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Recent Advances in the Dynamics of the Transition Zone

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RECENT ADVANCES IN THE DYNAMICS OF THE TRANSITION ZONE *

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1. Introduction

Interest in the dynamics of the transition zone has grown enormously in the last decade. In transport aircraft design, improvements in drag of even a few percent are now eagerly sought after; and much research effort has been expended on natural laminar flow, laminar flow control, turbulence management and related technologies to achieve lower drag. All of this demands greater understanding of the transition process in general. In internal flow applications, e.g. for turbomachinery, the transition zone plays an even more important role, as blade Reynolds numbers tend to be in precisely the range that is most awkward from the fluid-dynamical view-point, and a large fraction of a blade surface can be transitional. Peak heat transfer rates occur towards the end of the transition zone; and blades operate in a highly turbulent environment, often with a strong periodic component (when they are in the wake of a rotor, for example), and of course in strong pressure gradients. From the spate of papers in recent years on the subject, it is evident that applications in turbomachinery are now driving developments in the field. This is not difficult to understand, because a 25% difference in heat transfer rates on a turbine blade can mean an order of magnitude difference to its life (Reed 1985). The experiments of Turner (1971) showed already how complex the interaction between disturbance level and pressure gradient can be; thus in one case, an increase in free stream turbulence level advanced transition to lower Reynolds numbers and to a station where the pressure gradient was significantly different, the two effects being presumably responsible for a transition zone which tripled in length and covered more than three quarters of the blade. If we add to this the effects of surface roughness and curvature, periodic disturbances, compressibility, acoustic noise, three-dimensionality etc., it is easy to see how complex the process can be. The only hope for the foreseeable future seems to lie in understanding the physics of each of the processes involved to the extent possible, and in constructing models that contain the essential physics so discovered.

A small group has been working at the Indian Institute of Science and National Aeronautical Laboratory at Bangalore for many years now trying to unravel the effects of pressure gradient and flow convergence, among other parameters. This lecture is a summary of some of the work done as part of this programme, which in recent years has been supported by the Department of Science and Technology. The programme has actually covered some fundamental investigations concerning the possible connection between transition and dynamical systems (Bhat, Narasimha & Wiggins 1990) as well, but the material presented here will be confined to that directly concerned with the transition zone in boundary layers.

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The basic premise in much of this work is that the key variable in the transition zone is the intermittency γ (defined experimentally as the fraction of time that the flow is turbulent at any given station), so that an understanding of the γ distribution can provide considerable insight into the dynamics of the zone itself. It must be emphasised that this is *not* a question only of fitting curves to measured distributions, but rather of unravelling the physics that is revealed by them. The tool that makes this possible is the picture of transition as due to the growth and propagation of turbulent spots, first proposed by Emmons (1951). Certain assumptions of orderliness and independence in spot formation, while difficult to justify rigorously, appear nevertheless to be sufficiently close to reality that they provide effective means for data analysis. The major implication of these assumptions is that spot formation can be considered to be a Poisson process (Narasimha 1985), which has been extensively studied in connection with the theory of queues, for example. It is significant that Grek et al. (1990) have found, in experiments on a NASA 612 (420) (1) aerofoil, that the development of T-S waves and the structure of the turbulent spot that eventually emerges are both the same at a fairly high free-stream turbulence level of 1% as at the low level of 0.04%

This route to understanding the transition zone naturally demands investigations of turbulent spot behaviour under all the variety of influences that were mentioned above as relevant to transition in turbomachinery. Such investigations of spot behaviour are unfortunately far too few, but there are already enough of them to suggest that surprises may be in store.

2. Constant Pressure Flow

This is a logical baseline case and a necessary starting point. Early proposals postulated that spots are formed with equal probability everywhere on the surface, beginning from the leading edge (Emmons 1951)or from some specified station downstream (Emmons & Bryson 1952). The former implies a similarity of the distributions in $x/\bar{x}$, where x is distance downstream and $\bar{x}$ the station where $\gamma = 0.5$; this similarity is not observed (Narasimha 1985). In the light of the extensive investigations that have been made of the initial stages of the transition process *preceding* the birth of spots (e.g. Schubaur & Skramstad 1947, Klebanoff, Tidstrom & Sargent 1962, Arnal, Juillen & Michel 1977) this is not surprising, because the probability that a spot will be born ahead of the spike stage in the canonical route to transition must be virtually zero. Furthermore, either proposal implies that spots continue to be born all the way downstream (even in fully turbulent flow), which again seems most difficult to understand.

Based on such considerations, it seems reasonable to assume that most spots are born near a single downstream station (say x_t). This leads to the hypothesis of concentrated breakdown (Narasimha 1957), according to which spots are born at x_t but randomly in time (t) and in the spanwise coordinate (y); this gives the spot formation rate (per unit surface area and unit time) as proportional to a Dirac delta function,

$$g\,(x,y,t) = n\delta(x-x_t). \tag{1}$$

This cannot of course be literally exact; what is likely is that the spot formation rate is itself a distribution, with a peak around an effective onset location. Estimates of the width of this distribution (assuming it to be Gaussian) suggest that it is sufficiently small that introduction of an additional width parameter is not worthwhile (Dhawan & Narasimha 1958); and n in (1) becomes the total number of spots born per unit span and time.

A consequence of (1) is that

$$\gamma(x) = 1\text{-}\exp(-n\sigma(x\text{-}x_t)^2/U) = 1\text{-}\exp\text{-}0.41\xi^2 \tag{2}$$

where U is the free-stream velocity, σ is a spot propagation parameter introduced by Emmons (1951) (~0.25 according to an estimate of Narasimha 1978), and

$$\xi=(x\text{-}x_t)/\lambda,\quad \lambda=x(\gamma=0.75)\text{-}x(\gamma=0.25), \tag{3}$$

λ being a measure of the extent of the transition zone. If on the other hand g is assumed constant for $x>x_t$, and zero for $x<x_t$ (as in Emmons and Bryson 1952), the exponent of $(x\text{-}x_t)$ in (2) changes to 3, and the result for γ, after suitable normalisation, can be written in the form used by Abu-Ghannan & Shaw (1980),

$$\gamma=1 - \exp\text{-}5\eta^3. \tag{3}$$

Other expressions proposed for $\gamma(x)$ are listed in Table 1.

Table 1 Proposals for intermittency distributions in constant pressure flow

Author/s	Expression
Emmons (1951)	$1 - \exp[-(x/x)^3]$
Emmons & Bryson (1953)	$1 - \exp[-\text{const}\,(x\text{-}x_t)^3]$, $x>x_t$
	0, $x<x_t$
Narasimha (1957), Dhawan & Narasimha (1958)	$1 - \exp[-0.41\xi^2]$
Abu-Ghannam & Shaw (1980)	$1 - \exp[-5\eta^3]$
Michel et al. (1985)	$1 - \exp[-0.45(\theta/\theta_t\text{-}1)^2]$
Schubauer & Klebanoff (1955)	$1/2\,[1 + \text{erf const}\,(x\text{-}\overline{x})]$
Fraser & Milne (1986)	$0.5[1 + (0.0165\,\lvert\eta\rvert^4 - 0.073\,\lvert\eta\rvert^3$ $-0.094\,\lvert\eta\rvert^2 + 0.8273\,\lvert\eta\rvert)\eta/\lvert\eta\rvert]$

Several comparisons of these expressions with experimental data exist. Many of these support (2) (e.g. Narasimha 1957, Dhawan & Narasimha 1958, Owen 197 0 at hypersonic speeds, Fraser & Gardiner 1988, Gostelow & Walker 1990). On the other hand, (3) also has supporters (e.g. Soundranayagam & Potti 1991). Fraser et al. (1988), comparing their own measurements with the above expressions, find that (2) is a somewhat better representation *Figure 1*.

The fact of the matter is that if we make the fit by requiring coincidence of both location and extent parameters in the intermittency distribution (as is often done), the difference between the different proposed expressions is not considerable *Figure 2*. A preference has therefore to be based on considerations of physics and power for extension and generalisation - which appears to be greatest for (2).

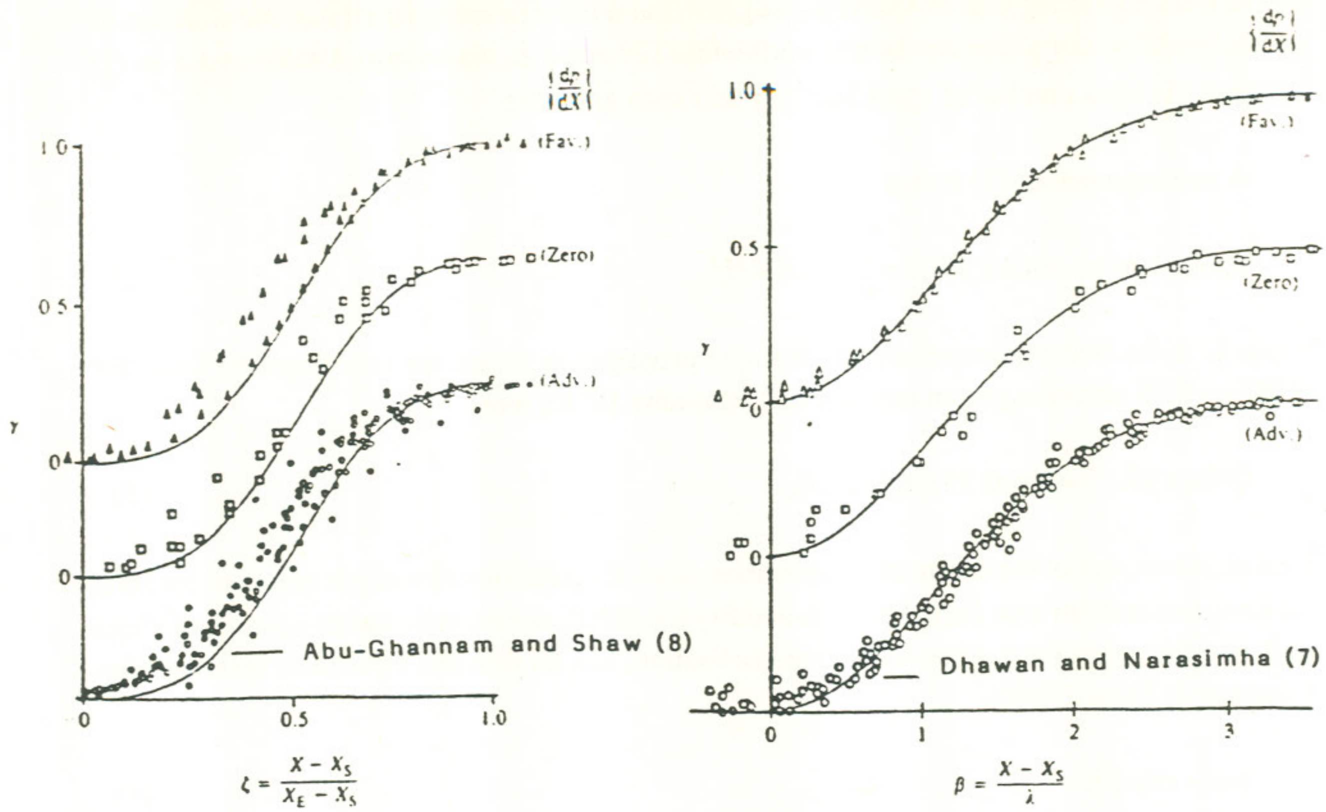

Figure 1 Comparison of measured intermittency distributions with the expressions (2) and (3) of text (from Fraser et al. 1988).

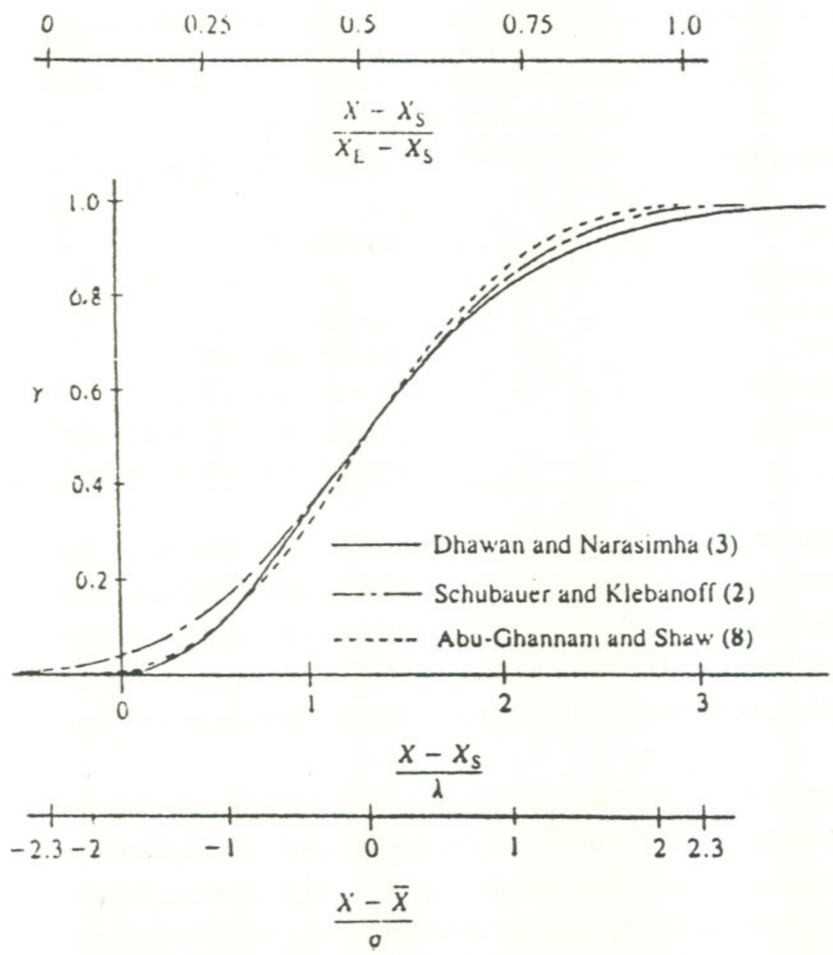

Figure 2 Comparison of three proposed expressions for the intermittency distribution.

Before we proceed further, we must note that both (2) and (3) assume that spot propagation is linear in space and time: i.e. the envelope of spot shapes is a wedge, and propagation velocities are constant. This is not always strictly true, and we must constantly keep in mind that departure from linear propagation may be responsible for departures from (2). Thus, it is sometimes found that there are slight departures from (2) near x_t (see e.g. the data compilation of Dey & Narasimha 1983). This may partly be due to the fact that breakdowns are not all concentrated at x_t, but may also be due to what we may call anamolous propagation, which we discuss next.

3. Anomalous Spot Propagation

Departures from linear propagation have been noticed from the very first studies of turbulent spots. *Figure 3*, from Schubauer & Klebanoff (1955), shows one example, in this case clearly due to low Reynolds numbers: effectively linear propagation occurs only beyond a momentum-thickness Reynolds number $Re_\theta \simeq 480$. (As an aside, the fact that standard turbulent boundary layer scaling does not in general apply at low Re must not be forgotten, especially in turbomachinery applications; see Coles 1968, Purtell, Klebanoff & Buckley 1981).

In the presence of pressure gradients, which strongly influence flow stability, such anomalous behaviour becomes even more common. *Figure 4* (Narasimha et al. 1984) shows once again how spot spread rates are far from being constant, especially in the initial stages. The evidence appears to suggest that once a flow has become supercritical (with respect to boundary layer stability) linear propagation is likely, but even here we must remember that in a sufficiently strong favourable gradient a turbulent flow can even laminarize. There is the intriguing finding of Wygananski (1981) that spot propagation velocities do not change in proportion to the free stream velocity in a favourable gradient: how long a spot retains memory of flow conditions at

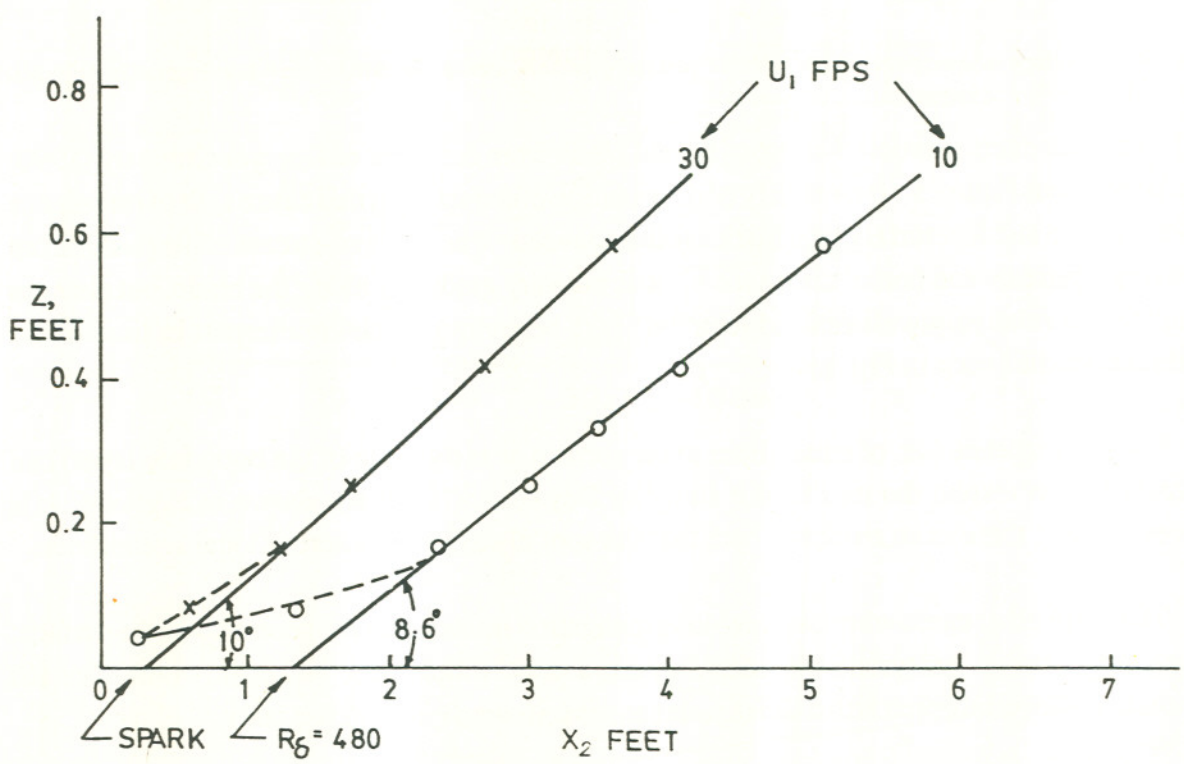

Figure 3 Envelope of spot growth at two different free-stream velocities (Schubauer & Klebanoff 1955), showing departure from linearity at low Reynolds numbers.

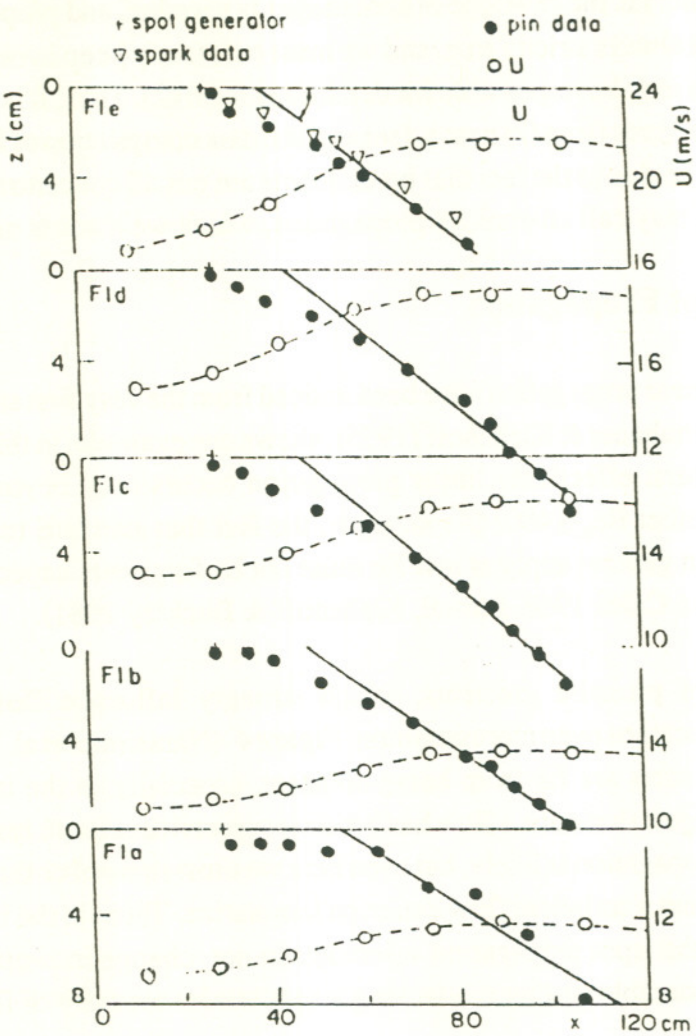

Figure 4 Envelope of spot growth in favourable pressure gradients, showing departures from linear spread in the initial stages (when the flow is subcritical).

birth is still an open question. An experimental result from the work of Dong & Cumpsty (1990) may be relevant *Figure 5* : the velocity of propagation of the spot - in this case a slab of turbulence created on the suction surface of a blade by the convection in *the* free-stream of the wake from a moving upstream rod (simulating a rotor) does not vary gradually along the blade, but changes abruptly at a relatively well-defined location. This behaviour is the counterpart in time of the spatial anomalies seen in Figure 4.

Flow divergence (i.e. of streamlines at the surface or at the edge of the boundary layer) can severely distort a spot: the results of a study by Dey et al. (1990) are shown in *Figure 6*. It is interesting that there is no evidence here that the spot always grows across local streamlines.

There are other cases where anomalous propagation is forced by the geometry of the surface: for example on an axisymmetric body, where a spot which near its origin resembles the Schubauer-Klebanoff picture becomes a sleeve after it wraps around the body.

The moral of this discussion is that while linear propagation is a convenient and standard assumption, departures are to be expected if Reynolds numbers are low, or if pressure gradient,

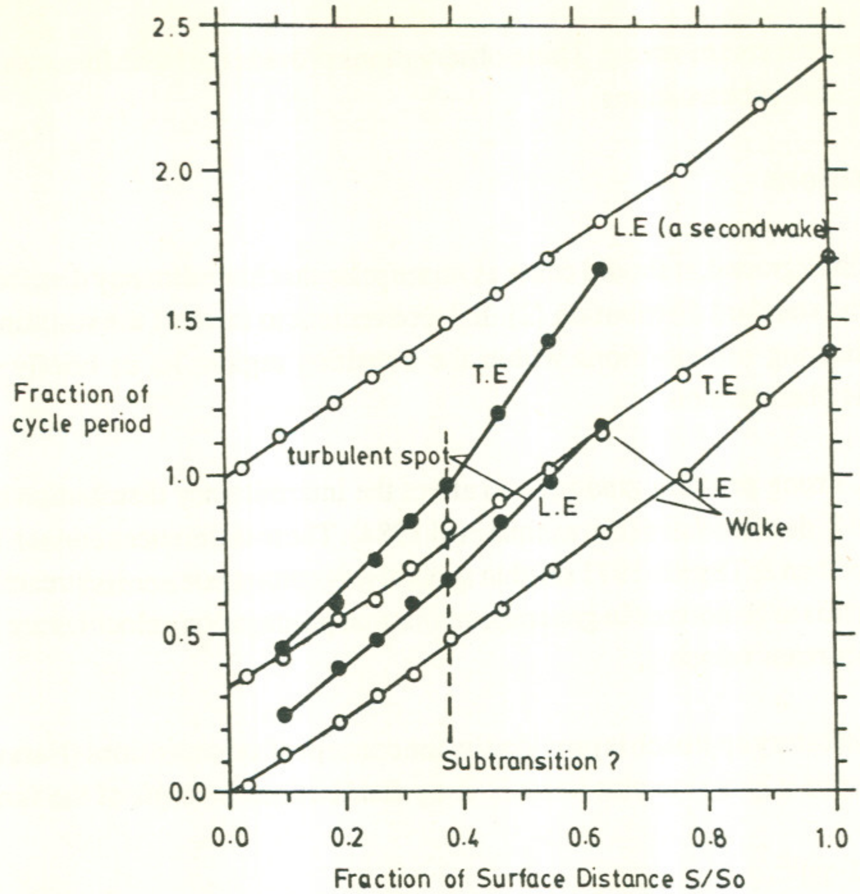

Figure 5 Propagation velocities of a turbulent spot (actually a slab in this case) on the suction surface of a blade. Flow is tripped periodically by the wake of rods upstream simulating the effect of rotor blades. Note the presence of very sudden changes in velocity close to $s/s_o = 0.4$. (From Dong & Cumpsty 1990).

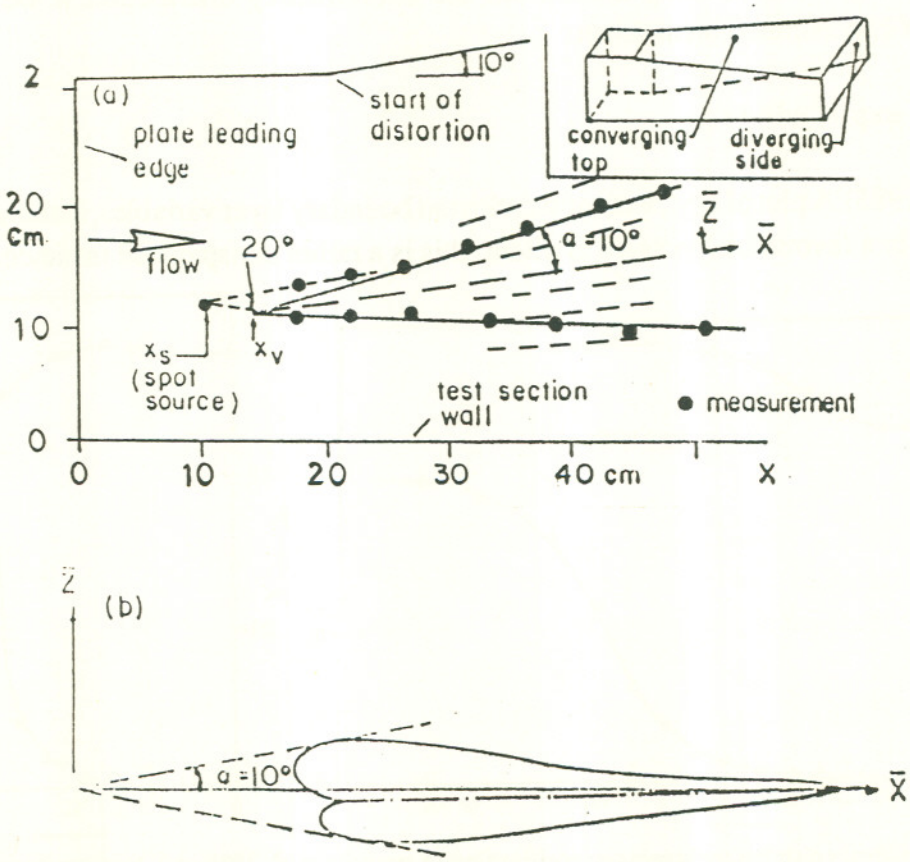

Figure 6 A turbulent spot in distorted constant-pressure flow (Dey et al. 1990). The long dashes around x = 40 cm in (a) show surface streamlines obtained from oil flow pictures: the spot is spreading at the familiar angle of about 10 deg, but is not cutting across streamlines at that angle. The spot shape is shown in (b).

curvature or other effects are strong. These observations provide the basis for an examination of what has been called subtransitions

4. Subtransitions

Given this background, it should come as no surprise that intermittency distributions do not always follow the standard distribution (2). It is convenient to think of the resulting departures from (2) as indicating subtransitions within the transition region; let us briefly examine the evidence for this phenomenon.

First of all, strong pressure gradients do affect the intermittency distribution even qualitatively, as *Figure 7* demonstrates (Narasimha et al 1984). These differences *cannot* be explained by assuming (as Chen & Thyson 1971 do) that spots always propagate *across* streamlines (Figure 6 already shows this to be not true in general), and/or that propagation velocities are proportional to the local free stream velocity.

A more satisfactory approach is provided by the concept of subtransitions (Narasimha 1984). To demonstrate this it is best to plot intermittency distributions in terms of the function

$$F(\gamma) = [-\ln(1-\gamma)]^{1/2}. \tag{4}$$

This quantity has the physical interpretation of being the square root of the so-called "dependence area" A_t for x (and hence of being a characteristic length scale of that area but suitably non-dimensionalised), which directly determines the intermittency distribution if we accept the hypothesis of concentrated breakdown:

$$\gamma(x) = 1 - \exp - \int n dA_t(x) \tag{5}$$

(Narasimha 1985). A plot of $F(\gamma)$, with other relevant boundary layer variables, is shown in *Figure 8* for a flow in a favourable pressure gradient; this is a rather conspicuous instance of subtran-

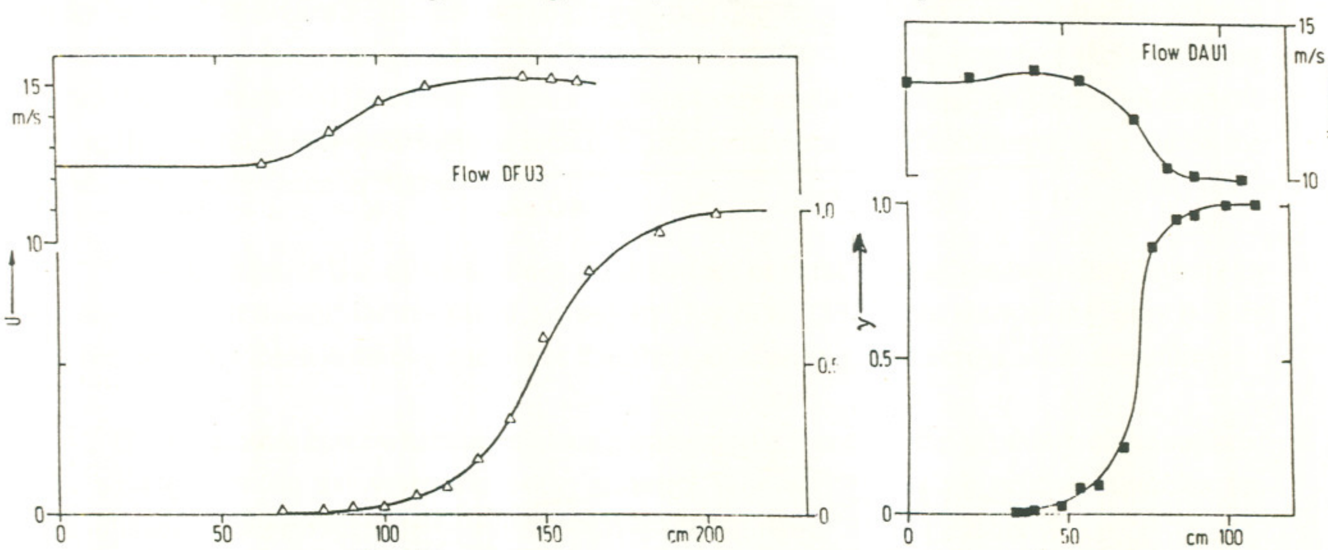

Figure 7 Intermittency distributions in pressure gradient flow (Narasimha et al. 1984). (a) A relatively mild favourable gradient lengthens the transition zone significantly near onset. (b) When the mild favourable gradient is followed by a stronger adverse gradient the distribution is skewed.

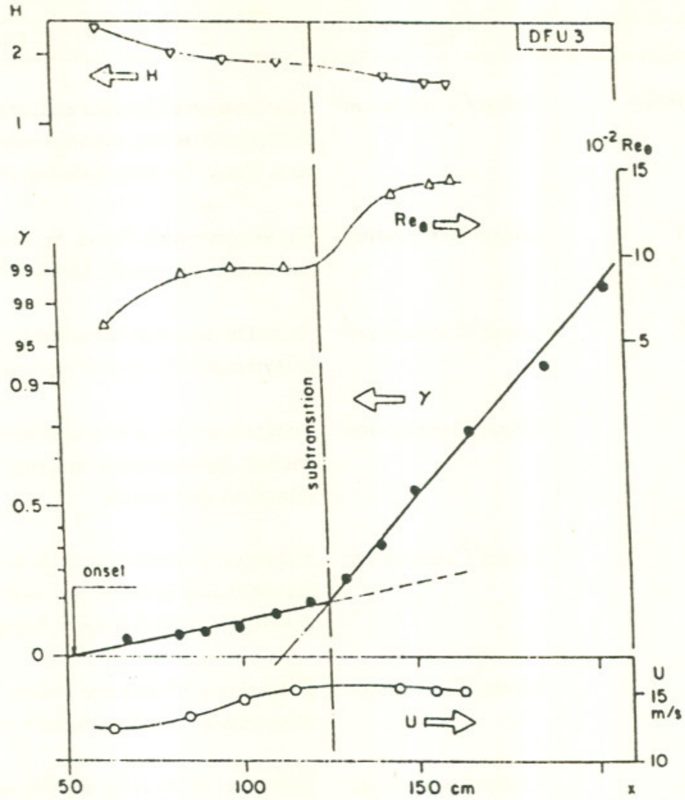

Figure 8 Flow parameters in the transition zone of a boundary layer subjected to a favourable pressure gradient (from Narasimha 1984), showing a distinct subtransition. The intermittency is plotted on a scale that makes the plot linear if (2) is valid.

sition. Other instances are given in Narasimha (1984, 1985). Further confirmation of the occurrence of such subtransitions has come recently from the work of Blair & Anderson (1987).

The question that arises is this: how can these physical phenomena be incorporated into a mathematical model that can help us to estimate the likely behaviour of a transitional boundary layer? While no completely satisfactory model is yet available, I would like to describe briefly our experience with one of them.

5. Modelling the Transition Zone

This is a subject that attracts increasing attention. It has been reviewed in detail recently (Dey & Narasimha 1990, Narasimha 1991), so it is unnecessary to do it again here. Nevertheless, it is useful to reproduce a summary of the available models *Table 2* from these reviews, as it gives us a good idea of where we stand.

One method of making direct use of the physical insight derived from a study of intermittency distributions is by adopting what has been called a linear-combination model: here the velocity fields are calculated separately assuming fully laminar and fully turbulent flow (the latter originating at x_t, *not* the leading edge), and weighting them appropriately with the intermittency (Narasimha 1985). This approach has certain limitations which we must recognise at the outset. For example, if the laminar flow is likely to separate under the prevailing pressure gradient but the transitional flow will not, a linear combination would not be appropriate. However, experience indicates that where separation is not involved linear combination is an effective

Table 2 A brief Summary of transition-zone models

Authors	Type	Remarks
Dhawan & Narasimha (1958)	Linear Combination	Combination of laminar and turbulent velocities in proportions determined by the intermittency. Requires onset (x_t) extent of zone, model for fully turbulent flow. Constant pressure. Simple.
Chen and Thyson (1971)	Linear Combination	For axisymmetric flows. Special intermittency model, correlation for length. Limited Validation
Lakshminarayana (1976)	Linear Combination	As in Dhawan and Narasimha (1958). Integral method for axisymmetric body and high speed flows.
Arnal (1986)	Linear Combination	Integral method. Linear combination for shape factor and skin-friction. Intermittency in terms of momentum thickness, not related to spot theory.
Fraser and Milne (1986)	Linear Combination	Velocity and skin-friction as in Dhawan and Narasimha. Intermittency is error-function. Extent in terms of standard deviation of intermittency. Integral method.
Fraser et al (1988)	Linear Combination	Extension of Fraser and Milne, but different correlation for zone-length. Good agreement with data on turbine blades.
Dey and Narasimha (1990b, 1990c)	Linear Combination	Extension of Dhawan and Narasimha. Extent from new spot formation rate parameter. Integral method. High favourable pressure gradient data also predicted.
Harris (1971)	Algebraic	Eddy viscosity and thermal diffusivity. Intermittency of Narasimha. Requires extent. Compressible plane and axisymmetric flows.
Kuhn (1971)	Algebraic	Eddy viscocity. Method of integral relations for high speed flows. Intermittency distribution of Narasimha (1957).
Adams (1972)	Algebraic	Eddy viscosity. Intermittency distribution of Narasimha (1957) takes extent = $x_t/2.96$
Cebeci and Smith (1974)	Algebraic	Eddy viscosity. Intermittency distribution of Chen and Thyson (1971). Predicts x_t.
Gaugler (1985)	Algebraic	Eddy viscosity, based on STAN5 code. Intermittency distribution of Abu-Ghannam and Shaw (1980). Onset and extent adjusted to obtain agreement with experimental data.
Michel et al (1985)	Algebraic	Intermittency in terms of momentum thickness, exceeds 1 for ensuring agreement with data.
Krishnamoorthy (1986)	Algebraic	Extension of Patankar-Spalding (1970) for predicting heat transfer rates on turbine blades and nozzle guide vanes. Intermittency distribution of Narasimha (1957) x_t and extent from measurements. Effect of large free-stream turbulence by addition to eddy viscosity, shows good agreement with experiments.
Krishnamoorthy (1987)	Algebraic	Extension of Krishnamoorthy (1986) with onset momentum thickness Reynolds number = 160. Dhawan-Narasimha correlation for extent extended to pressure gradients.

McDonald and Fish (1973)	Differential	Integral form of a turbulent kinetic energy equation. Source terms in governing equation through which free-stream turbulence triggers transition.
Blair and Werle (1980, 1981)	Differential	Extension of McDonald and fish (1973) and McDonald and Kreskovsky (1974). Zero pressure gradient heat transfer generally predicted well (but not for the flow at free-stream turbulence level = 0.25), less satisfactory for pressure gradient flows.
Wilcox (1981)	Differential	Stability related closure model. Tested for constant-pressure flows at low free-stream turbulence levels.
Arad et al (1982, 1983)	Differential	Modified two-equation model of Ng (1971). Requires adjustment of numerical constants.
Vancoillie (1984)	Differential	Based on K-ε model. Conditional averages of all quantities require intermittency, which is taken as that of Narasimha (1957). Good agreement with data considered.
Wang et al (1985)	Differential	Based on K-ε model; sensitive to boundary conditions for K,e for airfoil cascade. Discrepancy noted in transitional and turbulent regions on suction surfaces of turbine blades.
Krishnamoorthy (1987)	Differential	K-ε model of Jones and Launder with change in a constant. Tested for nozzle guide vana data. Under predictions near trailing edge at tributed to separation.

principle, *provided* proper account is taken of possible subtransitions.

The nature of the method is most easily seen from a block diagram *Figure 9* for a computer code called TRANZ 2 written to implement it. In the implementation described by Dey & Narasimha (1990), the laminar flow is calculated by an extended version of the Thwaites method, and the turbulent flow by the lag-entrainment scheme (Green et al 1973). Information on the extent of the transition zone is supplied through correlations for a non-dimensional spot formation rate (''crumble''; Narasimha 1984, 1985)

$$N = n\sigma\theta_t^3/\upsilon, \tag{6}$$

which is estimated based on the work of Gostelow (1989) and Dey and Narasimha (1991). (The logic behind the group (6) should be transparent. The Tollmien-Schlichting frequency at x_t scales with θ^2_t/υ. If spots are formed at the 'peaks' of the three-dimensional peak-valley structure observed by Klebanoff et al. (1962) and studied theoretically by Herbert (1988) and others, the average spanwise separation between spots born at x_t may be expected to scale with the Tollmien-Schlichting wavelength, which can also be characterised by θ_t. As far as the intermittency is concerned, only the product $n\sigma$ matters: see e.g. (2). Hence the combination (6) appears the most appropriate non-dimensional spot formation rate for use in transition zone dynamics.)

Some examples of the prediction from the model are compared with experiment in *Figures 10,11*. It is seen that the agreement is reasonable. An update of the model (Govindarajan 1990) is now available *Figure 12* . It is worth mentioning that, based on preliminary estimates, a sub-transition was inferred in some of the flows reported by Blair & Werle (1981), and this has since been confirmed by direct measurements of the intermittency (Blair & Anderson 1987).

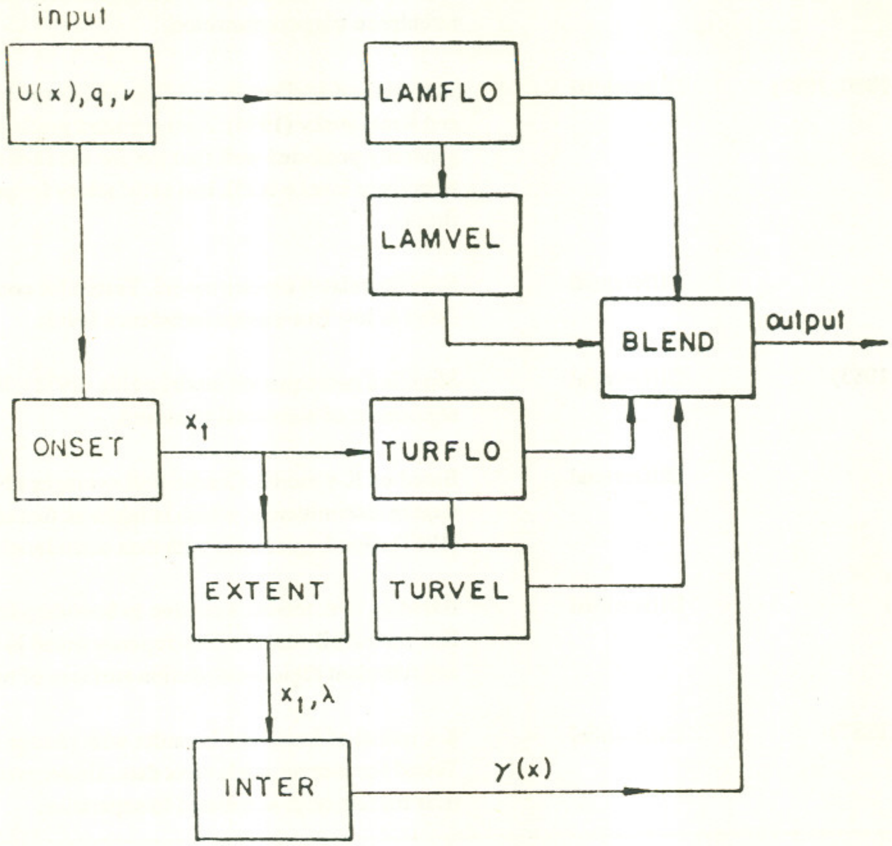

Figure 9 Schematic structure of a linear-combination model for computing the transitional boundary layer (from Dey & Narasimha 1990).

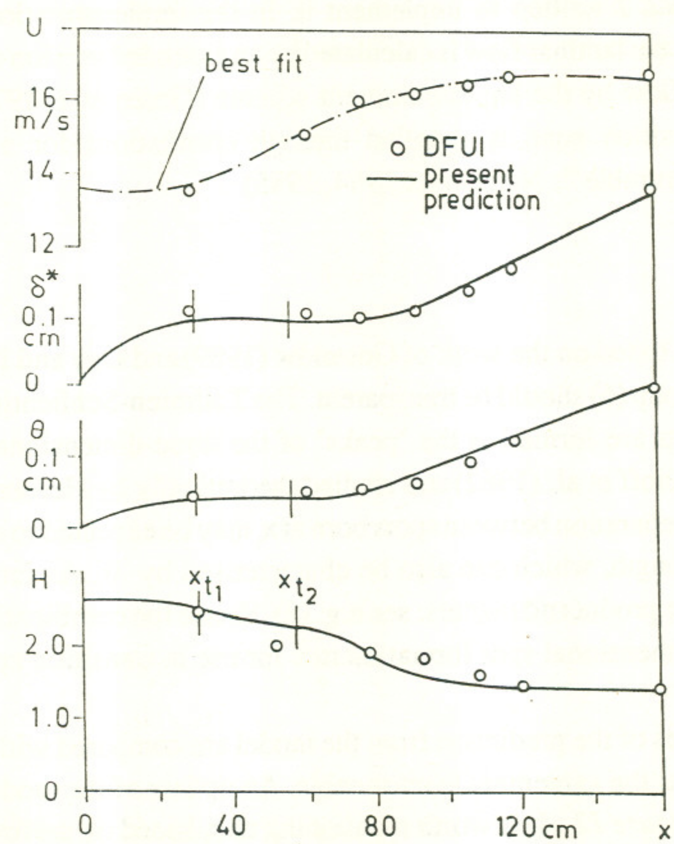

Figure 10 Comparison of results from a linear-combination model with one of the experiments reported by Narasimha et al (1984). (From Dey & Narasimha 1990).

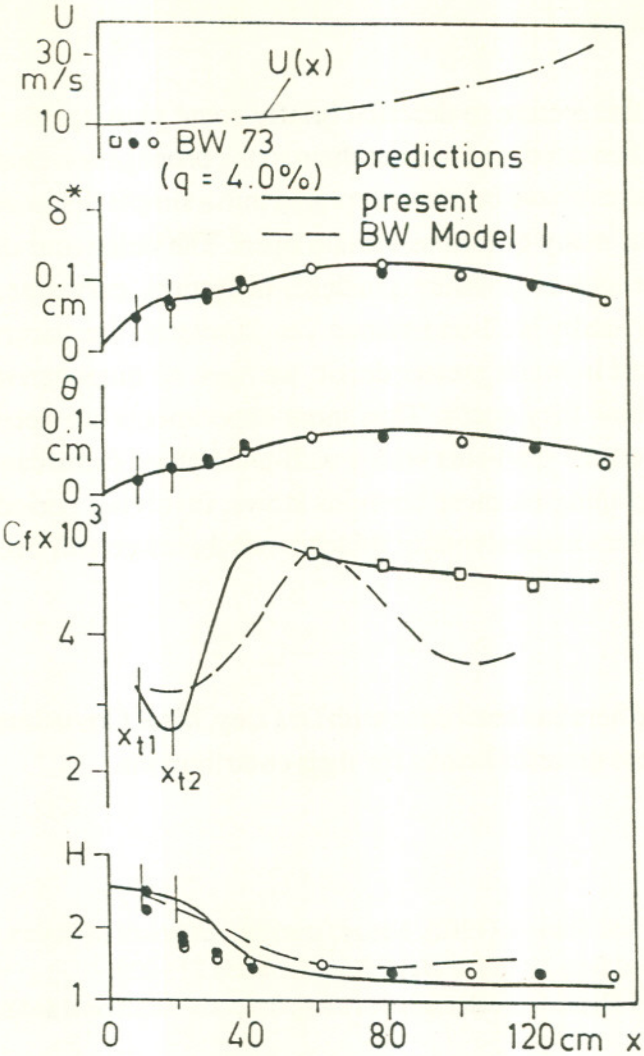

Figure 11 Comparison of results from a linear-combination model with an experiment reported by Blair & Werle (1981) (from Dey & Narasimha 1990)

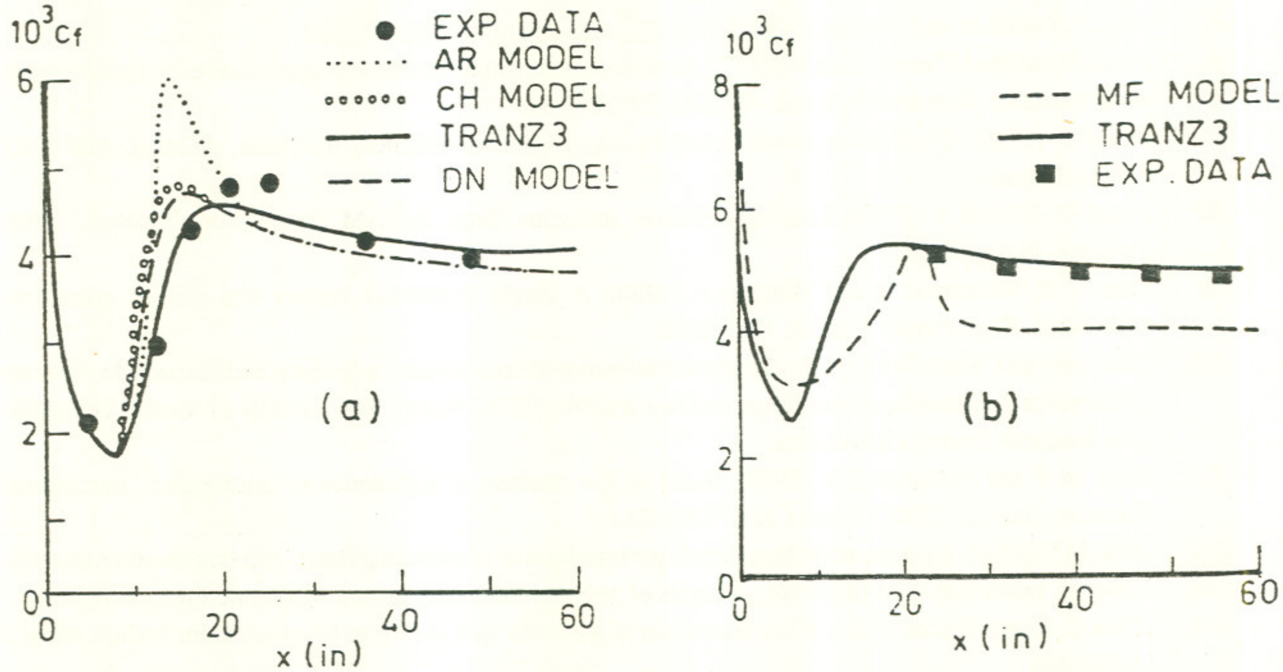

Figure 12 Comparison of the prediction of the updated TRANZ code (full bold curve, Govindarajan 1990) with t he experimental data of Blair & Werle (1981); other curves in the figure are from Abid (1990) and refer respectively to the models of Arnal (1984), Chen & Thyson (1971), Dhawan & Narasimha (1958) and McDonald & Fish (1973). (a) K = 0.2 x 10^{-6} grid 2; (b) K = 0.75 x 10^{-6} grid 3.

6. Concluding Remarks

I have sought in this lecture to describe briefly some physical phenomena that affect the dynamics of the transition zone, and to trace them to the propagation characteristics of turbulent spots. Some of these factors have been incorporated into a simple linear-combination type model for the zone. However, many questions remain open. The behaviour of turbulent spots when subject to such influences as pressure gradient, distortion, curvature, three-dimensionality, compressibility etc. is hardly well-understood yet. Similarly, the occurrence of subtransitions needs to be investigated in much greater detail: we have no quantitatively satisfactory way of predicting when and how they occur. Thus more experiments are needed in boundary layers subjected to strong pressure gradients with a well-understood disturbance environment. There has hardly been a beginning on more complex flows, involving periodic tripping, separation bubbles, and strong three-dimensionality. Much work therefore still needs to be done!

Acknowledgements

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Abstract : This paper is a survey of certain recent advances in our understanding of the transition zone in a boundary layer. It is emphasized that the behaviour of turbulent spots and the distribution of intermittency hold the key to an improved description of the dynamics of the zone. Evidence from many different sources is presented to show that, in strong pressure gradients, the concept of subtransitions provides an essential ingredient of the picture. A linear combination model that incorporates the possibility of subtransitions and allows for the computation of the effects of highly favourable gradients on fully turbulent flow is shown to be in reasonable agreement with experimental data. Diffuculties that remain are pointed out.