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Unsteady Transition in an Axial Flow Turbine

Part 2-Cascade Measurements and Modelling

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ABSTRACT

Part 1 of this paper reanalysed previously published measurements from the rotor of a low speed, single stage, axial flow turbine which highlighted the unsteady nature of the suction surface transition process. Part 2 investigates the significance of the wake jet and the unsteady frequency parameter. Supporting experiments carried out in a linear cascade with varying inlet turbulence are described together with a simple unsteady transition model explaining the features seen in the turbine.

INTRODUCTION

Traditionally, turbomachinery components have been tested in cascades using stationary inflow; sometimes using a grid to produce a turbulence intensity thought to be representative of the levels in a real machine. Similarly, designers make use of steady-state correlations based on many years experience of testing cascades and real machines and, again, assume a turbulence level thought to be representative. However, it has been shown by many studies (e.g. Hodson (1984), Doorly and Oldfield (1985), Walker (1974)) that the actual boundary layers are unsteady and that the passage of wakes from upstream blade rows allied to a high degree of inlet freestream turbulence results in behaviour which cannot be predicted satisfactorily by conventional methods.

Part 1 of the paper described experiments into this subject. The turbine used for the work was a large, low speed, single stage, axial flow machine designed as a free-vortex stage with zero inlet and exit swirl and 50% reaction at midspan. The 36 stator blades and 51 rotors blades had aspect ratios of 1.5 and 2.0 respectively and a hub-tip ratio of 0.7. This paper is concerned specifically with the rotor midspan blade section where the flow is known to be two-dimensional (Hodson and Addison, 1988). Experimental data were obtained at three stator-rotor axial gaps corresponding to 50%, 75% and 143% C_{xs} (stator axial chord).

Previously published measurements, including time-resolved hot wire traverses and surface hot film gauge measurements, were reassessed in the light of more recent findings. It was shown that the passage of wake segments over the blade surface boundary layer was dominated by the wake turbulence but it did not cause immediate transition. When transition occurred, it was characterised by the stochastic appearance of turbulent spots. The spreading of the wake segment in the freestream was small and the interaction of the wakes with the laminar boundary layers shown to be quasi-steady. Although transition location varied with distance from the surface, behaviour near the surface was very similar to that in the centre of the boundary layer justifying the use of hot-film gauges.

In this part of the paper, the action of the wake jet, and the significance of the unsteady frequency parameter are considered. The results of a linear cascade investigation and computer predictions of wake behaviour are presented and analysis of the data leads to the formulation of a simple for the start of transition. It will be shown that this can explain many of the features highlighted by the results of part 1.

THE ROLE OF THE WAKE JET IN UNSTEADY TRANSITION

Wakes are characterised by their turbulence and velocity profiles. The effect of the turbulence on boundary layer transition will be investigated in the cascade tests to be reported later. The effect of the wake-jet can be quantified by briefly considering the work of Obremski and Fejer (1975). They studied transition on a flat plate in non-reversing periodic flow and showed that the mechanism of transition had a strong dependence on a non-steady Reynolds number

$$Re_{ns} = \frac{(\Delta U/U_0)}{(\omega \upsilon/U_0^2)} \qquad (1)$$

which they related to the degree to which disturbances were amplified during one cycle. A low value (Re_{ns} « 26000 for zero pressure gradient) resulted in aperiodic formation of turbulent spots with the unsteady flow merely playing a role in encouraging or discouraging natural spot formation at certain times of the cycle. A high value resulted in periodic spot formation with the velocity perturbation assuming a dominant role. If it is assumed that ΔU is of the order of the wake-jet velocity U_j, then using the values applicable to the turbine

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rotor midspan gives $Re_{ns} \approx 1500$ which is significantly less than the limit of 26000. Therefore, the velocity fluctuation resulting from the wake jet will not be strong enough to force transition in its own right.

The extrapolation of these results to turbomachinery is not strictly valid since the plate was subjected to a standing free-stream velocity wave whilst the passage of a wake over the blade surface results in a convected disturbance (travelling wave). However, the mode of action of the jet will be similar and we can reasonably discount the velocity fluctuation as a primary cause of transition although it will modify the environment perceived by higher frequency disturbances from the free stream and wake turbulence.

THE SIGNIFICANCE OF THE REDUCED FREQUENCY PARAMETER

The surface distance-time plots of part 1 indicated that the wake turbulence penetrated the boundary layer without a significant delay. However, the value of the reduced frequency parameter

$$\varpi = \frac{\omega x}{U} \tag{2}$$

where x and U are representative values, is typically about 3 which suggests that the boundary layers should be truly unsteady. Although eqn. (2) defines ϖ in inviscid terms as the ratio of the convective and periodic time scales, this apparent paradox can be resolved by rewriting it as

$$\varpi = \frac{\upsilon}{Ux}\left\{\frac{x}{\delta}\right\}^2\left[\frac{\omega\delta^2}{\upsilon}\right] = \frac{1}{Re_x}\left\{\frac{x}{\delta}\right\}^2\left[\frac{\omega\delta^2}{\upsilon}\right] \tag{3}$$

It is noted that δ^2/υ is a diffusive (laminar) time-scale and thus the final term of eqn. (3) represents the ratio of the time taken for information to diffuse through the boundary layer to the periodic time of the unsteady flow (or the square of the ratio of the boundary layer and Stokes' layer thicknesses). For a laminar boundary layer,

$$\left\{\frac{\delta}{x}\right\}^2 \approx \frac{25}{Re_x} \tag{4}$$

so that eqn. (3) reduces to

$$\varpi \approx \frac{1}{25}\left[\frac{\omega\delta^2}{\upsilon}\right] \tag{5}$$

Thus the reduced frequency is both an inviscid and viscous parameter. However, in the present situation, we are concerned with the time taken for wake-turbulence to diffuse into the laminar boundary layer. At the simplest level, this is more accurately represented by using an eddy viscosity υ_t rather than the kinematic viscosity υ. Since υ_t is much greater than υ ($\upsilon_t \sim$ 10-100υ) the diffusion time is significantly shorter, and the effective reduced frequency given by

$$\varpi' = \varpi\left\{\frac{\upsilon}{\upsilon_t}\right\} \tag{6}$$

is significantly less than unity indicating that diffusion across the boundary layer is very rapid, and suggesting that the interactions can be treated as quasi-steady.

MEASUREMENTS IN A LINEAR CASCADE

Since the interaction of wakes with the boundary layers can be treated as quasi-steady, it is reasonable to investigate the development of the suction surface boundary layer in a linear cascade with stationary inlet turbulence and then extrapolate the results to the unsteady case.

The cascade used was a high aspect ratio linear cascade of seven epoxy blades with sections geometrically similar to the rotor midspan of the rotating turbine stage described in part 1. A biplanar turbulence grid consisting of a square lattice of $^{5}/_{16}$" diameter bars at $1^{1}/_{4}$" pitch was fitted upstream of the parallel sided inlet duct. The intensity of the free-stream turbulence at inlet to the linear cascade was varied by altering the separation between the cascade and the turbulence grid. The levels used here were $0 \leq (Tu_m)_{in} \leq 10\%$ measured at the inlet plane in the absence of the cascade. In the central blade passage, a hot wire probe consisting of two 5μm tungsten wires crossed at 90° and aligned with the wires at 45° to the mean flow at each point was used to measure the flow velocity and mean turbulence intensity. Oil and dye flow visualisation and hot film gauges were used to determine the state of the suction surface boundary layer. Further details of the cascade and experimental methods are given by Hodson (1984) and Hall (1985).

The measured values of Tu_m corresponding to the stations nearest the suction surface were scaled for the range of inlet turbulence intensity. These were then used with the predicted boundary layer parameters (using the boundary layer code of Cebeci and Carr (1978) as in part 1) to apply the start and end of transition correlation originally presented by Abu Ghannam and Shaw (1980). Fig. 1 shows the start of transition correlation and, superimposed, the predicted values of the momentum thickness Reynolds number Re_θ and pressure gradient parameter (modified Polhausen parameter) λ_θ

NOMENCLATURE

b	Wake Standard Deviation in the Eulerian Frame
C_{xs}	Stator Axial Chord
D(s*)	Decay Factor for Cascade Free-stream Turbulence Intensity
L	Characteristic Length of a Turbulent Fluctuation
Re	Blade Reynolds Number
Re_{ns}	Non-Steady Reynolds Number
Re_x	Reynolds Number based on (surface) distance
Re_θ	Reynolds Number based on Momentum Thickness
s	(Suction) Surface Distance
s*	Fractional Surface Distance = s/s_{max}
T	Blade Passing Period
t*	Dimensionless Time = t/T
Tu	Turbulence (or rms) Intensity
U	Flow Velocity
u	Streamwise velocity within the boundary layer
x	Distance
y	Surface Normal Distance
α	Factor in Transition Model
β	Wake Standard Deviation in the Time Domain
γ	Factor in Transition Model
δ	Boundary Layer Thickness
Δ	Change in ......
λ_θ	(Modified) Polhausen Parameter = $\frac{\theta^2}{\upsilon}\frac{\partial U_e}{\partial s}$
υ	Kinematic Viscosity
υ_t	Eddy Viscosity
ω	Radian Frequency
ϖ	Reduced Frequency Parameter
$\sim$	...is of the order of...
Subscripts	
bl	Within the Boundary Layer
e	Edge of Boundary Layer
fs	Free-stream
in	Inlet to Blade Row/Cascade
j	Wake Jet
m	Mean
max	Maximum
'	Fluctuation in......
0	Reference

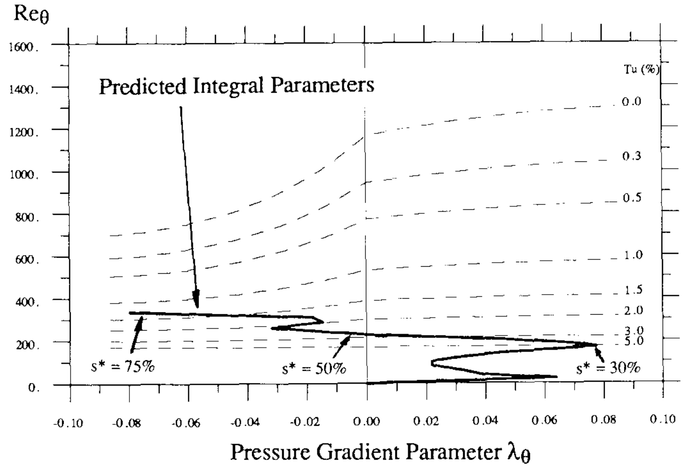


FIG 1: START OF TRANSITION CORRELATION OF ABU GHANNAM AND SHAW APPLIED TO THE TURBINE ROTOR SUCTION SURFACE

for this blade. The sensitivity of the critical turbulence level to Re$_\theta$, and hence s^*, is evident as is the relative insensitivity to λ_θ in the region of interest (i.e. $Tu > 1.5\%$).

Fig. 2 shows the observed boundary layer states as deduced from the flow visualisation (separation and reattachment) and hot film gauges (transitional behaviour), and compares them with the predictions. Overall, the agreement with the correlation is reasonable. It can be seen that the position of the separation line is only slightly affected by the changing levels of free-stream turbulence. This indicates that the disturbances which exist in the laminar boundary layer have relatively little effect on the wall shear stress. The separation line appears to move back slightly with increasing inlet turbulence due to an increase in momentum transfer. This is consistent with the results of part 1 showing increased momentum transfer in the laminar boundary layer on the turbine rotor due to wake turbulence.

The position of the start of transition was determined from the first appearance of high frequency disturbances in the hot film signals. The results show that the start of transition is strongly affected by the levels of free-stream disturbances. Although the data is limited outside the separation bubble, it agrees fairly well with the predictions; being between the predicted start of transition and 10% intermittency. An asymptotic forward limit of 36%s* is predicted for the start of transition with increasing free-stream turbulence due to a minimum critical Re$_\theta$ of 163. In the research turbine, laminar separation was prevented because transition occured forward of the lift-off line. From the cascade behaviour and the predictions of the transition correlation, it is clear that the levels of inlet turbulence intensity must exceed 9% in order to provide levels of about 2% in the neighbourhood of transition and it is noted that these levels did not exist in the free-stream of the research turbine but only at the peak of the wakes.

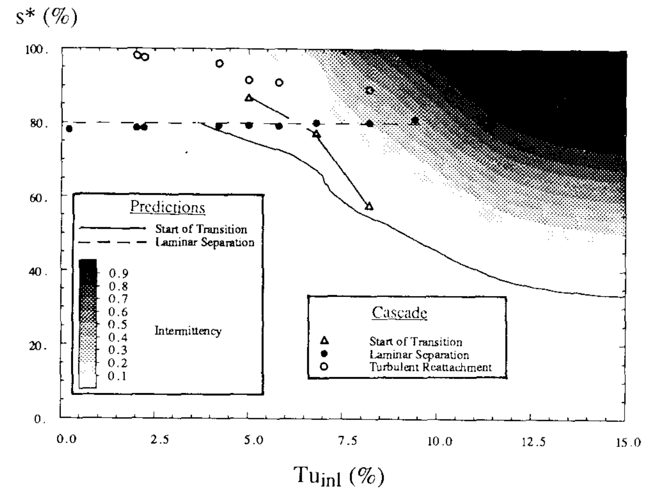


FIG 2: VARIATION OF SUCTION SURFACE BOUNDARY LAYER STATES WITH CASCADE INLET TURBULENCE INTENSITY

WAKE SPREADING DUE TO THE WAKE JET

In fig. 10 of part 1, distance-time plots of hotwire data were presented which suggested that time domain dispersion of the wake in the the freestream was minimal. One of the spreading mechanisms which operates is the wake-jet and, to show this effect more clearly, an unsteady inviscid finite volume code has been run using entropy as a convected marker (in a similar way to the earlier predictions of Hodson (1984a) and Giles (1987)). A wake velocity defect equal to 20% of the inlet velocity and therefore equivalent to about twice the value measured for an axial spacing of 50% C_{xs} was used in order to study the effect. Details of the computational method will be given in a future publication (Hodson (1989)). Fig. 3a is a composite plot showing the shape of a single wake as it passes through the rotor passage using contours of entropy. The results agree well with the earlier predictions for the same machine by Hodson and Giles as well as the hot-wire passage measurements of Hodson (1985). There is considerable distortion caused by the differing convection velocities at the front and rear of the wake segment. But if the values of entropy nearest to the suction surface are plotted in the form of a distance-time plot (fig. 3b), parallel traces result and it is clear that spreading in the time domain due to the wake jet is minimal.

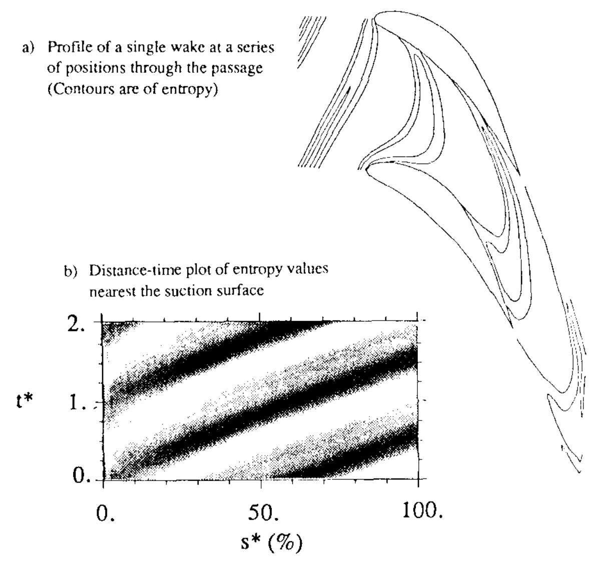


FIG 3: UNSTEADY TWO-DIMENSIONAL PREDICTION OF STATOR WAKE DISTORTION THROUGH THE TURBINE ROTOR

A SIMPLE TRANSITION MODEL

In order to understand the results described in part 1 more fully, a simple model has been devised. The details are summarised in figure 4. The model is based on the assumption that the principal effect of

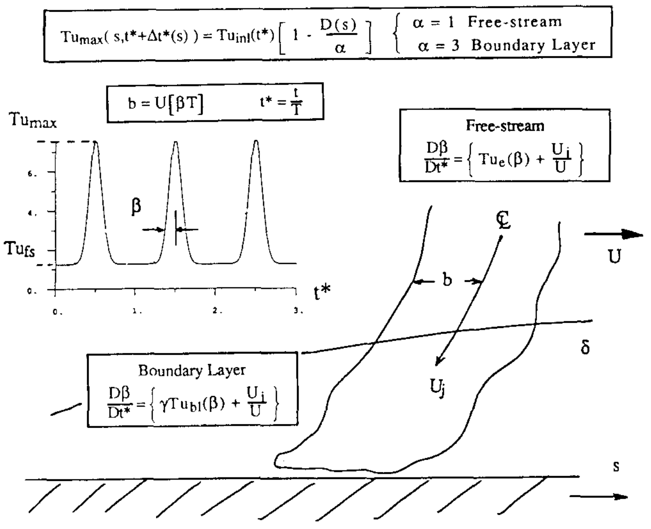


FIG 4: SUMMARY OF THE ASSUMPTIONS USED IN THE UNSTEADY TRANSITION MODEL

the wake is the promotion of early transition of the boundary layer as a result of increased levels of disturbances. It is further assumed that the effects initiated by turbulence will be quasi-steady in nature as has been shown to be the case in the research turbine. The effect of the wake jet as a direct cause of transition has already been discounted through consideration of the non-steady Reynolds number. Its indirect effect on transition through quasi-steady modification of the stability of the boundary layer is considered to be small when compared to the mean flow. This latter assumption is justified by recalling that the start of transition criterion of Abu Ghannam and Shaw (1980) showed that, when the levels of turbulence are greater than 1.5%, the influence of pressure gradient (λ_θ) is very much weaker than the influence of the boundary layer Reynolds number (Re_θ). This start of transition correlation is assumed to hold true in the quasi-steady case although it is noted that the transition length correlation based on a fixed start of transition location is not generally valid and most definitely cannot be used here. Boundary layer parameters predicted by the code of Cebeci and Carr (1974) are used, and the disturbances in the laminar boundary layer are assumed to be associated with low Reynolds stress and to have relatively little effect on the boundary layer parameters. The inlet turbulence profile is approximated by a periodic series of Gaussian profiles with peak value Tu_{max} and standard deviation b superimposed on a freestream level Tu_{fs} as shown in fig. 4. For the purposes of this model, the standard deviation (wake width) is best considered in the time domain where β is defined as the fraction of the wake passing period during which an observer on the blade surface would see turbulent flow in the free-stream and therefore

$$\beta T \approx b / U \tag{7}$$

where U is the local convective velocity. The values for the three axial gaps derived from the results of Hodson (1983) are given in Table 1. This results in inlet profiles for the 3 configurations as shown in Fig. 5. Initially, only the 75% C_{xs} case will be considered since most data is available for this turbine configuration.

Wake Parameter at Rotor Inlet Plane		Axial Gap (% Cxs) 50	 75	 143
Tu_{max}	Peak Turbulence (%)	9.5	7.5	4.0
Tu_{fs}	Freestream Turbulence (%)	1.25	1.5	2.0
β	Wake Width	0.008	0.012	0.015
Uj/U	Velocity Defect (%)	10.	9.	7.5

TABLE 1: WAKE PARAMETERS USED IN THE TRANSITION MODEL

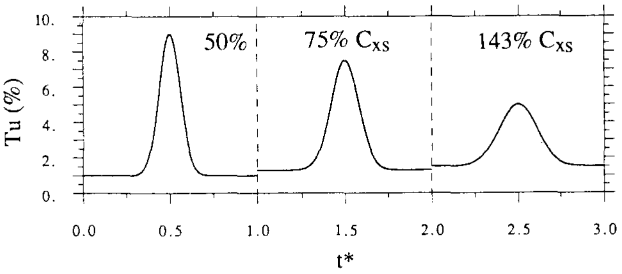


FIG 5: VARIATION OF WAKE TURBULENCE PROFILE AT ROTOR INLET WITH ROTOR-STATOR SPACING

The decay of the wake turbulence intensity through the passage is assumed to be proportional to that measured in the linear cascade for the grid generated turbulence. Thus the freestream turbulence level at a given point in space and time is

$$Tu_e(s^*, t^*+\Delta t^*) \approx Tu_{in}(t^*)\,[1 - D(s^*)] \tag{8}$$

where Δt^* is the time delay due to convection, itself a function of distance s^*, and $[1-D(s^*)]$ is the variation of turbulence intensity measured in the linear cascade.

The simplest model would assume that the wake segments are convected through the passage without spreading and that transition can simply be calculated from the free-stream turbulence at any point. This situation is shown in the distance-time plot of fig. 6, and clearly this has not modelled the behaviour measured by the hot film gauges or the hot wire traverses. It is predicted that laminar separation will reappear between highly localised transitional regions. Even assuming that the "patches" spread with trailing edge speed 55% $\overline{U_e}$ and leading edge speed 88% $\overline{U_e}$ as has been shown to be typical of turbulent spots (e.g. Shubauer and Klebanoff, 1955), the separation would still occur since the wake induced patches would not merge before the trailing edge. The cascade tests have shown that separation will only be

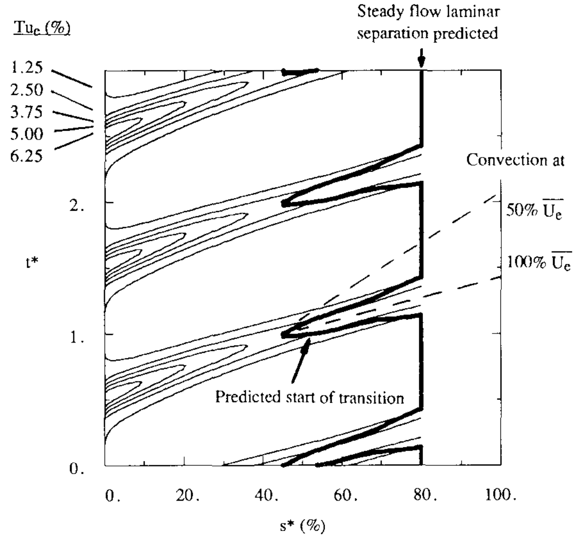


FIG 6: PREDICTED START OF TRANSITION - NO WAKE SPREADING MECHANISM (75% C_{XS} ROTOR-STATOR AXIAL GAP)

suppressed by levels of mean inlet turbulence intensity $(Tu_m)_{in}$ greater than 7%, and hot wire traverses and flow visualisation (Hodson and Addison, 1988) have shown that separation does not exist on the rotor of the research turbine. Since the inter-wake turbulence level is $\sim$ 1%, this cannot be responsible for the suppression of separation, and the implication is that the peak level is less highly localised. It is, however, reassuring to note that the decay of the peak turbulence results in earliest transition very much in line with the measured location suggesting that this combination of an approximate model for the decay of wake turbulence intensity and the start of transtition correlation is valid.

We can estimate the freestream spreading of the wake segment in the time domain by writing

$$\frac{D(U\beta)}{Dt^*} \sim u' \quad \text{or} \quad \frac{D\beta}{Dt^*} \sim Tu_e(\beta) \tag{9}$$

where $Tu_e(\beta)$ is the turbulence intensity at β from the wake centreline in the freestream (fig. 4). Additionally, there will be a spreading effect due to the wake jet, and a continuity argument suggests that

$$\frac{D(U\beta)}{Dt^*} \sim U_j \quad \text{or} \quad \frac{D\beta}{Dt^*} \sim \frac{U_j}{U} \tag{10}$$

If the two effects are assumed to add, then

$$\frac{D\beta}{Dt^*} \sim Tu_e(\beta) + \frac{U_j}{U} \tag{11}$$

Using this assumption, the time behaviour of the free-stream turbulence through the cycle can be determined at points downstream. The resulting boundary layer behaviour (not shown) is little different to that seen for the case described above with no spreading of the wake width. This agrees with the distance-time plots resulting from the hot wire traverses of part 1 and predictions described above which showed that there was little time domain spreading of the wake turbulence in the freestream. This result is important because it shows that the unsteady effect of the freestream on the wake can be neglected in a first order approximation.

Since transition occurs inside the boundary layer and the intensity of the fluctuations are maintained at a higher level by the more favourable production-dissipation balance, it might be expected that the spread of influence of the wake peak levels would be correspondingly more vigorous i.e.

$$\frac{D\beta}{Dt^*} \sim Tu_{bl}(\beta) + \frac{U_j}{U} \tag{12}$$

where Tu_{bl} is a turbulence level typical of the heart of the boundary layer and $Tu_{bl} > Tu_e$. The reduction in peak turbulence intensity is assumed to be somewhat less in the boundary layer than in the freestream such that

$$Tu_{bl}(s^*,t^*+\Delta t^*) \approx Tu_{in}(t^*)\left[1 - \frac{D(s^*)}{\alpha}\right] \tag{13}$$

where α is assumed to be a constant greater than 1. A constant value is not strictly justified given the changing pressure gradient on the blade but it is felt that it is a relatively small approximation in comparison with all the others. By trial and error, it was found that a value of $\alpha \approx 3$ gave levels of turbulence intensity typical of those measured in the disturbed laminar boundary layer of part 1. The boundary layer level is only used to allow the increased mixing to be calculated. The value used as input for the correlation (which is based on free stream levels) is derived from the peak value in the free stream and the wake width within the boundary layer. The results shown in fig. 7 are very similar to the behaviour predicted above (fig. 6) since the influence of the wake peak has still not spread far in the time domain. Similarly, the boundary layer levels have not spread as quickly as the hot film or hot wire measurements of fig. 4b, part 1 would suggest. Another effect must be dominant.

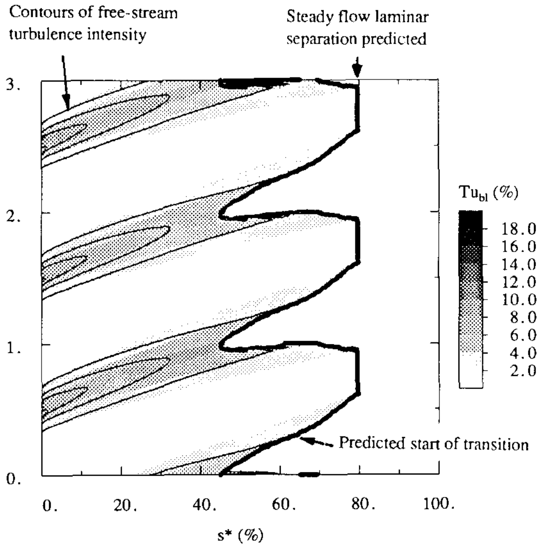


FIG 7: PREDICTED START OF TRANSITION - WAKE SPREADING BY STREAMWISE FLUCTUATIONS AND THE WAKE JET

Velocity fluctuations exist in all directions. Those in the chordwise direction have already been considered and the mechanism shown to be of insufficient strength to explain the observed results. Those in the spanwise direction contribute nothing to the chordwise mixing process as long as the flow is two-dimensional. However, following a mixing length argument, it is noted that a fluctuation normal to surface of typical length scale L gives rise to a streamwise fluctuation

$$u' \sim L\frac{\partial u}{\partial y} \tag{14}$$

In a boundary layer where $\partial u/\partial y$ is significant, the dispersion resulting from this effect can overwhelm the other spreading mechanisms. In order to model this in a simple way, we assume that

$$\frac{D\beta}{Dt^*} \sim \gamma\, Tu_{bl}(\beta) + \frac{U_j}{U} \tag{15}$$

where γ is again assumed constant for convenience. Trial and error is used to match the hypothesised boundary layer turbulence level to the hot wire traverse results, and this gives the value $\gamma \approx 8$ (using the value of $\alpha = 3$ as above). For a typical value of $Tu_{bl}(s^*,t^*) \sim 2\%$, this would imply a fluctuation length scale given by

$$L \sim \frac{u'}{\partial u/\partial y} \quad \text{whence} \quad \frac{L}{\delta} \sim \frac{u'}{U_e}\left[\frac{U_e}{\delta}\right]\frac{1}{\partial u/\partial y} \tag{16a}$$

$$\frac{L}{\delta} \sim \gamma\, Tu_{bl}(s^*,t^*) \sim 16\% \qquad (\gamma = 8) \tag{16b}$$

This is not unreasonable, and is reassuringly close to the value from conventional mixing length models (e.g. $L/\delta \approx 9\%$; Cebeci and Smith, 1974). The result of applying the approximation of eqn. (15) is shown in fig. 8. where it is compared with the hot film results of part 1. Again, the line contours are of the free stream wake turbulence, and the shaded contours are of the boundary layer level. The shape of the predicted start of transition line follows the observed results quite

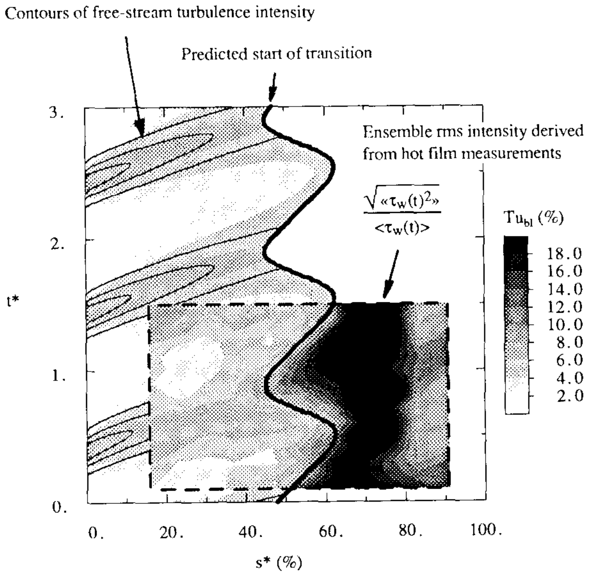


FIG 8: PREDICTED BOUNDARY LAYER BEHAVIOUR COMPARED WITH HOT FILM MEASUREMENTS (75% C_{XS} ROTOR-STATOR SPACING)

closely and the spread of the predicted boundary layer turbulence intensity corresponds well with the measured values.

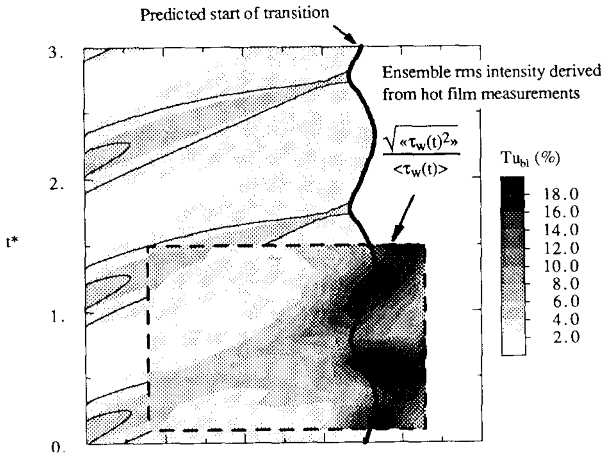
Given that two constants have been estimated by trial and error, the validity of the model can be judged by applying it to the two other turbine configurations reported in part 1 with 143% and 50% C_{XS} rotor-stator spacings. These results are shown in figures 9a and 9b respectively. Although there is some error in the location of the transition point, it can be seen that the trends for the start of transition are well predicted showing a steepening of the "leading edge" of the wedge with reducing axial spacing, as well as the spreading of the boundary layer turbulence intensity.

Superficially, the predicted behaviour and that observed on the turbine rotor are inconsistent with the results of Doorly (1987) and LaGraff et al (1988) in turbine cascades with simulated unsteady inflow. They showed a wake induced patch spreading with trailing edge speed 50% $\overline{U_e}$ and leading edge speed 100% $\overline{U_e}$ as if it were a single turbulent spot. However, the differences can be explained. The cascades used by these workers were both run at blade Reynolds numbers of about 2.0 x 10^6. This means that the boundary layer Reynolds numbers are correspondingly higher and transition occurs much earlier on the blade. Fig. 10 shows the result of increasing the values of Re_θ for the turbine rotor by 3; roughly equivalent to running at the same flow coefficient but 10 times the Reynolds number (3.0 x 10^6) since, for a laminar boundary layer, $Re_\theta \; \alpha \; Re_x{}^{1/2}$. The transition point moves up the blade and, with this movement, the spreading mechanisms have less time to operate. For the low Reynolds number research turbine used here the shape of the inlet wakes and the magnitude of the spreading is so great that the trailing edges of the spots formed move faster than the transition line recedes with the passing of the wake. However, in the higher Reynolds number case, the boundary layer sees larger differences between peak and inter-wake turbulence and this means the start of transition line moves back along the blade faster than the trailing edges of the spots formed earlier. Under these conditions, the wedge trailing edge speed becomes the same as the turbulent spots i.e. 0.55 $\overline{U_e}$ and this represents a limiting value. The leading edge steepens and would, in the limit, become 100% $\overline{U_e}$.

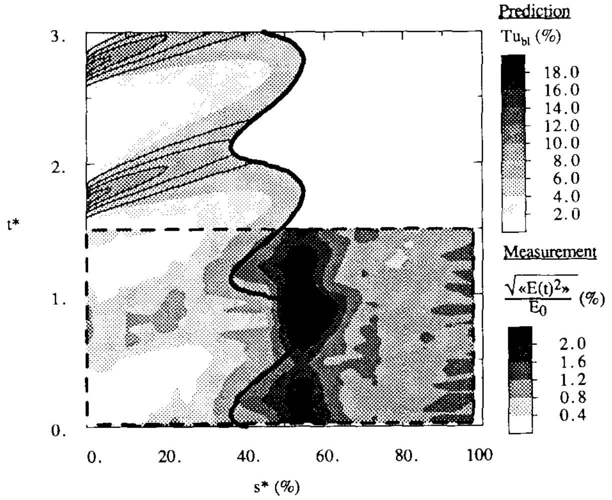
FURTHER DISCUSSION

The work reported in parts 1 and 2 of this paper has looked at the effect of blade wakes on the boundary layers of downstream rows and, especially, the forcing of early transition. Of particular note is the fact that the wake-jet seems to play a minor role. Comparison with the work of Obremski and Fejer (1967) has shown that the velocity fluctuation arising from the jet will not be a direct cause of transition. The transition correlation of Abu Ghannam and Shaw (1980) shows that, for the levels of turbulence intensity existing in a turbomachine, changes in the pressure gradient parameter λ_θ have very little effect. Finally, experimental results and computational predictions show that spreading of the wake segment by the jet action is not significant when viewed in the time domain. Therefore, we can reasonably ignore the effect of the jet when looking at wake-induced transition, and concentrate on the effect of the turbulence in the wake segment.

The incidence of the wake turbulence onto the blade boundary layer does not result in immediate transition. During the early stages of



A) 143% C_{XS} ROTOR-STATOR SPACING (calibrated gauge)



B) 50% C_{XS} ROTOR-STATOR SPACING (uncalibrated gauge)

FIG 9: PREDICTED BOUNDARY LAYER BEHAVIOUR COMPARED WITH HOT FILM MEASUREMENTS

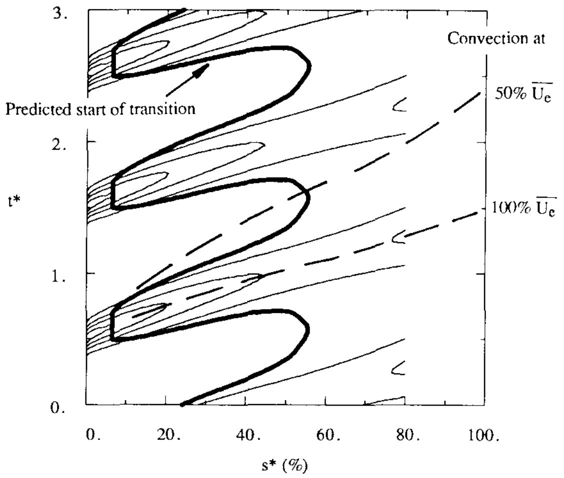


FIG 10: PREDICTED START OF TRANSITION FOR A HIGH REYNOLDS NUMBER TURBINE BLADE (Re ≈ 3 x 10^6)

boundary layer development, the production of turbulent kinetic energy within the boundary layer is exceeded by the dissipation. There is a little transfer of momentum but the hot-wire traverses show that the integral parameters are not far from those predicted for a laminar boundary layer. After a certain point, usually characterised by a critical momentum thickness Reynolds number Re_θ, transition occurs. The start of this process is in reasonable agreement with correlations based on flat plate experiments. In the presence of disturbed laminar boundary layers, the hot films show that this is characterised by the appearance of high frequency bursts over a low frequency background. The increased momentum transfer leads to large swings in the shear stress measured at the surface by the hot films. The stochastic (as opposed to phase-locked) nature of this process is shown up by the peak in the hot film rms intensity in the region known to be transitional. Once the boundary layer is fully turbulent, the wakes have relatively little additional effect as shown by the small variation between maximum and minimum rms intensity measured by the hot-film gauges and, consequently, steady predictions are fairly accurate.

The diffusion of the disturbances from the wake segment into the laminar boundary layer can be considered quasi-steady since $\upsilon_t \gg \upsilon$ i.e. diffusion times across the boundary layer are dominated by the short timescales of turbulent diffusion and are very much shorter than the blade passsing period. The hot wire traverses have also shown that, although transition is three dimensional (s,y,t), the differences between the surface behaviour measured by the hot-films and the regions of high shear in the middle of the boundary layer are small and hot films therefore give reasonably reliable results. In the time domain, as shown in the distance-time plots throughout this paper, the wake is not spread in the free-stream to any significant degree by either the turbulence or the wake-jet. However, inside the boundary layer, the higher levels of disturbances coupled with large velocity gradients result in a strong mixing process. For low Reynolds numbers, with the earliest transition at a reasonable distance from the leading edge, the transition "wedges" (which consist of several spots) bear little resemblance to the single spots of Obremski and Fejer (1967). However, when the blade Reynolds number is higher and transition correspondingly earlier, the turbulence has not spread as far in the boundary layer, and the wedges begin to look more like single spots.

Problems remain to be solved before we can predict the behaviour of arbitrary boundary layers with confidence; chiefly, the accurate prediction of spreading within the boundary layer (a constant spreading rate as used here being too simplistic to be of general use), a general method of predicting the decay of the wake turbulence though the passage and a start of transition correlation based on disturbance intensities within the boundary layer. However, all these would seem to be within reach and a semi-empirical approach with reasonable generality should be feasible.

CONCLUSIONS

For practical applications, the wake jet has a minimal effect on the transition of blade boundary layers. The interaction of the wake turbulence with the boundary layer is quasi-steady in nature and characterised by a modified form of the reduced frequency parameter. Spreading of the wake segment in the time domain is dominated by strong mixing within the boundary layer whilst there is little spreading in the free-stream. The wakes have little effect on the behaviour of the laminar and turbulent boundary layers but the increased level of disturbances within the boundary layer gives rise to early transition.

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REFERENCES

Abu-Ghannam, B.J. and Shaw, R., 1980, "Natural transition of boundary layers - the effects of turbulence, pressure gradient and flow history," Journal of Mechanical Engineering Science, Vol. 22 No. 5, pp. 213-228.

Cebeci, T. and Carr, L.W., 1978, "A Computer Program for Calculating Laminar and Turbulent Boundary Layers for Two Dimensional Time Dependent Flows," NASA TM 78470.

Cebeci, T. and Smith, A.M.O., 1974, Analysis of Turbulent Boundary Layers, Academic Press, New York.

Doorly, D.J. and Oldfield, M.L.G., 1985, "Simulation of the effects of shock wave passing on a turbine rotor blade," ASME paper No. 85-GT-112.

Doorly, D.J., 1987, "Modelling the unsteady flow in a turbine rotor passage," ASME paper No. 87-GT-197.

Giles, M.B., 1987, "Calculation of Unsteady Wake/Rotor Interactions," AIAA Paper 87-0006.

Hall, M., 1985, "An Investigation into the Effect of Free-Stream Turbulence upon the Development of Turbine Blade Boundary Layers," Internal Report, Cambridge University.

Hodson, H.P., 1983a, "The Development of Unsteady Boundary Layers on the Rotor of an Axial-Flow Turbine," AGARD Conference on Viscous Effects in Turbomachines, AGARD CP-351, Copenhagen.

Hodson, H.P., 1983b, "The Detection of Boundary Layer Transition and Separation in High Speed Turbine Cascades," Proceedings of the 7th Symposium on Measurement Techniques for Transonic and Supersonic Flow in Cascades and Turbomachinery, Aachen.

Hodson, H.P., 1984a, "An Inviscid Blade-to Blade Prediction of a Wake-Generated Unsteady Flow," ASME Paper 84-GT-43.

Hodson, H.P., 1984b, "Boundary Layer and Loss Measurements on the Rotor of an Axial Flow Turbine," ASME Journal of Engineering for Gas Turbines and Power, Vol. 106, pp. 391-399.

Hodson, H.P., 1985, "Measurements of Wake-Generated Unsteadiness in the Rotor Passages of Axial Flow Turbines," ASME Journal of Engineering for Gas Turbines and Power, Vol. 107.

Hodson, H.P. and Addison, J.S., 1988, "Wake-Boundary Layer Interactions in an Axial-Flow Turbine at Off-Design Conditions," ASME Paper 88-GT-233.

Hodson, H.P., 1989, to be published.

LaGraff, J.E., Ashworth, D.A., and Schultz, D.L., 1988, "Measurement and Modelling of the Gas Turbine Blade Transition Process as Disturbed by Wakes," ASME Paper 88-GT-232.

Obremski, H.J. and Fejer, A.A., 1967, "Transition in Oscillating Boundary Layer Flows," Journal of Fluid Mechanics, Vol 29, pp. 93-111.

Schubauer, G.B., and Klebanoff, P.S., 1955, "Contributions on the Mechanics of Boundary Layer Transition," NACA TN 3489.

Walker, G.J., 1974, "The Unsteady Nature of Boundary Layer Transition on an Axial-Flow Compressor Blade," ASME Paper 74-GT-135.