11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

PREDICTING BY-PASS TRANSITION WITH TURBULENCE MODELS

A.M. SAVILL

Engineering Department, University of Cambridge, Cambridge
& Visiting Research Fellow, Mechanical Engineering Dept, UMIST
UNITED KINGDOM

Abstract

Recent progress in a world-wide collaborative assessment of turbulence models, for predicting transition under the influence of variable intensity free-stream turbulence, is reported. A very large number of models, covering a wide range of closure levels, have now been evaluated on a series of flat plate test cases. Some clear recommendations have emerged regarding the best current approaches to adopt in attempting to accurately predict both the location and extent of transition in zero, favourable and adverse pressure gradients.

INTRODUCTION

The purpose of this paper is to report (particularly for the benefit of interested Australasian researchers) the recent progress which has been made in a European Research Community on Flow Turbulence and Combustion (ERCOFTAC) Project on Transition Modelling. This Project is in fact just one of the activities of an ERCOFTAC Special Interest Group (SIG) on Transition/Retransition, and **aims to evaluate and improve the ability of current turbulence models to predict transition** (and **re-transition** following **relaminarisation**) under a variety of flow conditions. It has its origins in the **T3A** & **T3B** Test Cases of the 1st ERCOFTAC Workshop on Numerical Simulation of Unsteady Flows, Transition to Turbulence and Combustion, held at the Swiss EPF Lausanne ERCOFTAC Pilot Centre in March 1990. Although much was learned at that time from a Synthesis (Savill, 1990) of the fifteen sets of different model predictions submitted to the Workshop by nine research groups from five countries, it was clear that a wider ranging evaluation of a larger number of current closure schemes, on a greater variety of test cases, was needed before any fair conclusions could be drawn and recommendations made. Accordingly, in April 1991, the present Project was launched through the ERCOFTAC UK North Pilot Centre at UMIST.

Since that time the number of European participants in the project has grown steadily to the point where thirty groups are now involved from Belgium, Finland, France, Germany, Greece, Italy, The Netherlands, Sweden, Switzerland & the UK. In addition several groups from Australasia (currently eight) and the USA (nine) have been asked to participate in the project in order to ensure that the widest possible range of the very latest refined models can be evaluated.

The models being assessed currently include:

Modified correlation/integral methods; One-equation q-l or k-l models; Single or Multi-scale two-equation low-Re k-ε or k-τ and 'partial' low-Re k-ε/k-l models; Several 'state-of-the-art low-Re and '2D/2C-limit' Reynolds Stress Transport closure schemes, and various sub-grid scale model Large Eddy Simulations.

THE TEST CASE PROBLEMS

Models are being evaluated on a series of two-dimensional Test Cases of increasing complexity:

T3A-: zero pressure gradient, 1% isotropic free-stream turbulence
(experimental initial conditions)
T3A: zero pressure gradient, 3% isotropic free-stream turbulence
(theoretical or experimental initial conditions)
T3B: zero pressure gradient, 6% isotropic free-stream turbulence
(theoretical or experimental initial conditions)
T3C2,3,4,5: pressure gradient representative of aft-loaded turbine blade, 3% isotropic fst (various mean flow initial conditions)
T3D1,2,3: zero pressure gradient, 0.1% isotropic fst, following laminar separation
(various mean flow conditions)

Further test cases for transition: under the influence of similar level isotropic and anisotropic Simulated **[T3BDNS]** and higher level **[T3B$^+$]** free-stream turbulence in zero pressure gradient; in a pressure gradient typical of compressor blading **[T3C$^+$]**; and re-transition in an adverse gradient following relaminarisation in a strongly favourable gradient **[T3E]**; as well as on convex **[T3F]** or concave **[T3G]** curved; or heated **[T3H]** surfaces are also proposed.

A number of complementary 3D and leading edge studies (currently 6, involving groups in Belgium, Germany, Greece, Sweden & UK) have also been initiated. These include detailed experimental investigations, Large Eddy Simulations, Rapid Distortion Theory analyses, and elliptic turbulence model computations.

SOME RESULTS

It would appear that current industrial design methods employing correlations, integral methods or k-l,k-ε models are insufficient to PREDICT transition for all required flow conditions (Savill 1990). Although many of these models do exhibit the correct sensitivity of transition to high levels of free-stream turbulence (>3%), most fail to predict the actual location of this to any acuracy, particularly under lower free-stream turbulence and variable pressure gradient conditions. The k-ε level of closure seems to be the minimum required to achieve any generality in predictions and there would appear to be little advantage in switching to alternative k-τ or k-ε/k-l schemes (Savill 1991).

TABLE OF ACTIVE PROJECT PARTICIPANTS, MODELS & PROGRESS

					T3 ABe	C
Europe						
* ROLLS-ROYCE plc	(Coupland)	k-lε	[Hassid-Poreh + Birch] [1]	E	X	X
+ VKI	(Grundmann)	k-lε	[Fish & MacDonald] [4]	P	p	p
* ARISTOTLE Univ.	(Prinos et al.)	k-ε	[Launder-Sharma] [5]	PE	X	X
p GHENT Univ.	(Dick)	k-ε + γ	+ Intermittency] [7]	P		
+ CRANFIELD	(Elder et al.)	k-ε?	[6]	P		
* SNECMA	(Fougeres et al?)	k-lε	[Fish & MacDonald] [1]	E		p
p EDF	(Baron)	k-ε or RST		E		
ONERA-CERT	(Arnal)	k-ε + correlations	[Michel] [1]	PE		p
* KARLSRUHE Univ.	(Rodi et al.)	k-ε	[Launder-Sharma]	P	X	X
(Computations by Fujisawa)		or	[Lam & Bremhorst]	P	X	
	&	k-ε/k-lε	[Norris & Reynolds] [1]	P		X
p CHALMERS Univ.	(Hall)	k-lε + correlations ?		P		
p	(Hedberg)	RST	[Launder-Shima + new ε]	P		
p NP-TEC	(Ghobadan)	k-ε	[Launder-Sharma] +x Diffusion	P		p
p UMIST	(Launder & Tselepidakis)	k-ε	[Launder-Sharma]	P		
	low-Re	RST	[Launder-Shima] [10]	P		
	2D/2C	RST	[Fu-Launder-Tselepidakis][11]	P		
* CAMBRIDGE Univ.	(Savill) low-Re	RST	[Savill-Younis] /Launder-Sharma] [1]	P	X	X
* QMW	(Voke & Yang)	DNS	[Fully Resolved Simulation][1]	E		p
USA						
+ VIRGINIA P.I. & STATE U.	(Moores)	k-lε + correlations	[Moores] [13]	P	p	
TEXAS Univ.	(Stephens & Crawford)	k-ε	[Launder Sharma], [Chien] &/or [Lam & Bremhorst] [15]	E		
+ NASA LANGLEY	(Gatski & Abid)	k-ε or k-τ	[Speziale et al.] [17,18]	P	p	
+	&	RST	[Launder-Shima][10,18]		P	
p ARIZONA STATE U.	(So et al.?)	RST	[Lai & So] [19]	E		
p NASA LEWIS	(Shih?)	RST	[Shih & Lumley] [20]	E		
	(Kim)	Multi-scale k-ε/k-lε	[21]	P		
Asia & Australia						
+ NAGOYA Univ.	(Nagano & Tagawa)	k-ε	[Nagano-Hishida] [22]	P	X	
+			[Nagano-Tagawa] [23]			
+ TOKYO Univ.	(Kasagi & Shikazono)	k-ε	[Myong-Kasagi+mods] [24]	P		X
* GUNMA Univ.	(Fujisawa)	k-ε	[Launder-Sharma+mods][25]	P	X	X
p KOREA Inst. Tech.	(Cho & Chung)	k-ε - γ	[Intermittency] [26]	P		
p SYDNEY Inst. Tech. & Univ. of TASMANIA	(Gostelow) (Walker)	Integral +	[Narasimha & Dey] [27]	P		p

{*: Original Lausanne Workshop Computor} {P: Parabolic Code, E:Elliptic Code}
{+: Have subsequently also computer original T3A/B Cases}
{X: Have also made predictions for TA/B with experimental initial conditions and/or T3C Case}
{p: Computations in progress or planned}
References as in (A)

Low-Re k-ε models which employ damping factors that are functions of a general property of low-Re flows (eg. turbulent Reynolds number Rt) are clearly more appropriate for the prediction of low-Re transition regions than those that introduce a specific dependence on wall-proximity (eg. via Ry or Rε), but models which satisfy the wall-limiting conditions for uv^+ and ε^+, also appear to provide better transition predictions than those which satisfy either only one or neither of these. Unfortunately many of the most recent low-Re model proposals (which satisfy additional necessary wall-limiting conditions so that they provide a better fit to low Re Channel and Boundary Layer flow Simulations, and produce superior predictions for a wide range of fully turbulent flows) contain damping factors that are functions of y; and thus fail to predict transitional flows correctly. This is perhaps not surprising since there is no *a priori* reason why any low-Re damping functions devised to handle wall-proximity effects in fully turbulent flows should apply to transition regions. However it has been found that the performance of such models in transitional flow can be improved by introducing extra x-dependent damping factors &/or partially replacing Ry,Rε by Rt (Savill, 1992). Future work will need to include an analysis of Transition Simulations to enable a clearer distiction to be drawn between low-Re near-wall and low-Re transitional flow effects and their modelling. Refinements like the adoption of alternative 2D/2C-limit modelling for wall-proximity effects is likely to aid this process considerably.

Of all the low-Re schemes examined thus far the Launder-Sharma L-S model (which employs damping factors that are both functions of Rt and satisfy the wall-limiting conditions for uv^+ and ε^+) provides the most accurate prediction of transition onset, at least in zero pressure gradient flows subjected to 1-6% free-stream turbulence, whether employed at the k-ε level of closure or at the RST level - in a Savill-Launder-Younis SLY model - see Figure 1. However the k-ε L-S model generally predicts too sharp a transition to fully turbulent conditions, so that the length of transition is under-predicted. Other models can only be adjusted to fit the Abu-Ghannam & Shaw correlations for both the start and end of Transition by applying additional damping to the turbulence energy Production in the manner proposed by Patankar & Schmidt (1987), although even when this is done Stephens & Crawford (1990) have shown that the change in Cf may be severely underpredicted. The SLY RST model appears to overcome this defficiency except at the lowest free-stream turbulence levels - see Figure 2 - when intermittency effects become important. For levels <1% the model terms may then need to be conditionalised by γ or modified to account for natural transition effects.

The k-ε L-S and other models also do not exhibit sufficient sensitivity to the additional influence of variable pressure gradients, but again when L-S low-Re treatment is employed at k-ε/RST level predictions for a turbine blade-type pressure distribution are improved even at off-design conditions - see Figures 3 & 4. All models, including the k-ε and RST L-S models exhibit some sensitivity to the initial and free-stream boundary conditions, especially those for dissipation length scale, even in zero pressure gradients. A similar sensitivity is also observed in favourable gradients, but when transition is triggered in a subsequent adverse gradient, as on a turbine blade this sensitivity is greatly reduced - see Figure 5.

Surprisingly, and contrary to some earlier indications, it would appear that the L-S low-Re treatment does not require excessive grid refinement to provide accurate transition predictions, at least when implemented at the RST level. Indeed adequate results have been obtained with the type of limited resolution practical in real blading computations - see Figure 6 (although the results are then sensitive to the exact grid distribution). In addition it would appear that some of the effects of anisotropic free-stream turbulence, as revealed by the Direct Simulations of Yang & Voke (1991), can be captured at the RST level - see Figure 7 & 8 - although the effects of anisotropic free-stream length scales cannot yet be accounted for. The RDT studies of Saxena et al (1992) indicate that this is an important capability if additional leading edge effects are to be correctly modelled.

Acknowledgement:

Rolls-Royce plc have very actively supported this project by sponsoring its co-ordination, the work at Sydney and Tasmania, the modelling at Cambridge and UMIST, and the Direct Simulations at QMW/Surrey University, as well as the Cambridge RDT studies; in addition to contributing both Test Case data and design method predictions from their Company Applied Science Laboratory andTheoretical Science Group.

References

SAVILL, A.M. (1990) Synthesis of T3 Test Case Computations, (see also individual computors reports). Proc. 1st ERCOFTAC Workshop, Lausanne O.Pironneau, W.Rodi, I.L.Ryhming, A.M.Savill & T.V.Truong, Eds. C.U.P. To appear.

SAVILL, A.M. (1991) Turbulence Model Predictions for Transition under Free-Stream Turbulence. Poster Paper RAeS Transition and Boundary Layer Control Conf., Cambridge.

SAVILL, A.M. (1992) Predicting Transition Induced By Free-Stream Turbulence. Summary of Poster Papers at 1st European Fluid Mechanics Conf., Cambridge and 4th European Turbulence Conf., Delft. (A)

SAXENA, V., HUNT, J.C.R. & SAVILL, A.M. (1992) Rapid Distortion Theory applied to the problem of large scale turbulence impinging on leading edges. Abstr. EUROMECH 288 on Turbulent Flows Undergoing Distortion and Rotation, Lyon.

SCHMIDT, R.C. & PATANKAR, S.V. (1988) Two-Equation Low-Reynolds-Number Turbulence Modeling of Transitional Boundary Layer Flows Characteristic of Gas Turbine Blades. NASA CR 4145.

STEPHENS, C.A. & CRAWFORD, M.E. (1990) An Investigation into the Numerical Prediction of Boundary layer Transition Using the K.-Y.Chien Turbulence Model. NASA CR 185252.

YANG, Z.Y. & VOKE, P.R. (1991) Numerical Simulation of Transition to Turbulence. Univ. of Surrey Dept. Mech. Eng. Rep. ME-FD/91.01.

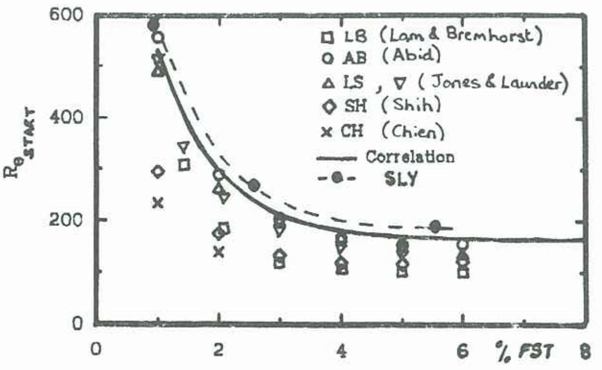

Fig.1 Predicted correlation of start of transition with free-stream turbulence intensity

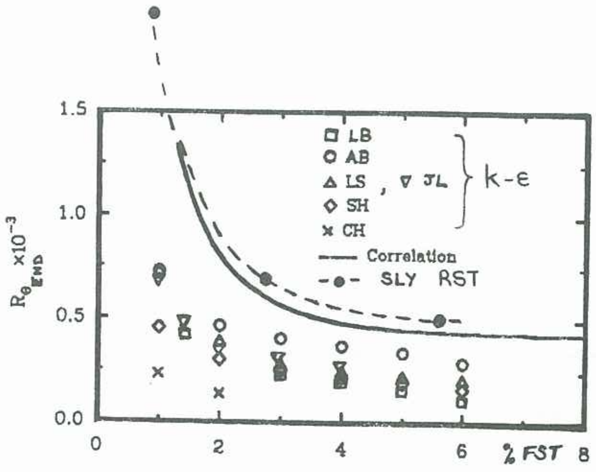

Fig.2 Predicted correlation of end of transition with free-stream turbulence intensity

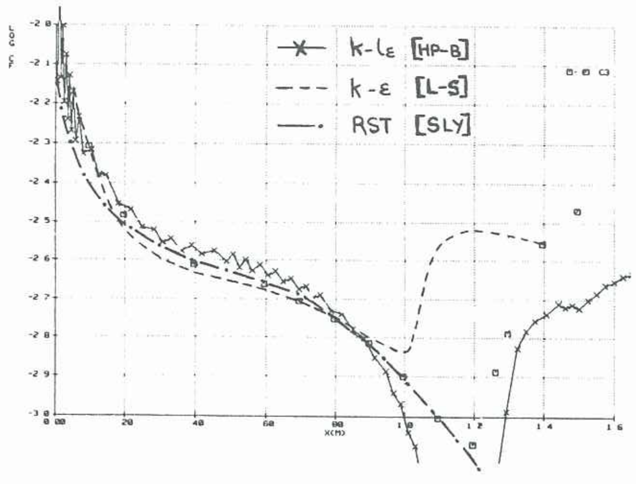

Fig.3 Predictions for T3C3 Test Case versus Rolls-Royce data

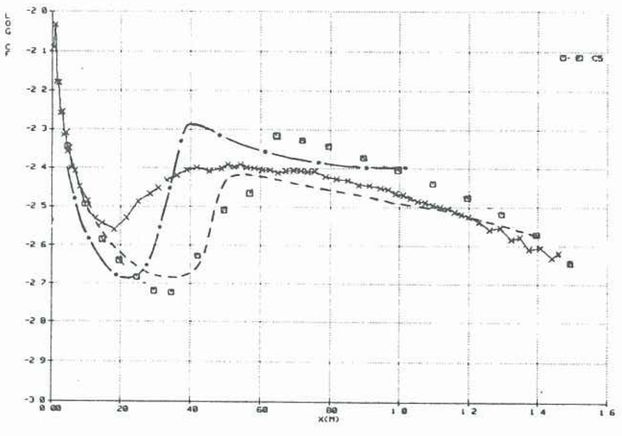

Fig.4 Predictions for T3C5 Test Case versus Rolls-Royce data

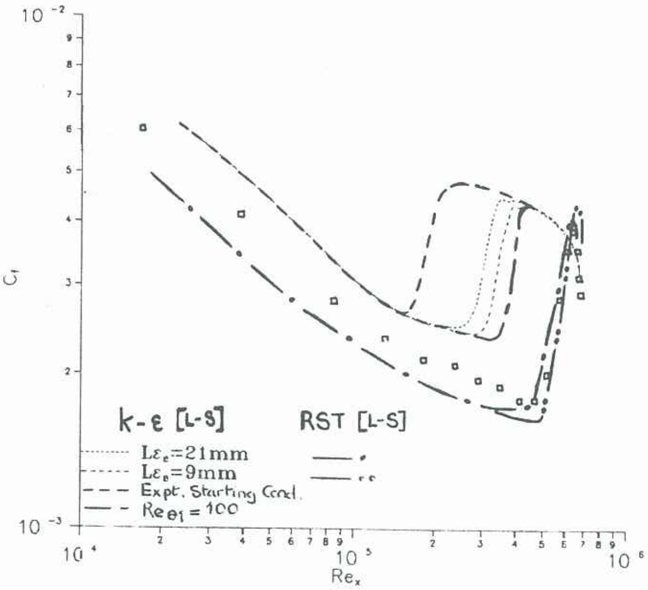

Fig.5 Effect of factor two change in free-stream length scale on predictions for T3C2 Test Case

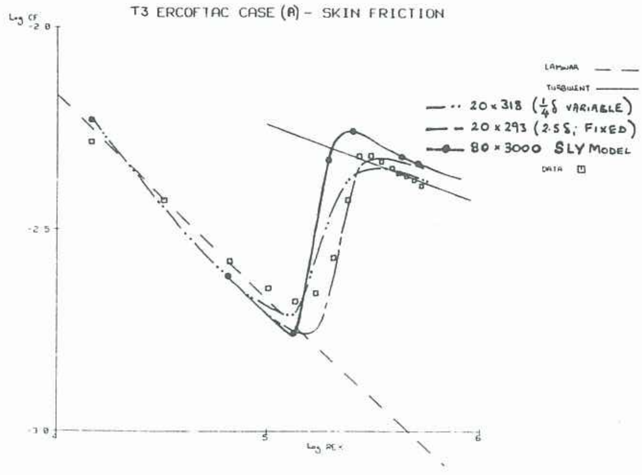

Fig.6 Comparison of high and low resolution SLY RST model predictions for Test Case T3A

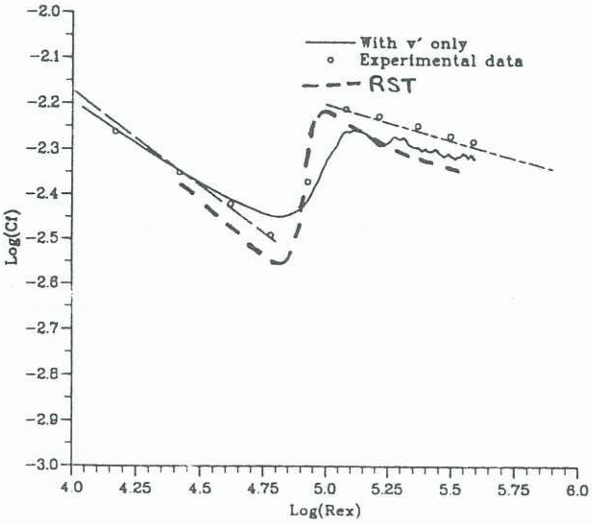

Fig.7 Predicted and Simulated effects of vertical free-stream fluctuations alone.

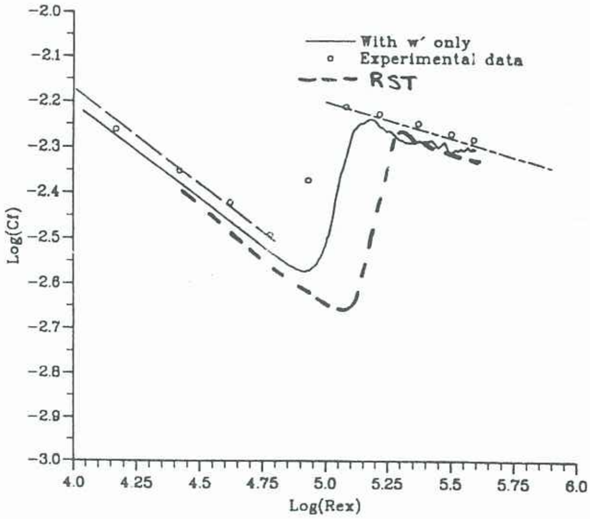

Fig.8 Predicted and Simulated effects of spanwise free-stream fluctuations alone.