbulent strips are noted to be very close to the freestream value. It was proposed that initially turbulent spots can only develop under the centre-line of the wake path. This initial turbulent spot then propagates at the well-known documented celerity rates, but the wake propagates at the freestream value. This moves the wake ahead of the initial spot. Subsequently, as the laminar boundary layer develops away from this location, it becomes possible for turbulent spots to develop in regions of lower turbulence intensity, as found away from the centre-line of the wake. Hence further spots are induced ahead of the initial spot, causing the ensemble-averaged turbulent strip leading edge propagation rate to appear to be faster than the freestream. This mechanism shall simply be referred to as 'destabilisation' of the boundary layer in this thesis.

This is also seen by Dong & Cumpsty (2000b) who describe in a simple schematic the development of secondary turbulent spots upstream of initial spots created by the advancement of the wake ahead of the induced disturbances.

Boundary layer wake interaction experiments by Jeon et al. (2002) report turbulent strip propagation rates matching the freestream velocity and hence travelling synchronously with the passing wake. This is a celerity rate of 1.0. Wakes were shed in both clockwise and counter-clockwise directions, similar to the primary and secondary scenarios of the present research, and it was found that the equivalent to 'secondary' wakes induced turbulent strips that 'disassociated' themselves from the passing wake and propagated at velocities lower than the freestream. In the author's research the secondary wake induced strips appear to travel slower than the primary (according
to data from technique 2), but still at a value marginally greater than the freestream and hence in speed with the wake.

The wakes of Jeon et al. were reported to have a turbulence intensity near $Tu = 8\%$, much lower than those of the present research peaking at $Tu = 20\%$. It is therefore perhaps less likely that any destabilisation of the boundary layer as described above occurs in their experiments, prohibiting the possibility of turbulent strip celerity rates greater than 1.

Work by Stieger (2002) on a bar passing rig cascade of turbine blades does not report accelerated leading edge velocities for suction surface turbulent strips induced by the passing wakes. What is briefly described is the slow acceleration of convecting pressure fluctuations up to 50% of the freestream velocity, a feature that is noted in the trailing edge velocities discussed later.

Furthermore, pressure gradients effects upon celerity rates are known to be significant (Gostelow et al. 1995, Johnson 1998, D'Ovidio et al. 2001b). Strong adverse pressure gradients decrease the propagation rates for turbulent spots. Therefore a degree of scatter will be present in the data of Table (5.2).

**Turbulent strip trailing edges**

Table (5.1) also shows the celerity rates for the trailing edges of the two different types of wake induced turbulent strip. Due to prevalence of the trailing calmed region throughout the surrounding turbulent boundary layer it was seen that the trailing edge locations could be detected across the entire length of the measured chord, from beginning through to $x = 0.80$ m, giving a more accurate linear fit and, hence, velocity estimation (see Figure 5.22).

Regardless of their wake origin, whether primary or secondary, the two different disturbances have identical trailing edge propagation rates, indicating that the two differing jet effects from the two wakes have no influence on the trailing edge of the induced turbulent strips. This is presumably due to the fact that the wakes travel with the freestream, and carry their influence downstream, beyond the domain of the calmed region. As the disturbances
develop they grow in length because the leading edges travel faster than the trailing edges. This also leaves the trailing edge of the packet outside of the influence of the wake, hence both the primary and secondary wake induced disturbances evolve at their trailing edges in a similar manner to each other as there are no external influences affecting either.

The calculated celerity rate of 57% is similar to that seen for propagating turbulent spots. Gutmark & Blackwelder (1987) noted a celerity rate of 58.3% for the trailing edge of spots in an adverse pressure gradient. They also catalogued some previously published results which all ranged between 50—62% of $U_{\infty}$. This is compelling evidence for the predictability of the turbulent strips and the postulation that they are a spanwise grouping of turbulent spots is accurate.

As with the leading edges, 80% of the trailing edge curve fits indicated a deceleration with chord. Again, this is most likely to be due to the decreasing velocity distribution; dividing the velocities by the local freestream values to give celerity rates does indeed show a linear response with chord.

The research of Jeon et al. (2002) reported differing trailing edge celerity rates for their ‘primary’ and ‘secondary’ wake induced turbulent strips. They calculated maximum values of 0.50 and 0.41 respectively using the method of Gostelow et al. (1996).

### 5.3 Separation bubble closure (Figures 5.23–5.25)

Contours plots of ensemble-averaged velocity, RMS of velocity and intermittency, Figures (5.23–5.25), in a centreline plane normal to the blade surface show the progression and interactive effects of the wake with the natural boundary layer. All three figures synchronously demonstrate the passing of a primary wake, as it convects downstream. The plots of RMS of velocity best represent regions of perturbation, and demonstrate the propagation of the wake through the transition zone; the natural undisturbed mode of transition can be studied in frames (a) and (j). The extreme severity of the fluctuations in the reattachment region, and immediately downstream,
is clear and this is consistent with the computational findings of Lou & Lakshminarayana (1997).

The incoming wake is seen in frame (b) as the large region of high RMS\(^1\) that merges with the existing region of transition as it progresses downstream (frame (c)). This resulting, longer, turbulent region is swept downstream with the wake, leaving behind a more stable region of flow, very much like laminar flow (frames (g) and (h)). This region corresponds to the calmed region, normally observed behind a turbulent spot, as seen by Schubauer & Klebanoff (1955) and Gostelow et al. (1997). In comparison with previous conducted work on turbulent spots, a calmed region produced by an imposed wake is stronger, with a more stable velocity profile, and persists for a longer time. In the same way as the calmed region produced by a triggered turbulent spot it is ultimately overrun and supplanted by the encroaching naturally turbulent boundary layer.

The plots of ensemble-averaged velocity, Figure (5.23), are used here to show the distribution of velocity through the boundary layer. They therefore highlight well the fate of the bubble under the influence of the disturbances, such as the impingement of wakes from upstream blade rows. In the undisturbed flow the long and thin laminar separation bubble exists between chord locations \(0.56 < x < 0.75 \text{ m}\), with a maximum height of approximately 0.75 mm towards its end. The subsequent figure, Figure (5.24), gives the corresponding wake locations in each frame as it interacts with the boundary layer. The wake suppresses the bubble as it convects downstream, causing a reattachment of the boundary layer and the removal of its bubble. The calmed region that follows demonstrates an elevated shear stress at the wall (Halstead \textit{et al.} 1995a-d), which has the effects of delaying transition and stabilising the boundary layer against separation (Gostelow \textit{et al.} 1997).

It can be seen from frames (f) and (g) that the prominent calmed region has a more stable laminar like velocity profile. The adverse pressure gradient promotes separation, and, in a natural mode of separated transition, the amplification of instabilities in the shear layer causes reversion to the natural turbulent boundary layer (frames (i) and (j)).

\(^1\)Note that the intermittency parameter also demonstrates these regions well.
5.4 Calmed region

The definition of a calmed region was described earlier in §2.3. Inspecting the Intermittency and RMS contours, plus velocity profiles from within the calmed region, shows that calmed regions are laminar in nature, i.e. steady and without perturbation, yet the profile shape is very full, much like a turbulent boundary layer. It would seem the velocity profile is 'remembered' or 'inherited' from the passing turbulent strip, and takes a length of time to revert to the inflectional, and eventually separated, boundary layer profile.

As the turbulent strip propagates through the boundary layer it resists separation and effectively wipes away the existing recirculation bubble. The calmed region exists due to the temporal distance created by the slower moving T-S instabilities, which eventually develop in the recovering separation region to reinstate transition and complete the steady state boundary layer.

Not only does the calmed region resist separation, but it is also resistance to the development of turbulence. More accurately, a suppression of the boundary layer instabilities is seen. Figure (5.26) shows example velocity traces at a height of $y = 2$ mm for a typical wake induced strip and its calmed region, plus a copy of Figure 9 from Gostelow et al. (1999) plotting surface shear layer values, each for various streamwise locations. The similarities between each are clear to see, successively demonstrating the ability of the calmed region to suppress the development of ambient boundary layer instabilities.

One can see the new T-S waves developing very quickly in the last moments of the calmed region at all chordwise locations of Figure (5.31)—this Figure is described in detail in §5.5.

5.4.1 Calmed region celerity

Technique 3, incorporating the relaxation parameter $\kappa$, was used to determine the extent of the calmed region behind each turbulent strip. The development of a calmed region is retarded by the growth of laminar instabilities at the rearward (upstream) end. Relaxation implies that the velocity
is in a constant decline (and hence calmed), so the influence of a laminar instability is incompatible with a relaxed state.

The detected trailing edges of the calmed regions give a larger error than techniques 1 and 2 due to the strong variation in the location of developing laminar instabilities behind the calmed region from record to record. Nevertheless, the estimated celerity rates were fairly consistent across the data sets and were seen to collapse onto the following trend:

- During the early inflected laminar boundary layer profiles of $0.15 \leq x \leq 0.45$ m, celerity rates for the trailing edges of the calmed regions were seen to be approximately 40% and 43% for the primary and secondary wake induced calmed regions respectively.

- Upon reaching the separation point, the celerity rates drop to approximately 33% and 37% for the primary and secondary respectively.

- Once natural transition is reached, although the calmed region persists, the trailing edge accelerates very quickly up to celerity rates of 55% and 59%.

An example of relaxation contours can be viewed in Figure(5.27), showing the extent of the calmed region behind a primary and a secondary induced turbulent strip.

It is known that the celerity rate for the trailing edge of a calmed region is dictated by the propagation rate of the growing laminar instabilities in the surrounding boundary layer. It can be recalled that in §4.2.3 the natural instabilities in the transitional flow were seen to travel at approximately 44% $U_\infty$. This is very close to the speed of the calmed region trailing edge in the attached region, and reasonably close to their rates elsewhere.

As a comparison, Figure (5.28, reproduced from Gostelow et al. (1997), shows the intermittency and relaxation contours for a compressor stator boundary layer, including the effect of removing one blade to investigate the

\footnote{Occasionally the relaxation contours would be seen to ‘reverse’, indicating an ‘upstream’ movement, or negative velocity, for the calmed region trailing edge. This was also seen, although not discussed, by Gostelow (1997).}
effect of varying wake impingement frequency. The similarities between the boundary layer behaviour in this extended wake frequency region and the data of the present research are clear to see.

Inspecting the relaxation contours, Gostelow et al. (1997) quote that the calmed region trailing edge has a celerity rate of 20% and 54% for the two chord regions of laminar attached flow and natural transition flow respectively. These values are comparable to the measured celerities of the present research.

What is not specifically mentioned, however, is the short region of apparently reversed celerity between 0.5 and 0.7 m. This is sometimes seen in the present work, more clearly perhaps in the paired wake data of the following chapter (see Figure 6.34).

It is unlikely that this is truly a negative celerity, as it would indicate the travel of disturbances in the upstream direction emanating from the surrounding turbulent boundary layer back into the laminar region. Therefore, it would perhaps indicate that the use of relaxation is not the best indicator for the extent of the calmed region. In this case, it would seem that flow beyond the extent of the calming zone has been falsely detected as relaxed, which for a laminar boundary layer without perturbations is relatively easy to do.

5.5 Pressure field

Figure (5.29) is a contour plot of ensemble average microphone voltages across the entire array. It is useful to compare the plot to Figure (4.6) without any wakes.

As with Figure (4.6), the steady state boundary layer can be seen with natural transition developing in the usual way, and similarly, after the instabilities develop and breakdown, both the anti-alias filter and a lack of temporal resolution make it difficult to detect the turbulence in the contour plot, resulting in the appearance of smooth flow.

An expected feature of the plot is the two strong turbulent strips, seen
running from left to right (as in Figure 5.27) each from time steps \( t = 0.1 \) and \( t = 0.7 \) s respectively. The turbulent strips manifest themselves as strong increases in the local pressure. In the turbulent region, \( x = 0.75 \) m onwards, this feature adjusts to become a single period sinusoidal perturbation, which begins precisely at the leading edge of the induced disturbance. Figure (5.30) shows microphone signal information for the secondary wake induced turbulent strip across a range of chordwise locations. As reattachment completes, the single pressure peak can be seen to change form to become a full period pressure perturbation.

Work by Lou & Hourmouziadis (1999, 2000) has revealed the shedding of vortex structures downstream of a collapsing separation bubble under the influence of inlet velocity perturbations. Boundary layer velocity profiles in this region show single period wave behaviour similar to that shown in Figure (5.30).

Following the disturbances are the calmed regions, each detectable as a region of visibly reduced wave activity in the transition region downstream of each turbulent strip. Outside of the calmed regions the wave activity is strong and still highly visible after ensemble averaging over 128 repetitions. This does not necessarily signify any phase coherence between the generation of independent spots in relation to the passing of each wake.

To see these instabilities more clearly, and inspect the way they develop after the calmed region, a contour plot for one single record has been presented for the second half of the array only \((0.65 \leq x \leq 1.00 \) m\) in Figure (5.31). As this data is for a single record the turbulent strips are now no longer visible because their magnitude is much smaller than the detected instabilities and do not show clearly on this contour scale (compare the scale to the that of Figure 4.9). Here the instabilities are strong in amplitude and can easily be detected. The turbulent strip paths are identical to those of Figure (5.29), being careful to adjust for the change in the abscissa scale, and these and their calmed regions can be 'seen' as the regions lacking natural transition.

An interesting feature to be observed is the presence of laminar instabilities directly following the calmed region after the transition completion
location $x_T$ where normally turbulence is so well developed that laminar instabilities can not exist (see region $x = 0.90$ m, $t = 0.40$ s). Normally the flow here is fully turbulent, but the prior calmed region is laminar in nature and therefore the development of instabilities can occur here. Power spectral analyses of this short region reveal that the instabilities are of the same frequency as the T-S waves of the natural transition region, approximately 91 Hz (see §4.2.3). Therefore, these instabilities have originated from the same upstream location yet remained undeveloped due to the laminar nature of the calmed region, thereby convecting through to a downstream location as far as $x = 0.95$ m. This is 39% further than those instabilities undergoing normal steady state transition.

Shortly afterwards, these instabilities amplify, breakdown and reinstate the turbulent boundary layer.

5.6 Discussion

Wakes of differing turbulent intensity have been introduced into the freestream flow of the steady state flat plate boundary layer. These wakes are representative of those seen in some axial compressor stages with low freestream velocity deficit, turbulent content approaching 20% and approach angles in the region of 10 degrees.

Their interactions with the boundary layer have been studied and shown to induce disturbances within the attached laminar boundary layer that grow and convect with the boundary layer. The stronger, or more turbulent, primary wake induces turbulence in the laminar boundary layer very quickly, and at a location far upstream of the measurement compass, creating a strongly turbulent strip underneath its footprint. Whereas the weaker, less turbulent secondary wake takes more distance to slowly encourage the amplification of perturbations, perhaps already present in the boundary layer, creating a transitional strip that grows to become a turbulent strip, most likely via a more natural mechanism.

The internal structure of each turbulent strip has been studied and it has been shown that the convecting wake encourages the continual growth
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of new turbulence at the leading edge of each turbulent strip, accelerating celerity rates to values above that of the freestream. The remainder of the turbulent strip, moving slower and outside of the influence of the wake, follows traditional natural breakdown techniques and develops into more 'mature' turbulence with reduced RMS of velocity values, propagating in a manner similar to those of ordinary turbulent spots.

As seen in many classic experiments, both turbulent strips resist separation and remain attached as they pass the separation point, subsequently eradicating the downstream separation bubble. Behind each turbulent strip follows the calmed region, a region of laminar-like flow devoid of flow perturbations, approximately identical for both wakes. It grows with chord until the following slower flow instabilities develop into early turbulence and accelerate to reclaim the calmed region.
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1.01 \approx 0.99 > 0.98 > 0.97 > 0.96 > 0.95

Figure 5.1: Normalised freestream velocity $u/u_\infty$ at $x$ location 0.15 m, showing the velocity deficit imparted by wakes.

Figure 5.2: Intermittency $\gamma$ of the freestream wakes at $x$ location 0.15 m (—), with RMS of velocity $u'$ shown on the second abscissa (—).
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Figure 5.3: Timewise development of RMS of velocity $u'$ for a primary turbulent strip within laminar and separated boundary layer.
Figure 5.4: Timewise development of RMS of velocity $u'$ for a primary turbulent strip during transitional and turbulent regions.
Figure 5.5: Time-wise development of intermittency for a primary turbulent strip within laminar and separated boundary layer.
Figure 5.6: Timewise development of intermittency for a primary turbulent strip during transitional and turbulent regions.
Figure 5.7: Three plots showing the velocity $u$, RMS of velocity $u'$ and intermittency $\gamma$ for a hot-wire reading within a secondary wake induced disturbance. Plots show the strong yet laminar nature of the developing instabilities.
Figure 5.8: Timewise development of RMS of velocity $u'$ for a secondary turbulent strip within laminar and separated boundary layer.
Figure 5.9: Timewise development of RMS of velocity $u'$ for a secondary turbulent strip during transitional and turbulent regions.
Figure 5.10: Timewise development of intermittency for a secondary turbulent strip within laminar and separated boundary layer.
Figure 5.11: Timewise development of intermittency for a secondary turbulent strip during transitional and turbulent regions.
Figure 5.12: Example of a turbulent spot. Data shows contours of RMS of velocity. Contours and axes scales unknown. From Gostelow (1990)

Figure 5.13: Cartoon describing the core and tail features seen in the RMS of velocity $u'$ data of a propagating turbulent strip.
Figure 5.14: Turbulent strip intermittency $\gamma$ at $y = 2.0$ mm for various secondary wakes with the corresponding Narasimha Universal Distributions. Abscissa scale drawn for $x$ and $\xi$ to show the different transition onset locations, $x_t$, between experiments.
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Figure 5.16: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma =0.5$, 0.6, 0.7 and 0.8 for primary wakes. Data clipped to within sensible ranges.
Figure 5.17: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for secondary wakes. Data clipped to within sensible ranges.
Figure 5.18: Turbulent strip celerity rate averages for primary and secondary wakes. Data clipped to within sensible ranges.
Figure 5.19: Examples from various heights of detected leading edges for a primary turbulent patch, showing linear and polynomial curve fits.
Figure 5.20: Conceptual diagram of the velocity deficit within wake flows for a typical turbine (a) and compressor (b). Velocity triangles colours: blue steady flow, red wake flow, (-) absolute frame of reference, (- -) relative frame of reference. Small green arrows demonstrate the jet effect upon the suction and pressure surface boundary layers due to the wake deficit (see Figure 2.2).
Figure 5.21: Examples from various heights of detected leading edges for a secondary turbulent patch, showing linear and polynomial curve fits.
Figure 5.22: Examples from various heights of detected trailing edges for primary and secondary turbulent patches, showing linear and polynomial curve fits.
Figure 5.23: Contours of velocity in boundary layer region for primary wake interaction. Time slices demonstrate the separation bubble closure, the expansive calmed region and the return to natural state. See Figure 4.2 for freestream velocities (mean RPM≈194), frames (a) to (j) referenced in §5.3.
Figure 5.24: Contours of RMS of velocity $u'$ in boundary layer region for primary wake interactions. Time slices demonstrate the arrival of the wake and induced turbulent strip, the eradication of the bubble, the laminar-like calmed region and eventual return to natural state. Frames (a) to (j) are referenced in §5.3.
Figure 5.25: Contours of intermittency in boundary layer region for primary wake interaction. Time slices demonstrate the highly turbulent wake induced turbulent strip, the laminar calmed region and the eventual return to natural state. Frames (a) to (j) are referenced in §5.3.
Figure 5.26: Example velocity traces and hot-film shear stress data from the current work and Gostelow et al. (1999) respectively. Traces demonstrate the ability of the calmed region to suppress surrounding turbulent activity.
Figure 5.27: Relaxation contours (—) drawn behind each turbulent strip intermittency contour map. Areas of highly relaxed flow represent the calmed region.
Figure 5.28: Plot of intermittency with relaxation overlaid from Gostelow et al. (1997), Figure 1.
Figure 5.29: Microphone signals with wake impingement ensemble averaged over 128 records. Data has been calibrated, filtered and contour corrected.
Figure 5.30: Microphone traces for selected chord locations showing secondary wake induced disturbance.
Figure 5.31: Microphone signals with wake impingement from record 14. Data has been calibrated, filtered and contour corrected.
Chapter 6

Paired Wakes

In a true multistage environment wakes are shed in a continuous and periodic fashion from each row of blades, and not individually as described in the previous chapter. The interaction of consecutive wakes is a more realistic simulation of the situation in turbines and compressors, and this chapter describes the results of investigations using paired wakes, providing detailed information on their interaction with the boundary layer and also the interactions with themselves.

Again, as in Chapter 2, the term 'primary' is used to describe those wakes generated nearest to the leading edge of the flat plate, and 'secondary' for the further wakes. Also used here, to distinguish between each wake within a pair, the author has simply used 'initial' and 'following' since the first of each pair is identical the those of the isolated-wake experiments, and the second of each pair quite literally follows the first.

6.1 Experimentation

The coupled-wake experiments required the generation of two wakes, arriving close together with an adjustable delay between them for the analysis of their paired behaviour. Modifications to the wake generator were needed to permit the controlled creation of coupled wakes.
6.1.1 Wake generator modifications

To achieve two juxtaposed wakes identical in form and nature, a second rod was attached to the wake generator disc. Its circumferential location was adjustable to conform with the requirement for differing arrival times of the wakes. For a description of the modifications see §3.1.2.

A range of differing time delays between the two wakes was covered, ranging from the closest case with the turbulent strip of the following wake developing sufficiently close to advance upon and interact with the initial wake’s turbulent strip, to the farthest case whereby the following turbulent strip arrived just after the termination of the initial turbulent strip’s calmed region (and therefore outside of it’s region of influence). Hence, with this broad accommodation of distributed wakes, it was intended that a thorough understanding of the effect of variably spaced wakes upon a boundary layer would be gained.

6.1.2 Theorising wake arrivals

A model was developed to simulate the likely arrival times and extents of the primary and secondary turbulent strips, plus their associated calmed regions, using kinematic analysis of the wake generator. The following three equations were derived to allow for the estimation of three parameters (see Appendix A.3 for a detailed description of the model and its derivation): the arrival of a turbulent strip leading edge $t_i^W$, its subsequent trailing edge (or similarly the calmed region leading edge as these are coincident) $t_i^C$, and the calmed region trailing edge $t_i^E$, for the downstream location $x = 0.80$ m.

\[
\begin{align*}
t_i^W &= \frac{d + x(1 - \cos \theta)}{\nu} + \frac{\theta_i + \alpha}{\omega}, \\
t_i^C &= t_i^W + \frac{\pi[0.211 + 0.019(-1)^i]}{\omega}, \\
t_i^E &= t_i^C + 0.008(-1)^i + 0.094.
\end{align*}
\]
Using those algorithms, carpet plots were created relating the location for the second rod to the disc rotation speed, the incidence and the clearance. Incidence and clearance are terms created here to clearly represent the degree of interaction between the pairs of wakes for the downstream location \( x = 0.80 \) m, described as so:

- **Incidence** represents the proportion of chordwise turbulent strip overlap as a percentage of calmed region length. Therefore 100% incidence describes a 'following' turbulent strip completely overlapping the calmed region of an initial turbulent strip, and hence in contact with its trailing edge; 50% incidence describes a 'following' strip advancing up to the midpoint of the initial strip's calmed region, and 0% incidence describes the near limit of no interaction. Note that greater than 100% incidence must therefore indicate a merging of two turbulent strips.

- **Clearance** represents the time in seconds between each pair of wakes, i.e. the delay between the trailing edge of the 'following' turbulent strip of the primary pair and the leading edge of the initial strip for the following secondary pair. It is not the intention to achieve interaction between the primary and secondary wake pairs, therefore a positive clearance between both combinations of primary and secondary turbulent strips is desirable to prevent unwanted interactions.*

Figures (6.1–6.4) show four carpet plots, each representing one of four clearances: the leading edge of the primary turbulent strips followed by the trailing edge for the same pair, then again for the leading and trailing edges of the secondary strips. Each plot compares curves of constant clearance and rod angle on axes of wake generator disc rotation, speed and incidence, such that for a given disc speed \( \omega \) one can determine the necessary rod angle \( \alpha \) to provide a positive clearance at the desired incidence.

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* A potential problem was that of preventing the trailing calmed flow of the secondary pair of wakes from prevailing in time through to the arrival of the next primary pair. It was later seen not to cause any undesirable influences.
To attain a positive clearance across a wide range of incidences it was necessary to reduce the rotational speed from $\omega = 2.0\pi$ to $\omega = 1.6\pi$ rad/s. This increases one full rotational period from 1.0 to 1.25 sec, and has the theoretical effect of lengthening wake passage times.

### 6.1.3 Experimental strategy

A similar experimental procedure to that of Chapter 5 was adopted in terms of acquisition and analysis techniques applied to the data. With the need to repeat the coupled-wake experiments at a variety of arrival delay times,\(^{1}\) it was necessary to reduce the time of each experimental program, hence the existing configurations were analysed to determine areas that could accommodate economisation.

As a result, the number of hot-wire locations, both in the streamwise and transverse direction, were assessed to both improve the data quality in areas of high data gradients (such as the separated shear-layer), and also to reduce the total number by coarsening the grid in the freestream, thereby reducing the total acquisition time. The limits were kept within their original ranges ($0.15 < x < 0.80$ m and $0.15 < y < 50.00$ mm).

With the coupled-wake strategy using a wake generator rotational speed $\omega$ at 80% of that used in the isolated wake experiments, longer acquisition times were necessary to accommodate the larger rotational period of 1.25 s. In order to reduce experimental run times, the number of records was reduced from 128 to 64, the effect of which upon the data quality has been discussed in Appendix A.4 and was seen to be insignificant.

### Chosen arrival delay times

A preliminary decision was made regarding the choice of arrival delays, hence the choice of $\alpha$ values, between the wakes to cover a suitable range of wake interactions. Chosen values for $\alpha$ were 40, 50, 60, 70 & 80 deg. These

\(^{1}\)The delay between the arrival time for each wake of a pair is directly related to the angular displacement of the second rod with respect to the first on the wake generator circumference, hence values stated are for $\alpha$ in degrees and not time.
CHAPTER 6. PAIRED WAKES

<table>
<thead>
<tr>
<th>PRIMARY (Est./Exp.)</th>
<th>SECONDARY (Est./Exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (deg)</td>
<td>Incidence (%)</td>
</tr>
<tr>
<td>30</td>
<td>138.8/132.0</td>
</tr>
<tr>
<td>35</td>
<td>121.8/125.6</td>
</tr>
<tr>
<td>40</td>
<td>104.8/86.9</td>
</tr>
<tr>
<td>50</td>
<td>70.7/62.0</td>
</tr>
<tr>
<td>70</td>
<td>2.6/9.8</td>
</tr>
<tr>
<td>60</td>
<td>36.7/—</td>
</tr>
<tr>
<td>80</td>
<td>-31.4/—</td>
</tr>
</tbody>
</table>

Table 6.1: Comparison of Estimated and actual Experimental values for incidence and clearance at a downstream location of $x = 0.80$ m for each of the rod angular displacements $\alpha$. The 60 and 80 degrees tests were not performed.

were later modified after performing the ranges $\alpha = 50 \& 70$ deg, as it was seen that the chosen close spacings would not be close enough to cover the tightest range as previously thought. A wide separation of less than zero incidence, $\alpha = 80$ deg, was abandoned, along with $\alpha = 60$ deg, for closer separations of $\alpha = 30$ and $35$ deg, giving two more theoretical incidences greater than 100%.

It is probably wise to reiterate here that although the two turbulent strips will be overlapped to some degree when the incidence is greater than 100%, these values relate to a downstream chordwise location of 0.80 m, at the end of the hot-wire streamwise traverse range. The early regions of induced transition are much smaller and ergo will still be initiated apart. It is some distance downstream before they grow sufficiently to unite.

With a large variation of $\alpha$ covered by the experimental schedule, the effect of turbulent strips that merge at different downstream locations, and hence under different surrounding boundary layers, has been studied. Table (6.1) compares the measured experimental parameters to the theoretical estimates.
Briefly, it can be seen that the algorithms developed for the mathematical model were fairly accurate when the actual experimental values are compared to the estimations. There is a slight but consistent trend for overestimation of the incidence parameter for both primary and secondary pairs, and the clearance parameter is equally over- and under-estimated with an average error of 20 ms.

6.2 Turbulent strip interaction

The first results presented here from the paired wake experiments are RMS of velocity data, $u'$, chosen as a simple identifier of regions of flow perturbation. The intermittency parameter has also been presented, which highlights only the turbulent flow. Comparing the two contour plots allows one to identify any perturbed yet non-turbulent flow regions, such as laminar boundary layer fluctuations that are yet to breakdown and develop any identifiable turbulence.

It has been seen that newly formed turbulence exhibits a much higher RMS of velocity than 'older' turbulence that has developed, or matured. This has been discussed and demonstrated in §5.2.1 and Figure (5.4) where it can be seen that the naturally forming transition region at first creates high values of $u'$, then diminishes to approximately half of that value with a chordwise progression. This ability to classify the turbulence as either young or old aids in the discrimination of two turbulent strips when the core of a following strip advances into the trailing edge of an initial strip. The following sections describe these interactions in detail.

6.2.1 Primary pairs (Figures 6.5-6.12)

The effect of moving each pair of primary wakes closer together is demonstrated in Figures (6.5-6.12). Ranging from far upstream at $x = 0.20$ m to the downstream turbulent boundary layer region at $x = 0.80$ m, the development of the turbulent strips has been plotted at progressive streamwise locations to help understand the sequence of changes experienced upon
the surrounding boundary layer and the separation bubble for the different combinations of wakes. Starting at the upstream location of \( x = 0.20 \) m, each chordwise location is discussed below for both RMS of velocity \( u' \) and intermittency \( \gamma \).

\( x = 0.20 \) m

At the uppermost upstream location, Figure (6.5), the spot clusters are newly formed and hence very small. Note from the intermittency (Figure 6.9) that they are turbulent at their centres and the shapes are already indicative of two-dimensional turbulent spots. They each have the uniformly distributed intermittency content as seen in the isolated turbulent strips of Chapter 5, and do not present any visible interactive effects at this early stage, even for the wakes of the closest spacing at \( \alpha = 30 \) deg. The following spot cluster is yet to exhibit any change regardless of its existence within the calmed region of the initial disturbance. \(^1\)

\( x = 0.40 \) m

Moving onto the more developed location of \( x = 0.40 \) m, Figure (6.6), the spot clusters have developed into more recognisable turbulent strips with a core and the entraining tail. The beginnings of an interaction between the two turbulent strips can be seen for the closest of spaced wakes at \( \alpha = 30 \) deg, the core of the following strip having adequately advanced into the calming region. It is difficult to observe, but a slight reduction in \( u' \) for the following strip’s core of turbulence seems to be the result. This becomes more evident when we analyse them further downstream.

The intermittency \( \gamma \) for \( \alpha = 30 \) deg seems to show that the two disturbances are yet to connect, and that their turbulent extremities are still

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\(^1\)The author is unsure as to why the values for \( u' \) at \( \alpha = 35 \) deg are lower than the other four \( \alpha \) distributions, however, since no interaction is evident here, no potential information has been lost. Also \( \gamma \) at \( \alpha = 50 \) deg is erroneous for this location, seen afterwards to be the result of noise interference in the hot-wire data from an unknown source. This problem is also therefore evident in the matching secondary wake data.
separate, except for perhaps the lowest values of $\gamma$ where it can be argued the two disturbances are on the limit of coinciding.

$x = 0.60 \text{ m}$

Now at $x = 0.60 \text{ m}$, Figure (6.7), the turbulent strips are more developed, surrounded by a highly inflectional velocity profile and those that are leading encroaching upon a naturally transitional boundary layer. The two most extremely displaced disturbances of $\alpha = 70 \text{ deg}$ and $\alpha = 50 \text{ deg}$ are still to show any contact as the following strips have so far only advanced into the beginnings of the calmed region of their downstream pairs.

The more closely spaced turbulent strips are showing similar trends, with reductions in the strength of $u'$ at the core of the following strips. For the closest setting of $\alpha = 30 \text{ deg}$ the core has nearly been reduced to an equivalent strength as the remainder of the disturbance, creating a single long turbulent strip nearly twice the length of the original isolated strips. The core feature of the original strip is unaffected by these changes in its tail.

The intermittency $\gamma$, Figure (6.11), shows very little change in the values throughout the disturbances, even for those of $\alpha = 30 \text{ deg}$ that have connected, the interaction between the two seems to have the effect of simple superimposition, where the maximum of the two intermittency values prevails at each spatial location. It is still possible to clearly determine the two separate disturbances from one another as one can see from here that they are yet to fully merge. Note that although the four closer spaced strips have demonstrated reductions in core turbulence intensity, the intermittency shows that they are still to contact. This indicates that the calming region behind the initial strip is most likely responsible for the changes seen in the following strip.

$x = 0.80 \text{ m}$

At the final downstream location $x = 0.80 \text{ m}$, Figure (6.8), the surrounding boundary layer is now a fully developed reattached turbulent flow. Due to
unavoidably low clearances for the higher $\alpha$ ranges, the calmed region of
the previous pair of disturbances prevails and can even be spotted to the
far left in the $\alpha = 70$ deg plot. Therefore the leading edge of the initial
disturbance for $\alpha = 70$ deg encounters a laminar calmed region, that for
$\alpha = 50$ deg encounters a newly forming turbulent boundary layer and the
closely spaced tests with $\alpha \leq 40$ deg encounter the usual steady-state well-
established turbulent boundary layer. For these ranges of $\alpha$, the leading
core of the initial strip becomes absorbed into the surrounding turbulence.

Recalling that contours of red represent regions of newly formed turbu-
lence, it is thought that the leading core, a region of constantly regenerated
turbulence caused by the overhead wake, becomes merged with the existing
surrounding turbulence. The wake can no longer induce new turbulence as
the boundary layer is no longer laminar.

Regarding the interaction between the disturbance pairs, all except one
now exhibit core turbulence reductions, the exception being that of $\alpha = 70$
deg where the strips are still far apart. For the remaining four cases, the
suppression of the core of the following disturbance is clearly proportional to
the proximity of the two strips. For those pairs having the closest spacing,
the following strip has been in contact with the calming region for a sufficient
time to eliminate the core feature completely, fabricating a much longer
turbulent strip with an extensive entrainment of turbulent spots.

The intermittency data $\gamma$, Figure (6.12), again shows very little change
within the region of merging disturbances, subscribing to the superimposi-
tion property as observed in the upstream location $x = 0.60$ m. One can
still use the $\gamma$ contour plots to discriminate between the two turbulent strips
by inspection above the boundary layer. Note once more how those strips
that remain apart still demonstrate the reduction in turbulence intensity,
indicating the source of the effect to be from the calmed region.

### 6.2.2 Secondary pairs (Figures 6.13–6.20)

Apart from the aforementioned differences between primary ‘by-pass’ gener-
ated spots and secondary ‘naturally’ generated spots, there are few deviances
from the behaviour of the primary pairs when the secondary wake induced disturbances are paired together.

\[ x = 0.20 \text{ m} \& x = 0.40 \text{ m} \]

For these two upstream locations, Figures (6.13-6.14), the clusters all behave identically to one another with no interaction between any pairs, and individually develop in an identical way to those of the isolated wake in Chapter 5. Even for the closest spacing at \( \alpha = 30 \text{ deg} \) there are no interactions.

The intermittency \( \gamma \) data, Figures (6.17-6.18), show little worthy of note. (Note that the odd features for \( \alpha = 50 \text{ deg}, x = 0.20 \text{ m} \) are due to data acquisition errors, as mentioned in §6.2.1.)

\[ x = 0.60 \text{ m} \]

Further downstream at \( x = 0.60 \text{ m} \), Figure (6.15), the spots have developed into recognisable turbulent strips and now show regions of positive interaction for the two closest spacings \( \alpha = 30 \& 35 \text{ deg} \). As in the primary wake, the following strip starts to reduce its \( u' \) value in the core.

Similarly, as with the primary case, the intermittency \( \gamma \) data, Figure (6.19), shows a definitive gap between the two disturbances, so in actuality they are completely separate. Again, the reduction in RMS of velocity \( u' \) indicates that there has been a definite influence on the following core.

\[ x = 0.80 \text{ m} \]

Moving onto the farthest downstream location, where the surrounding boundary layer is again entirely turbulent, Figure (6.16), the behaviour here is identical to that of the primary pairs. The naturally turbulent boundary layer is clearly visible to the left-hand side within each plot. As in the primary case the initial strips again lose their core of newly forming turbulence to the surrounding natural turbulence.

The following strips, for those cases where the leading edge has advanced sufficiently into the calmed region of the initial strip, have also lost their core
of newly forming natural turbulence, in the same way as the primary pairs, which again results in one long strip.

### 6.2.3 Calmed regions

The calmed region of a following turbulent strip appears to be unaffected by any downstream influences, such as a merger between its owner's turbulent leading edge and a fellow turbulent entrainment region. This shows that the calming can survive the apparent demise of the turbulent strip to which it owes its existence.

The calmed region sandwiched between each pair, however, is slowly masked by the advancing turbulence but presents a degree of resistance. There is a suppression of the turbulence intensity within the core of each advancing strip. The degree of suppression appears to be related either to the length of time that the following turbulent strip exists within the calming zone, or to the streamwise proportion of calmed region that the following strip encounters. Of course, in the current experiment the two parameters are linearly dependant upon one another, therefore it would be very difficult to determine which, if not both of them, are primarily responsible for the 'strength' of the suppressive effect.

The overhead wake has been hypothesised to continually supply turbulent flow to the boundary layer at the leading edge of the turbulent strip, therefore perpetuating its existence. It may be that the suppressive effect is a balance between the quelling capacity of the calmed region and amplification by the wake. Without the wake it may be that the following core would exhibit a greater level of suppression.

To quantify this suppressive effect, non-dimensional values for the maximum $u'$ value of the core against strip separation, $\psi$, have been plotted for the four chord locations $x = 0.2, 0.4, 0.6 & 0.8$ m (Figure 6.21). The abscissa ($u'_{\text{max}}/u'_{\text{max,undis}}$) shows the maximum value for $u'$ in the core of the following strip normalised against the value for an isolated, or undisturbed, strip. In theory, this value should not be greater than 1, but a small amount of scatter exists due to experimental error. $\psi$ is a non-dimensional time de-
fined by the strip separation (leading edge to leading edge) over the initial strip temporal width at that location in space, coined the 'non-dimensional wake spacing'. Unity therefore represents two strips that have coincidental boundaries, less than unity a degree of overlap and upwards from unity an increasing spacing.

One can clearly see that the disturbance levels within the core of strips travelling into calmed regions exhibit a reduction exponentially proportional to the non-dimensional separation $\psi$. The effect begins for distances below $\psi \approx 2$ (a spacing between two strips comparable to twice their temporal length), indicating that the calmed region influence extends beyond the trailing edge for a time equivalent to the temporal existence of one strip. The calmed region, as indicated by the relaxation contours, enlarges at a rate slower than that of the turbulent strip. Therefore, the ratio of calmed region length to turbulent strip length is not a constant. This non-linearity would account for some of the scatter seen in the data.

$$F(\psi) = 1 - \exp\left[-\left(\frac{\psi + 0.4}{1.2}\right)^2\right]. \quad (6.2)$$

Equation (6.2) is an attempted exponential curve fit to the data. The fit is reasonable, and can be used to represent the capacity for suppression of the $u'$ parameter (effectively a multiplication coefficient) with non-dimensional wake spacing $\psi$ between successive strips (leading edge to leading edge).

**Comparisons with previously published observations**

It has been shown that the wake induced turbulent strips from both the primary and the secondary wakes behave in similar manners, with the main difference being their early magnitudes, having a direct relation to the turbulence intensity within the wakes.

Careful consideration must be made when comparing their properties to the results of researchers inducing individual spots via a controlled boundary layer perturbation, without freestream wakes.
Work by Gutmark & Blackwelder (1987) on the generation of turbulent spots within boundary layers from a spark generator investigated, among other circumstances, the interaction of two spots generated a short time apart. Ultimately the two spots merged to produce one larger spot, with the occasional ‘trapped’ cell of laminar flow resulting from the interaction of the upstream leading edge overhang with the downstream trailing edge.

Similar merging behaviour is seen in the current research. The advancing following strip encounters the calmed region of the initial strip and continues to propagate, exhibiting an increasing reduction in the strength of $u'$ at its core with increasing travel. Given sufficient streamwise distance, the two strips merge to create one long turbulent strip, displaying a single core and an extended tail of entraining spots. The calming influence of the initial strip is masked, leaving simply one calmed region belonging to the trailing edge of the following strip, which survives the merging process unaffected.

Unlike turbulent spots, the turbulent strip does not demonstrate the recognisable ‘overhang’ at its leading edge. Such an overhang, a lip of turbulent flow that extends downstream by a distance comparable to the half-length of the turbulent spot, was the first point of contact with the trailing edge of a downstream spot in the research of Gutmark & Blackwelder (1987), thus trapping a small region of laminar fluid in-between. In the current research, the leading edge of the turbulent strip is effectively a vertical wall of turbulence, a combination of the freestream wake and the induced turbulent strip within the boundary layer. Consequently, no trapped cell of laminar flow is created at the moment the two strips begin to merge. The absence of an overhang is discussed in more detail in §6.3.

Wake induced disturbance experiments by Pfeil et al. (1983) and Orth (1993), although a little vague on the interactive effects of successive wakes, do not demonstrate any influential properties of systematic turbulent strips upon one another.
6.3 Celerity rates

Determining the celerity rate of the leading and trailing edges of the disturbances is a task complicated by various issues regarding edge detection techniques, disturbance growth, local deceleration, trend curve approximation and variation with boundary layer height, to name but a few. The techniques developed here are described in §5.2.3.

Due to the fact that these wakes are generated in closely spaced pairs, the following turbulent strip often propagates within the calmed region of the initial strip. For the purposes of calculating the celerity rates, this is useful as it makes the detection of the turbulent strip leading edge easier across the full chord.

6.3.1 Initial turbulent strips

The initial wake generates a disturbance that behaves identically to the isolated wakes of Chapter 5, having leading and trailing edge celerity rates in the order of 100—200% and 54% respectively. The appearance of an over-accelerated leading edge has been discussed in §5.2.3 and reasoned to be due to the effect of the wake passing in the manner of a negative jet.

6.3.2 Following turbulent strips

Technique 1

As a quick reminder, technique 1 implements intermittency contouring to determine edge detection gradients and hence propagation rates. Celerities take into account the variable freestream velocity.

The data produced from celerity measurement technique 1, presented in Figures (6.22—6.31), show that there are no noticeable differences of celerity rate between the pairs of wake induced turbulent strips. Each following turbulent strip has celerity rates matching those of its downstream partner.

The red and blue curves represent the initial and the following turbulent strip data respectively. The intermittency contours are shown in the plot.
to the left, and their associated celerity rates in the plot to the right, with four different threshold settings divided into rows. Figure (6.32) shows the average celerity rates, and proves that no significant deviation in celerity rate from that of an isolated turbulent strip occurs for those propagating into calmed regions.

**Technique 2**

Technique 2 uses the RMS of velocity $u'$ data coupled with a set threshold to determine leading and trailing edges. Linear fits are then applied to the data to determine constant propagation rates across chord. Celerities are determined using $U_{\text{omax}}$.

The data from technique 2 perhaps tells a different story. As discussed, the following wakes, for both the primary and secondary cases, induce turbulent strips with leading edges that propagate into the calmed flow behind the downstream initial turbulent strip. It is seen from these measured celerity rates (see Table 6.2) that all following wakes have a slightly lower leading edge celerity rate than their initial counterpart. This could perhaps indicate that the calmed region slightly retards the advance of the entraining turbulent strip.

However, not all of the following turbulent strips reach the downstream calmed region, as is the case for the farthest distribution of primary wakes ($\alpha = 70^\circ$). For this case the leading edge of the following turbulent strip remains outside the influence of any calmed zone, yet a reduction of celerity, albeit smaller, is still seen. It is possible that any calming influence present is weakened by the greater distance between them.

This said, however, it must be remembered that these values are linear chord-wise averages of each strip's varying celerity rate because they are attained from linear fits to the $u'$ contour data (polynomial fits were not feasible) and use the maximum freestream velocity for normalising. Moreover, the following turbulent strips have a longer chordwise distance over which to determine their locations than the initial strips due to their existence within

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1Celerity rates from a model are superimposed, see §6.3.3 for details of the model.
a calmed boundary layer. Therefore, as the linear fits are performed across dissimilar chord extents, coupled with the fact that they are non-constant, they cannot be compared with true assurance.

With this in mind, and the evidence from technique 1 to argue the contrary, it can therefore not be stated with absolute certainty that the calmed region has a definite retarding influence on the celerity rate of encroaching turbulence.

**Comparisons with previously published observations**

Work by Krane & Pauley (1994) into turbulent spots and the influence of calmed regions did not see any alteration in leading edge propagation velocity, with the exception of those following spots initiated directly within the calmed region where a reduction was seen.

In the current research, those wake induced turbulent strips that do encounter calmed regions have to propagate into them. In no cases are turbulent strips initiated within a calming zone. This would not be possible with the current experimental configuration as each calmed region is the result of a developed turbulent strip, and to induce further turbulence within the calmed region would require an alternative to the bar passing mechanism that operated locally (such as a spark generator). Hence, it may be that a turbulent spot generated with the calmed region of the wake induced turbulent strips would indeed exhibit a reduced celerity rate, but this has not been investigated.

The results of Gutmark & Blackwelder (1987) disagree, however, with those of Krane & Pauley. Gutmark & Blackwelder observed in their paired turbulent spot research a definite celerity rate reduction for turbulent spots advancing into calmed regions.

The greatest celerity rate reductions were seen in the overhang of the following turbulent spot, by up to as much as 20%. Adjacent to the plate surface, celerities were reduced by 15%, and remained fairly constant elsewhere. Gutmark & Blackwelder incorporate an RMS strategy in their determination of spot turbulent boundaries, similar to that of technique 2 here.
It is possible that their following spots were suppressed in a similar way to
those of the current research, reducing the RMS levels inside each spot. A
reduction of this kind can lead to a delayed detection of the leading edge,
and subsequently to underestimations of the local propagation rate.

In the current work, no overhang is present for the turbulent strips.
Since any calming influence is presumably restricted purely to within the
boundary layer, it can be presumed that the following wake propagates in
the freestream without influence from the calmed region of the downstream
turbulent strip. Hence maintaining the existence of the turbulent strip core
directly beneath its leading edge. Therefore, regardless of any potential
calming effect upon the turbulent strip within the boundary layer, the con­
tinuous presence of the wake directly above ensures that the turbulent strip
does not recede by providing a constant source of turbulent energy directly
above the leading edge. A reduction in the RMS level is seen, indicating
a suppression of the turbulence amplitude, however celerity rates are unaf­
fected.

This hypothesis could explain the differences seen between the interac­
tion of turbulent spots with calmed regions and turbulent strips with calmed
regions.

Most authors investigating a turbulent spot shape have reported the
well-documented overhang feature, however, in the current research the tur­
bulence is induced by a passing wake. Similar turbulent strips, without
overhangs, were observed by Pfeil et al. (1983) in his wake induced bound­
ary layer transition experiments. Wakes shed in a similar manner to the
current research technique produced clusters of boundary layer turbulent
spots, for which the leading edge does not demonstrate the typical overhang
of a singular turbulent spot.

With regard to the trailing edge celerity rate, Gutmark and Blackwelder
(1987) state that “no influence on either one of the spot’s trailing edges was
detected.” This is also true in the results of the present research.
6.3.3 Variation with streamwise distance

Changes in the celerity rate with respect to chord location are difficult to determine. Technique 1 provides full streamwise celerity values, and some trends have been seen across the ensemble averaged data of technique 2.

An unfortunate artifact of applying technique 1 to intermittency contours is the production of false propagation velocities for the very early stages of transitional strip production. Due to the fact that the strips are initially transitional results in low intermittency values that gradually rise toward unity, following Narasimha's Universal Intermittency Distribution. When using intermittency contours, choosing values close to unity produces the cleanest results for turbulent strips, but consequently neglects the early transitional regions. Inspecting the contours of Figures (6.27-6.31) shows how the contour lines 'wrap around' the upstream part of the turbulent strip. The effect is greater in the secondary wake analyses due to their weaker wake induced turbulent strips. Gradients taken from these upstream contours are not accurate due to this contour wrapping.

Leading edges

Primary and secondary wake leading edge celerity rates were all noticeably decelerative, as discussed earlier in §5.2.3. They all begin with highly elevated celerity rates, which quickly decelerate to a settled value in the region of 100—115% of the local freestream velocity (see Figure (6.32)).

Trailing edges

Revisiting Figure (5.22), one can see that the trailing edge velocities have a detectable deceleration in the majority of cases. However, this reduction in velocity is mostly matched by the freestream velocity gradient, producing a fairly constant celerity rate with respect to chord.

The data from technique 1, Figures (6.22-6.31), show a similar trend. For the primary wakes the celerity rate is reasonably constant across the full chord. For the secondary, an initial low value (due to the contour wrapping)
quickly rises to a mean value of 55% freestream for the remainder of the chord.

The speed of this boundary is dictated by the well-known propagation rate for turbulent spot trailing edges — in the region of 50% — and does not appear to be influenced by the freestream wake or, where applicable, the encroachment of disturbances.

**Simple validating model**

At a late stage of the research, a basic model was developed, as described in Appendix (A.5), to aid in the appreciation of the strongly variant celerity rates derived by technique 1.

In no way designed to simulate the disturbance physics, the model simply follows a set of rules in its attempt to fit a partly-prescribed curve to the leading and trailing edges of the experimental intermittency data.

Included in the average celerity rates of Figure (6.32) are the celerity rates derived from the model. They exhibit the elevated and highly decelerative leading edge celerity rate curve as seen in both the primary and the secondary cases, and both types of trailing edge curve: the constant 50% value for the primary case, and the contrasting slowly accelerating trailing edge curve in the secondary case.

Given the many degrees of freedom in the model, it is not so remarkable that the results match very closely with the data. What is worth noting, however, is the strong variation in calculated celerity rates for the modelled disturbance, and how closely they again match those taken from technique 1.

Although the modelled disturbance is based on the experimental data, and therefore one might reasonably expect the celerities to match, this process does provide support for the celerity rates as calculated using technique 1.
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Comparison with previously published observations

Little has been published on the variation of celerity rate with streamwise distance. Authors tend to report constant celerity rate and propagation rate values. Determining acceleration and deceleration trends from ensemble averaged data is difficult because of the disassociated nature of the chordwise mapped values. As reported by Gostelow et al. (1997), a large amount of scatter can result from ensemble averaging processes. Accordingly, authors tend to generate only linear fits to edge detection results, and thus report singular celerity rates, as discussed in §5.2.3.

6.3.4 Variation with height $y$

A study of the variation of celerity rate with turbulent strip height within the boundary layer was undertaken using technique 2. The code was executed with $x \sim t$ data slices for a variety of different heights $y$, and a plot of the average celerity rate for each wake induced turbulent strip has been drawn for comparison in Figure (6.33).

Due to contour wrapping around the turbulent strip leading edges, no realistic data on celerity rates could be constructed for the two most upstream locations of the secondary wake ($x = 0.2$ and $x = 0.3$ m). The leading edge values for $x = 0.4$ m are also slightly affected by this wrapping, resulting in occasional sporadically elevated celerity rates.

The naturally turbulent boundary layer interferes with the leading edge detection for the initial strip after $x = 0.55$ m, so these celerity rates are from the following strips, whose paths are predominantly within laminar or calmed boundary layers and have been traced throughout the full streamwise extent.

There is a common trend among the data, and that is one of uniformity with boundary layer depth. It is difficult to determine anything other than this from the data as measurement complications result in the creation of misleading trends. For example, at the early chord locations the strip grows rapidly, creating high leading edge celerity rates, but this is short lived, giving the appearance of a strong deceleration before settling out at a steady
celerity rate. This effect seems to be more prominent at both the near surface and in the freestream, but for the most part any variation with surface distance appears to be insignificant.

Comparisons with previously published observations

Pfeil et al. (1983) published a distribution of celerity rate with height. Although not strictly an overhang feature, the turbulent strips had a forward lean, with the fastest propagation velocities towards the freestream, and the slower values towards the surface.

There is no evidence of increasing celerity with height in the current work, except at regions very close to the surface where the high velocity shear and the no slip theory mean local velocities are far reduced. Although technically this is an overhang, it is not the same overhang as that seen in turbulent spot work. Turbulent spot overhangs project at a height comparable with the boundary layer thickness. The small overhang present in the turbulent strip is much closer to the plate surface.

6.3.5 Variation with wake distribution

Variations with wake distribution were performed to investigate the effect of increasing the following wake’s proximity to a calmed region. Variations from ‘completely immersed within calmed flow’ to ‘developing outside the extremities of a calmed flow’ were obtained by adjusting the angle ($30 \leq \alpha \leq 70$ deg) between two successive rods on the wake generator.

The effect upon turbulent strip development with local proximity has been discussed in §6.2. Here the effect upon local celerity rates is discussed.

From Figures (6.22-6.31) the various celerity rates for the induced disturbances can be observed for each of the $\alpha$ configurations as determined from technique 1.

For the primary wakes, one can see that moving the wakes closer together by decreasing $\alpha$ (advancing from Figure 6.22 to Figure 6.26) has little to no effect on the celerity rates for either of the induced disturbances. Within the
bounds of experimental error, the celerity plot curves have identical values and identical trends.

The secondary wakes are harder to judge due to the sparse nature of the calculated celerity rates. However, after careful observation, one can perhaps agree that, as with the primary wakes, the response of the celerity rates to changes in $\alpha$ is indiscernible.

These results provide empirical evidence to suggest that calmed regions upstream of a developing turbulent strip do not give rise to influences that might retard advancing turbulence that has been induced by an overhead wake. No slowing of the advancing turbulence is seen, although, as mentioned previously in §6.2, the turbulence intensity is seen to reduce quite significantly.

Technique 2 shows a reduced celerity rate for the following wake induced turbulent strips, but without any proportionality trend with regard to proximity. One would perhaps expect to see a greater reduction in celerity rate with an increased proximity between a following turbulent strip and a calmed region. The data in Table (6.2) shows no such trend, with a uniform celerity rate for all primary cases, including perhaps that of $\alpha = 70$ deg where the following turbulent strip is actually outside the influence compass of the calmed region. Furthermore, for the secondary wake cases, there is no convincing trend for decelerated celerity rate for those turbulent strips encroaching calmed regions. Therefore, as stated in §6.3.2, there is not enough evidence to state that the calmed region has a retarding influence on the celerity rate of encroaching turbulent strips.

Comparisons with previously published observations

The work of Gutmark and Blackwelder (1987), as already discussed, saw a deceleration of following spot leading edge propagation rates in proportion to the proximity of the two spots. Effects were first seen when the two spots were initiated exactly one spot’s width apart, with an increasing deceleration of the following spot by up to 20% as they were moved closer together. Attention must be drawn again to the different techniques applied
in the precipitation of boundary layer transition between these works and the author’s research.

Work involving the use of wakes to induce turbulence includes that of Pfeil et al. (1983) and Orth (1993). Neither publication refers at any time to a change in celerity or propagation rate for either the leading or trailing edges of their wake-induced turbulent strips. Propagation rates were seen to be constant regardless of the surrounding boundary layer, be it naturally laminar, turbulent or calmed.

6.3.6 Calmed region celerity rate

The trailing edge of the calmed region propagates at a speed dictated by the natural boundary layer perturbations, i.e. Tollmien-Schlichting waves. This has been discussed previously in §2.3.

The relaxation parameter has been used to determine the extent of calmed flow behind each turbulent strip, as described in §5.2.3. An example of the detected relaxation region has been included in Figure (6.34) for the farthest spacing of wakes, case $\alpha = 70$ deg.

The propagation of the trailing edge of this relaxed region varies with chord. For a calmed region uninterrupted by an entraining turbulent strip, the trailing edge exhibits three distinct zones identical to the single wakes of Chapter 5, and has hence been previously discussed in §5.4.1.

In contrast to the single wakes of the previous chapter, the following wake induced turbulent strip of each pair interacts with and masks the calmed region of a downstream turbulent strip.

In such cases there are only two distinct linear celerity rates, that before and that following the instant of contact. From initiation up to the point of contact, the calmed region acts much like that from a singular turbulent strip (as in Chapter 5), yet the celerity rate deviates slightly from that of an undisturbed calmed region. A slight reduction of the celerity rate is seen, with both the primary and the secondary induced calmed regions dropping by 7% of $U_\infty$ to approximately 36%.
CHAPTER 6. PAIRED WAKES

Beyond the instance of contact, the calmed region becomes masked by the ensuing turbulent strip leading edge celerity, and hence appears to adopt that exact same celerity rate.

From this statement it would seem that the presence of advancing turbulence upstream of a calming zone encourages that trailing edge celerity rate to reduce. The extent of this relaxed flow is known to be dictated by the advancing boundary layer perturbations. For the celerity rate to reduce, these perturbations would need to be slowed, or quelled. It is hard to envisage any feasible fluidic mechanism that could achieve this, and the author, therefore, views this finding as questionable. It is possible that the technique employed here to determine the calmed region trailing edge, and hence its propagation velocities, has a larger margin of error than previously thought.

6.4 Discussion

The behaviour of closely spaced wakes upon a boundary layer is not the same as those of individual wakes. Induced boundary layer disturbances interact with one another, consequently a clearly defined suppression of turbulent activity is observable in the core of every turbulent strip encountering becalmed flow. The rate of suppression is exponentially proportion to the proximity of the strip to the calmed region, increasing dramatically once within the influence compass.

Work by Gutmark & Blackwelder (1987) reported reductions in the propagation rate for turbulent strips within calmed regions. Their measurements were based on the local RMS of velocity, using an edge detection algorithm to determine leading and trailing boundaries. The arrival time of each boundary was then used to estimate the varying propagation rate. However, the author believes that Gutmark & Blackwelder failed to notice the potential for varying RMS levels in the turbulent spot induced by the calming regions. Without taking these non-constant RMS levels into account, the edge detection algorithms would incorrectly report a later arrival time for the influence spots. It is conceivable that Gutmark & Blackwelder therefore mistakenly
observed a slowing of their turbulent spots, when what they in fact saw was a reduction in the turbulent content.

The suppression has been quantified in Figure (6.21). The scales are non-dimensionalised in an attempt to account for the many variations with streamwise distance, and show the data to collapse onto a reasonable curve. An exponential trend line has been superimposed and described in eqn. (6.2). This trend line provides a guide for future researchers to compare their own data to that of the current research.

The suppression of turbulent content within wake induced strips is an important finding. The turbulence can be reduced by up to 40% with the correct spacing of incoming wakes. Current trends in engine design are to reduce weight and cost by minimising the number of blades without sacrificing performance. Consequently, to achieve fewer blades, one requires a greater performance from each individual blade. This has the added effect of reducing the frequency of wakes impinging onto downstream stages. With the above realisations in mind, it must be considered that reducing the total number of blades could result in a reduction in the influence of the calmed region as the non-dimensional wake spacing $\psi$ climbs above the compass threshold $\psi \approx 2$.

Figure (5.28) taken from Gostelow et al. (1997) is a plot of intermittency data taken from a turbomachinery stator blade encountering the wakes of an upstream rotor. Estimated measurements of $\psi$ from this plot span the range 3.2 to 1.4 when advancing the surface distance from $s^* = 0.4$ to 0.9, crossing $\psi \approx 2$ at $s^* \approx 0.75$. The wake induced turbulent strip is therefore under the influence of the calmed region for one quarter the chord length.\footnote{The influence is not visible in the plot because the intermittency parameter is not affected by reductions in turbulence intensity when the flow is fully turbulent.} Increasing the wake spacing would subsequently increase $\psi$ across the chord, with each turbulent strip eventually circumventing the influence of the calmed region completely.

The capacity of a calmed region to suppress the turbulence in an advancing strip does not affect the propagation rate. The use of intermittency contours to track the exact boundaries of propagating turbulent strips has
shown absolute consistency in their celerity rates. The existence of becalmed flow ahead of a strip does not in any way reduce the propagation rate. Unlike turbulent spots that travel at speeds slower than the freestream, turbulent strips travel no slower than the overhead wake. Due to a combination of negative jet theory and increasing boundary layer receptivity, turbulent strips give the appearance of celerity rates in excess of the wake. Were these disturbances to occur without a freestream wake, one might expect their propagation rates to mirror turbulent spot theory. It is precisely the wake existence itself that alters the growth and development of the strip underneath its footprint.

This fact is consistent for both the primary and secondary wakes. The turbulence intensity therefore has little to no effect on the influence of the wake upon the fully developed turbulent strip. The level of turbulence remains important in establishing the early transitional strip, as demonstrated in Chapter 5, but bears no relationship to the behaviour of the turbulent strip upon encountering becalmed regions.
Table 6.2: Table of calculated (leading/trailing) edge propagation rates averaged over the range $0.50 \leq y \leq 2.00$ mm for the primary and secondary turbulent patches using best linear fit to RMS of velocity $u'$ data and local $U_\infty$. 

<table>
<thead>
<tr>
<th>$\alpha$ (deg)</th>
<th>Velocity (m/s)</th>
<th>Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>11.74±0.42/4.64±0.43</td>
<td>10.32±1.16/4.44±0.21</td>
</tr>
<tr>
<td>35</td>
<td>11.26±0.19/4.84±0.25</td>
<td>9.49±1.19/4.68±0.32</td>
</tr>
<tr>
<td>40</td>
<td>10.30±0.07/4.42±0.17</td>
<td>8.44±0.38/4.45±0.22</td>
</tr>
<tr>
<td>50</td>
<td>11.06±1.10/4.55±0.17</td>
<td>9.10±0.22/4.62±0.23</td>
</tr>
<tr>
<td>60</td>
<td>10.27±0.71/4.54±0.26</td>
<td>9.86±0.70/4.48±0.25</td>
</tr>
<tr>
<td>70</td>
<td>138.5±5.0/54.7±5.01</td>
<td>121.7±3.7/52.3±2.23</td>
</tr>
<tr>
<td>35</td>
<td>131.2±13.8/56.4±2.93</td>
<td>110.6±13.9/54.6±3.69</td>
</tr>
<tr>
<td>40</td>
<td>131.7±4.4/55.5±2.19</td>
<td>105.9±4.8/55.8±2.73</td>
</tr>
<tr>
<td>50</td>
<td>125.6±12.7/52.9±2.95</td>
<td>105.8±2.6/53.7±2.89</td>
</tr>
<tr>
<td>60</td>
<td>124.2±8.6/54.8±3.10</td>
<td>119.3±8.5/54.1±2.97</td>
</tr>
<tr>
<td>70</td>
<td>124.2±8.6/54.8±3.10</td>
<td>119.3±8.5/54.1±2.97</td>
</tr>
</tbody>
</table>

The table above provides the calculated edge propagation rates for the primary and secondary wakes, averaged over the range $0.50 \leq y \leq 2.00$ mm. The propagation rates are given in terms of the leading and trailing edges of the turbulence patches. The table includes the angles $\alpha$ at which the measurements were taken, as well as the corresponding velocities and capacities. The data was obtained using a best linear fit to the RMS of velocity $u'$ data and local $U_\infty$. The table highlights the variation in propagation rates with different angles and provides a comprehensive view of the edge propagation characteristics in the context of paired wakes.
Figure 6.1: First of four carpet plots relating the variables clearance and location of the second rod on axes of disc rotation speed and incidence percentage, for the primary wake leading edge (see §6.1.2).
Figure 6.2: Second carpet plot relating constants of clearance and location of the second rod on axes of disc rotation speed and incidence percentage, for the primary wake trailing edge.
Figure 6.3: Third carpet plot relating constants of clearance and location of the second rod on axes of disc rotation speed and incidence percentage, for the secondary wake leading edge.
Figure 6.4: Fourth carpet plot relating constants of clearance and location of the second rod on axes of disc rotation speed and incidence percentage, for the secondary wake trailing edge.
Figure 6.5: Primary spots. RMS of velocity $u'$ at station $x = 0.20$ m for decreasing values in $\alpha$. 
Figure 6.6: Primary spots. RMS of velocity $u'$ at station $x = 0.40$ m for decreasing values in $\alpha$. 
Figure 6.7: Primary spots. RMS of velocity $u'$ at station $x = 0.60$ m for decreasing values in $\alpha$. 
Figure 6.8: Primary spots. RMS of velocity $u'$ at station $x = 0.80$ m for decreasing values in $\alpha$. 
Figure 6.9: Primary spots. Intermittency $\gamma$ at station $x = 0.20$ m for decreasing values in $\alpha$. 

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Figure 6.10: Primary spots. Intermittency $\gamma$ at station $x = 0.40$ m for decreasing values in $\alpha$. 
Figure 6.11: Primary spots. Intermittency $\gamma$ at station $x = 0.60$ m for decreasing values in $\alpha$. 
Figure 6.12: Primary spots. Intermittency $\gamma$ at station $x = 0.80$ m for decreasing values in $\alpha$. 
Figure 6.13: Secondary spots. RMS of velocity $u'$ at station $x = 0.20$ m for decreasing values in $\alpha$. 

$u'$ (m/s)
Figure 6.14: Secondary spots. RMS of velocity $u'$ at station $x = 0.40$ m for decreasing values in $\alpha$. 
Figure 6.15: Secondary spots. RMS of velocity $u'$ at station $x = 0.60$ m for decreasing values in $\alpha$. 
Figure 6.16: Secondary spots. RMS of velocity $u'$ at station $x = 0.80$ m for decreasing values in $\alpha$. 
Figure 6.17: Secondary spots. Intermittency $\gamma$ at station $x = 0.20$ m for decreasing values in $\alpha$. 
Figure 6.18: Secondary spots. Intermittency $\gamma$ at station $x = 0.40$ m for decreasing values in $\alpha$. 
Figure 6.19: Secondary spots. Intermittency $\gamma$ at station $x = 0.60$ m for decreasing values in $\alpha$. 
Figure 6.20: Secondary spots. Intermittency $\gamma$ at station $x = 0.80$ m for decreasing values in $\alpha$. 
Figure 6.21: Effect of calmed region suppressive plotted as RMS of velocity $u'$ in the core non-dimensionalised with freestream against $\psi$, the temporal proximity between strip leading edges normalised against one strip temporal width.
Figure 6.22: Turbulent strip celerity rates calculated from Intermittency contours at \( \gamma = 0.5, 0.6, 0.7 \) and 0.8 for primary coupled wakes of \( \alpha = 70 \) degrees. Data clipped to within sensible ranges.
Figure 6.23: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for primary coupled wakes of $\alpha = 50$ degrees. Data clipped to within sensible ranges.
Figure 6.24: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for primary coupled wakes of $\alpha = 40$ degrees. Data clipped to within sensible ranges.
Figure 6.25: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for primary coupled wakes of $\alpha = 35$ degrees. Data clipped to within sensible ranges.
Figure 6.26: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5, 0.6, 0.7$ and $0.8$ for primary coupled wakes of $\alpha = 30$ degrees. Data clipped to within sensible ranges.
Figure 6.27: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5, 0.6, 0.7$ and $0.8$ for secondary coupled wakes of $\alpha = 70$ degrees. Data clipped to within sensible ranges.
Figure 6.28: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5, 0.6, 0.7$ and $0.8$ for secondary coupled wakes of $\alpha = 50$ degrees. Data clipped to within sensible ranges.
Figure 6.29: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for secondary coupled wakes of $\alpha = 40$ degrees. Data clipped to within sensible ranges.
Figure 6.30: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5, 0.6, 0.7$ and 0.8 for secondary coupled wakes of $\alpha = 35$ degrees. Data clipped to within sensible ranges.
Figure 6.31: Turbulent strip celerity rates calculated from Intermittency contours at $\gamma = 0.5$, 0.6, 0.7 and 0.8 for secondary coupled wakes of $\alpha = 30$ degrees. Data clipped to within sensible ranges.
Figure 6.32: Averaged turbulent strip celerity rates calculated from Intermittency contours for primary (—) and secondary (− −) coupled wakes. Model celerities superimposed (⋯)
Figure 6.33: Turbulent strip celerity rates showing distribution with height $y$ at various chord locations for both primary (top) and secondary (bottom) coupled wakes. Leading edge ($\circ$), trailing edge ($\times$)
Figure 6.34: Relaxation contours (---) showing the extent of the calmed region behind each turbulent strip. Intermittency data from $\alpha = 70$ deg configuration.
Chapter 7

Conclusions

7.1 Conclusions

Wake induced transitional/turbulent strips have been experimentally simulated on a large flat plate with an imposed adverse pressure gradient in the low-speed recirculation tunnel at the University of Leicester.

The steady state boundary layer has been measured and natural transition proved to be the prevailing form of transition via the process of upstream Tollmien-Schlichting waves that steadily amplify and begin their breakdown in the separated shear layer.

The long thin laminar separation bubble is terminated by a transition region. Detailed measurements in this region have shown that the transition region closing the bubble is accurately represented by the Universal Intermittency Curve of Narasimha. As such this work supports the use of such theory for modelling transition regions in laminar separation bubbles under strong adverse pressure gradients.

Unsteadiness was introduced by an upstream wake generator simulating the velocity deficit and elevated turbulence levels of a passing wake originating from the trailing edge of an upstream multistage blade row.

Turbulent structures were seen to be regularly induced beneath the footprint of each passing wake, of a strength related to the magnitude of the
turbulence intensity within the wake. Peak levels nearing \( Tu = 20\% \) produced instantaneous turbulence in the boundary layer, whereas lower levels nearer to \( Tu = 10\% \) created transitional regions that required a short period of chordwise development before becoming a fully turbulent strip.

The present results show some behavioural similarities to artificially generated spots initiated by sparks or the injection of small perturbations. Distinctions are apparent in their individual propagation rates and also in the manner with which they mutually interact.

**Isolated wakes**

Turbulent spots excited from single point sources convect and develop within the boundary layer, disassociated from any additional artificial influence. Their behaviours exactly mirror those of naturally occurring turbulent spots. Turbulence initiated by the influence of a passing freestream wake cannot progress or develop independently within the boundary layer due to the continuous existence of that wake. The two turbulent entities — wake and strip — are forced to remain associated, coexisting throughout the entire course of their passage.

This difference between a spot and a strip is responsible for affecting the measured celerity rate of the turbulent patch leading edge. For individual spots, induced without a passing wake, these leading edges have been well documented to travel at 88\% of the freestream velocity. In the case of wake induced turbulent strips, the celerity rates are far different.

The leading edge of the turbulent strip never travels slower than the freestream velocity. This is due to a combination of negative jet theory and destabilisation of the boundary layer. Celerity rates in excess of twice the freestream have been observed for early boundary layer strips. The celerity rates decelerate asymptotically to approximately 1.15, where they steadily remain. The strip is initiated in the laminar boundary layer, directly under the center of the passing wake. Due to these elevated celerity rates, the leading edge soon advances downstream to match the location of the front of the wake. Trailing edge celerity rates are consistently 50\% throughout their streamwise extent.

A wake induced strip contains a higher turbulence intensity than a nat-
urally developing spot, and its association with a passing wake ensures that additional turbulent energy is always available. Furthermore, the strength of the induced wakes in the current research is relatively high when compared to those of other researchers. These factors evidently demonstrate that the strength of the incoming turbulence is an essential contributor to the behaviour of induced turbulence within the boundary layer.

This raises the important issue of the degree to which similarities between artificially generated turbulent spots and wake induced turbulent strips extends. The parallels between flat plate experimentation and data acquired from high-speed turbomachinery are cited in many publications. They clearly demonstrate the capability of large-scale low-speed research to represent the true multi-stage environment. However, these parallels must have limitations. In the simulation of multi-mode transition wake data will give a better representation of transition than triggered spots.

**Paired wakes**

Two parameters to represent the suppressive effects of the calmed region were analysed in the present work; celerity rate and root-mean-square of velocity.

Study of the strip celerity rates showed no change when a becalmed region was encountered. Turbulent spots have been reported by Gutmark & Blackwelder (1987) to slow upon entering a calmed region, though the technique adopted to determine spot boundary propagation rates has been proposed as being sensitive to variations in turbulence intensity. The current algorithms use intermittency to accurately locate the true extent of propagating strips. The use of this technique has clearly demonstrated the unchanging celerity rates of turbulent strips advancing into calmed regions.

However, this is not to say that the calmed region does not resist the advance of turbulent flow. Analysis has shown an undeniable suppression of turbulence intensity. Strong reductions were seen for the core regions of strips where the RMS of velocity normally remains very high. The propagation of the strip itself is not altered, yet the calmed region succeeds in quelling the strength of the incoming turbulence by up to 40%.

This research raises many philosophical questions. Especially regarding
periodic closure of the separation bubble and the ability of a calmed region to suppress turbulence and subsequently reduce local surface heat transfer.

It has been shown that precipitated transition from the passage of free-stream wakes prevents the separation of the boundary layer at the natural separation point. Convecting boundary layer turbulence remains attached, eradicating the detrimental effects seen from separated shear layers. The entraining calmed region is also seen to demonstrate significant separation resistance, observed as the consequence of a full velocity profile inherited from its turbulent parentage.

Such behaviour can be used to strong advantage in an unsteady multi-stage turbomachine. The perpetual prevention of blade suction surface separation by the periodic impingement of upstream wakes allows a designer to utilise blade methodologies normally susceptible to severe separation problems. The manipulative use of wakes inherent to multi-stage ideology can increase compressor blade lift, improve stage efficiency and reduce overall losses at not to the designer.

The demonstrable suppression of the strip’s turbulence level is evidence of a calmed region’s ability to subdue encroaching turbulence. Conforming to substantialism, the phenomena of calming has been shown to prevail, even in those environments where encroaching turbulence apparently engulfs the calmed zone entirely. It is the case that here the calmed region is merely masked, and its influence survives to suppress the amplification of local instabilities and reduce turbulence intensity.

Additionally, reduced levels of turbulence intensity have implications for reductions in overall surface heat transfer rate. Advanced HP turbine blade cooling techniques including surface film cooling and rail cooling reduce surface heat transfer rate by reducing the physical temperature of the contact flow. The application of these intrusive techniques can be eased by adopting unsteady surface boundary layer predictions that incorporate the suppressive effects shown to arise in the calmed region. An overall reduction in surface turbulence intensity can supplement the benefits gained from the aforementioned techniques, pushing back the temperature tolerances of current HP turbine stages.
CHAPTER 7. CONCLUSIONS

The most important message to be learned from this research must be one of understanding the implications these complex turbulent strip interactions offer to turbomachinery design. There exists the possibility of controlling the time-mean surface turbulence intensity by managing the calming phenomena prevalent between wake-induced transitions. This can be achieved by careful control of the wake frequency and knowledge of the strength of each wake. Manipulation of the boundary layer in this way can result in an optimised unsteady blade performance.

Today's trends in modern gas turbine design are toward fewer blades. This leads to stronger but fewer wakes impinging onto downstream blade rows in the multi-stage environment. A designer must take great care in establishing a suitable wake frequency. Too few wakes will result in values for non-dimensional wake spacing $\psi > 2.0$. In this domain the suppression benefits of the calmed region are not utilised because subsequent wakes arrive too late. This also heightens the risk of separated flow between wake paths due to the expiry of the calmed region and hence its resistance to separation. These compounded issues can adversely affect the overall blade losses, the stall behaviour and the time-mean heat transfer rate.

Keeping $\psi < 2.0$ will ensure that the benefits of calmed regions are exploited, and also reduce the risk of the naturally separated boundary layer developing between wake paths.

7.2 Recommended future work

This research leaves many questions unanswered. As a project it covers many of the areas of interest regarding unsteady transition in separation bubbles in an adverse pressure gradient, and has revealed strong dissimilarities between turbulent spot and turbulent strip activity.

There are several areas within which the scope of the experimentation ought to be furthered.

Crucially, the true chordwise extent of the calmed region ought to be tracked further downstream in order to determine the limitations of its re-
CHAPTER 7. CONCLUSIONS

sistance to the natural transition of the boundary layer.

The strength of turbulence within the wakes seems to be an important factor in the strength of the associated boundary layer turbulence. Inducing weaker wakes with a reduced peak $Tu$ level would provide information on wake induced turbulence at conditions closer to those of LP turbine environments. It may be found that weaker wakes produce weaker transitional/turbulent strips that would react more measurably to the existence of calmed regions.

It would be interesting to extend the traverse plane to three dimensions, and also advance into two dimensional hot-wire anemometry. Consequently, the ability to visualise velocity vectors could elucidate features of the passing wake, including the presence of negative jet behaviour.

Certainly, reversing the direction of the wake generator would provide an insight into the validity of the 'jet effect' proposals presented in this thesis. This effect is hypothesised to be responsible for the differences seen in celerity rate between the primary and secondary wakes, the primary having a 'downward' velocity component and thus enhancing the development of leading edge turbulence; the secondary having an 'upward' component and not presenting this effect. A reversal of direction would provide primary wakes with an identical turbulence intensity but a positive jet, and secondary wakes with the negative jet. If a reversal of leading edge celerity rates is seen between the two cases then the jet effect can be reasonably accepted.

But a more interesting hybridised project is at the heart of the author's future interests: involving the true determination of a calmed region's ability to suppress the development of turbulence. As an extension to the current research, the injection of a small jet of air to encourage the growth of a turbulent spot, as used by previous researchers on this wind tunnel configuration, within the substantially developed calmed region of a wake induced turbulent strip would allow for the investigation of a calmed region's response to encroaching turbulence without a freestream wake. If current academic debate over the effectiveness of a calmed region to suppress turbulence is correct, one would expect to see no turbulent spot development. There is currently insufficient understanding of the calmed region's influential na-
ture and the author is interested in quantifying the currently qualitative appreciation.
References


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Appendix A

Appendices

A.1 Contour anomalies

During periods of analysis, it was noticed that, under certain conditions, contouring routines were not performing as expected, and generating anomalous plots. The reason for the anomalies is due to incompleteness in the data sets, or more accurately, a lack of spatial resolution. To compensate for incompleteness, missing values can be estimated using predictive interpolation techniques to increase the spatial resolution.

In the example below (Figure A.1) a simulated propagating instability wave, as detected by the microphone experimentation, has been generated using simple sine waves. The true direction of the instability is from left to right as you scan down the plot.

The application of a contouring algorithm to these traces fails to correctly determine associated wave patterns, which results in a plot that appears to describe uneven waves travelling in an opposite sense to the true wave direction. In actuality we know that the waves are travelling from left to right, and that this contour plot is a bad representation of the data.

Using a predictive interpolation technique, extra trace lines can be generated to improve the contour mapping routine. With this technique an estimate of the wave propagation velocity is required, however various values can be attempted until a reasonable plot is achieved. For this example, each successive trace exhibits the feature by a delay of 24 sample points
(a) Manufactured sine wave  (b) Resultant contour plot

Figure A.1: Example of an inaccurate contour representation.

Figure A.2: Example of an interpolated contour plot. New traces (——) created using corrective interpolation.

(which at a sample rate of 3200 Hz translates into a time delay of 7.5 ms, or a propagating velocity of approximately 3.3 m/s).

Figure A.2 shows the interpolated traces amongst the original signals, and it can be seen from the newly-calculated contour plot that a much better representation of the data has been achieved.

It has been argued that estimating missing values by predictive techniques does not improve the quality of a data set, as although the issue of data insufficiency is improved, the overall data attribute inaccuracy is increased (Guptil 1995).
A.2 Jitter analysis

In the late stages of the analysis of the data acquired during the extensive experimental period, it was considered that a variation in the arrival time of the turbulent patches due to slight variations in their growth characteristics and the flow dynamics from repetition to repetition could encourage erroneous statistical parameters, as explained below. Therefore, a test was performed upon the $\alpha = 40$ deg coupled disturbance data sets to determine the effect of the jitter, if any, on the results.

Theoretical errors caused by jitter

Jitter in the data arises because of variations in the turbulent patch arrival time for each repetition. The effect of jitter is to alter the sharpness of ensemble averages in regions of high gradient and introduce false levels of high RMS in regions of inconsistency. These slight differences can affect the statistical parameters, in particular the standard deviation.

Jitter removal

To remove the effect of the jitter, the velocity data has to be analysed to compensate for the variation in leading edge arrival times for each turbulent patch. Using intermittency techniques, the exact location of each turbulent patch can be determined and these time indices can then be used to offset the data and align each turbulent spot before ensemble averaging and standard deviation techniques are used.

Actual jitter in the data

Figure (A.3) shows disturbances at $x = 0.50$ m and $y = 1.40$ mm arriving discontinuously, due to natural differences between each turbulent patch, and also how the data would look with a jitter correction (drawn in red), performed using intermittency analysis to determine the leading edge of each patch.
Figures (A.4a-f) shows the mean and RMS of velocity for both the original and the corrected velocity data. The test shows that there is actually very little effect created by the variation in arrival time for each turbulent spot.

Figures (A.4a,c,e) show the ensemble averaged velocity \( u \) at heights of \( 1.00 \leq y \leq 2.00 \text{ mm} \) with and without jitter correction. It is plain to see that very little benefit is gained from the use of jitter correction here, slight improvements in the leading edge sharpness are evident (see Figure (A.4a) \( 0.16 \leq t \leq 0.17 \text{ sec} \)).

However, due to the independence of the two turbulent spots, the jitter of the second disturbance is not correctly compensated by the jitter correction factors of the first disturbance. Therefore, any benefits gained from the use of jitter correction for the first leading edge would be negated by the 'worsening' of the arrival time differences for the second disturbance.

This is more evident in the calmed region between the two disturbances, as seen in RMS of velocity \( u' \) (Figures A.4b,d,f), where the normally low levels of \( u' \) are not consistently detected. This is caused by the effect of 'pushing-back' those disturbances that arrive slightly earlier than the average arrival time, effectively lengthening their temporal extent into the calmed region. This can perhaps be seen more clearly in Figure (A.3) where the calmed region of the jitter-corrected data (red) is not so consistently laminar as the original data (black), creating a heightened level of \( u' \).

The 'pulse' of high RMS, the initial jump in \( u' \) at the leading edge of the disturbance, still exists in the jitter-corrected statistics. It was thought that perhaps the jitter-corrected data would eliminate this feature, but its persistence shows that this is a genuine feature of the original data and not (entirely) a result of inconsistent arrival times.
Figure A.3: Velocity data for $x = 0.50$ m, $y = 1.40$ mm. Black plots show the uncorrected data for 64 repetitions, the red plots have been jitter-corrected. Data has been artificially offset for clarity.
Figure A.4: Comparisons for ordinary phase averaged and RMS data to jitter-corrected version for \( x = 0.50 \) m at three heights. Red plots represent the jitter-corrected data, black plots ordinary.
A.3 Wake generator model

A mathematical model of the wake generator was constructed with an aim to estimating the arrival of the wakes from the rods. Incorporating all the variable properties, including rotational speed, angular distance between the rods, flow velocity etc., the model can be used to predict the approximate flow conditions required to achieve incoming wakes of a specified arrangement.

A.3.1 Creating the model

The model, see Figure (A.5), incorporates all the important features of the wake generator to aide accurate estimation of wake arrival times. In the calibration of the model, data were taken from previous experiments performed using the single rod, and used to define values for the turbulent patch width and calmed region strength.

Assuming the time taken for the wake to reach the sensor is a constant, then the horizontal distance from the rod to point A is,

$$\overline{AP} = d + x(1 - \cos\theta), \quad (A.1)$$

Figure A.5: Wake generator model, showing first rod P and second rod S, at distance r from hub. A is an arbitrary distance downstream.
and therefore the time taken for the wake to reach the sensor is,

\[ t_p = \frac{d + x(1 - \cos \theta)}{v} + t \quad \text{where } t \text{ is time passed since } t_0. \quad (A.2) \]

Here \( d \) is an arbitrary distance as its effect is to simply add a constant delay to the arrival time of each wake, and it can therefore be set to zero.

Since \( \theta = \omega t \),

\[ t_p = \frac{d + x(1 - \cos \theta)}{v} + \frac{\theta}{\omega}. \quad (A.3) \]

For wakes aligned with the plane of the flat plate, \( \theta \) is limited to integer multiples of \( \pi \), hence discretisation of \( \theta \) into,

\[ \theta_i = i\pi \quad \text{where } i = 0, 1, 2, 3 \ldots \quad (A.4) \]

and substitution gives,

\[ t_{pi} = \frac{d + x(1 - \cos \theta_i)}{v} + \frac{\theta_i}{\omega}. \quad (A.5) \]

Introducing a second rod \( S \) at an angle \( \alpha \) behind rod \( P \) onto the disc effectively requires the addition of a time delay \( \alpha/\omega \). Hence eqn. (A.5) becomes,

\[ t_{Si} = \frac{d + x(1 - \cos \theta_i)}{v} + \frac{\theta_i + \alpha}{\omega}. \quad (A.6) \]

Equations (A.5) and (A.6) calculate the arrival time for any desired wake.

### A.3.2 Expanding the equations to include the calmed region

Assuming, for simplicity, that the wake paths have a width proportional to the speed of the rotation of the disc, and that the calmed regions exhibit a time width that is constant regardless of wake size, then it can be possible to advance the equations to estimate time arrival, plus wake and calmed region behaviours. From the intermittency results of the single wake interaction experiments (see Figure 5.27), time constants for the wake and the calmed region widths of both the primary and the secondary wakes can be measured and used to modify the equations, hence eqns. (A.5) and (A.6) become,

\[
\begin{align*}
t_i^W &= \frac{d + x(1 - \cos \theta_i)}{v} + \frac{\theta_i + \alpha}{\omega}, \\
t_i^C &= t_i^W + \pi \left[ 0.211 + 0.019(-1)^i \right] \\
t_i^E &= t_i^C + 0.008(-1)^i + 0.094.
\end{align*}
\] (A.7)
Figure A.6: Estimated locations of the primary and secondary wakes, with calmed regions, from both rods using $\omega = 0.8 \times 2\pi$ and $\alpha = 50\, \text{deg}$.

Figure A.7: Intermittency values taken at $x = 0.7\, \text{m}$, $y = 1.20\, \text{mm}$ showing a high accuracy in the model’s estimated values.

The arrival of the wake leading edge, wake trailing edge (or calmed region leading edge), and the calmed region trailing edge can be estimated as $t_i^W$, $t_i^C$ and $t_i^E$ respectively.

Schematics can be drawn up to represent the wakes and their respective calmed regions, allowing the visualisation of the relative positions of each wake with respect to one another. Figure A.6 shows an example with variables set to $\omega = 0.8 \times 2\pi$, and $\alpha = 50\, \text{deg}$.

To show the accuracy of the model, intermittency values for $x = 0.7\, \text{m}$ at a height $y = 1.20\, \text{mm}$ are in Figure (A.7) for comparison. The four wakes arrive as predicted, with the two uninterrupted calmed regions showing similar lengths to the estimates.

### A.4 Total records review

Due to time restrictions, the number of ensembles dedicated to each experimental acquisition was reviewed. It was found, from comparisons between
phase-averaged and standard deviation results of data across different numbers of records, that a reduction in the ensembles created minimal variations in the data.

Figure A.8 compares differing numbers of records to the quality reduction in the phase averaged data, as well as for the standard deviation of the same data. Halving the number of ensembles from 128 to 64 has the consequence of altering the phase-averaged data by as little as 0.5%, and altering the standard deviation by no more than 7%.

For the laminar regions of flow, one could invariably choose relatively few ensembles for their acquisition, knowing that the variations between each record would be small relative to the scale of the data, and therefore suffer no loss in data accuracy. However, when considering turbulent regions, it would be wise to reduce the number of ensembles to gain a better representation of the data, because regions with a strong variation between records succumb greatly to high levels of phase-averaging, with a loss of local transient behaviour in the standard deviation parameter.

For these reasons, it was decided to reduce the number of ensembles for the data analysis from 128 to 64, except for the microphone acquisition and other regions of close hot-wire inspection where data may be used for intermittency calculations. Figure A.9 shows phase-averaged and standard deviation plots for an arbitrary turbulent region for both 64 and 128 records.

![Figure A.8](image)

Figure A.8: Plot of variation in mean value for ensemble average data and standard deviation data for differing numbers of ensembles.
Phase average traces for $x = 0.775 \text{ m}, y = 0.30 \text{ mm}$

(a) phase average

Standard deviation traces for $x = 0.775 \text{ m}, y = 0.30 \text{ mm}$

(b) standard deviation

Figure A.9: Traces for ensemble average data and standard deviation data for 128 (red) and 64 ensembles (black).

The differences, as can be seen, are minimal.

### A.5 Expanding control volume model

This model was constructed purely to assist the determination of turbulent strip leading and trailing edge propagation rates. It does not attempt to simulate in any way the physics of the flow, nor resolve any of the unanswered questions regarding the phenomena of boundary layer disturbance generation.

The model is based on the simple concept of an expanding control volume, free to propagate at a speed constantly proportional to the freestream flow, $m$, and grow in volume at a rate proportional to elapsed time, $at_i$. Volume is calculated from the multiplication of spatial dimensions, and for
spherical objects $V \propto r^d$. For a monotonic growth of volume with time, $V \propto t$, therefore $r \propto t^{1/d}$, or $r = at^n$ where $n = 1/d$ and $a$ is an arbitrary constant.

This concept is three-dimensional, yet turbulent strips are two-dimensional. Therefore, the code was allowed to adjust the above parameters in order to attain a better fit to the empirical data. The volume is neither spherical (3D) nor circular (2D), therefore the dimension variable $n$ is also non-constant.

The leading and trailing edges of this modelled control volume are considered separately to allow for freestream velocity variations, resulting in the calculation of two 'displacement tracks' representing the front ($F_{t.e.}$) and back ($F_{t.e.}$) of the volume respectively. Their independent iterative equations are,

\[
\text{Origin} = (t_0, x_0) = (t_{or}, x_{or}), \\
F_{t.e.} = (t_i, x_i) = (t_i, x_{i-1} + a(t_i^n - t_{i-1}^n) + mU_{\infty - 1}\Delta t), \quad (A.8) \\
F_{t.e.} = (t_i, x_i) = (t_i, x_{i-1} - a(t_i^n - t_{i-1}^n) + mU_{\infty - 1}\Delta t),
\]

where $t_i = t_0 + i\Delta t$.

Allowing the code to manipulate the constants resulted in the following values for the primary induced disturbances,

\[
a = 0.6896, \quad m = 0.6337, \quad n = 0.3720,
\]

and these for the secondary,

\[
a = 0.5935, \quad m = 0.5963, \quad n = 0.4508.
\]

An example result for the primary wake of $\alpha = 70$ deg is shown in Figure (A.10) with the calculated celerity rates in Figure (A.11). The result is a close fitting pair of leading and trailing edges.
Figure A.10: Example results from model for primary wake intermittency data at $\alpha = 70$ deg, showing leading and trailing edges (···), plus centreline (--).