Periodic Turbulent Strips and Calmed Regions in a Transitional Boundary Layer

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Nomenclature

R_x = Reynolds number, $U_e X/\nu$
t = time
U_e = local freestream velocity
U_n = apparent celerity of new spots inside the calmed region
U_r = freestream velocity at $X = 50$ cm
w = initial spot duration
X = streamwise distance from leading edge
Y = distance normal to the wall
Z = spanwise distance from spot source
γ = intermittency factor
Δt = duration
ΔZ_p = distance between spot sources
τ = spot duty cycle, 100–500 ms

Subscripts

cr = calmed region
lam = laminar boundary-layer values
le = spot leading interface
opt = optimum
p = spot source location
s = distance from spot source
std = undisturbed boundary-layer values
te = spot trailing interface
tr = unforced transition location (defined as $\gamma = 50\%$)
tur = turbulent boundary-layer values

Introduction

WHEN the turbulent wakes of one row of blades in a turbomachine impinges upon the boundary layer of a blade in the following row, it may periodically generate quasi-two-dimensional turbulent strips and calmed regions in between.[1] These have a major impact on the transition and separation process of the blade boundary layer.[2] Authors have previously shown[3] that the spot wake has a stabilizing (calming) effect on boundary-layer transition. They speculated[3] that spots could be used to delay the completion of transition when periodically generated at an optimal rate, and this has been observed in turbomachines.[2,4,5] An optimal rate was also shown to exist.[5] Unfortunately, the calmed region is eroded by the surrounding turbulent flow. The evolution of the spot calmed region and its erosion in a turbulent boundary layer is the subject of this Note. Results of experiments simulating wake boundary-layer interactions in turbomachines are presented. Trains of two side-by-side spots were generated in a transitional, adverse-pressure-gradient boundary layer. A simple, kinematic model of the modified transition process describes the experimental findings and should assist the development of prediction tools.

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Experiment

The experimental setup was described elsewhere,[6,7] and only essential details will be repeated here. The setup allows the repeatable generation of single or side-by-side turbulent spots. For most of the runs, the reference velocity was $U_r = 8.6$ m/s. A gentle trip, located at $0.42 < X < 0.49$ m ($R_x \cong 2.5 \times 10^5$), was used to promote and regulate the boundary-layer transition. This generated what is referred to as the baseline boundary layer in this Note. Two spot generators were used for the side-by-side spot formation ($X_p = 30$ or 50 cm and $Z_p = 0.04$ and 0.08 m) with a spanwise separation of $\Delta Z_p/(X_{tr} - X_p) \approx 0.13$. Under these circumstances nominally two-dimensional turbulent strips were generated upstream of the unforced transition zone. Spots were triggered by a momentary blowing from 0.5-mm-diam holes in the wall at a rate of 2.5–10 Hz, with an initial duration of 10 ms. The main indication of transition was the near-wall intermittency.[8] An intermittent event was identified whenever the velocity, measured by a hot wire, at a given point in a time series deviated by more than a specified threshold (typically 0.005 U_e) from a running averaged velocity. The width of the averaging window was 3 ms. Time points where turbulent events were identified were given a value of one, otherwise it remained zero. The detection scheme was rather insensitive to the selected threshold level. These values were then ensemble-averaged over hundreds of events to calculate the intermittency factor for every time point in the cycle.

An uncertainty analysis of the experimental and calculated results indicated that the reference velocity was within ±0.5%, the hot-wire velocities ±1.5%, and the temperature was maintained at 21 ± 1°C. The uncertainties in the probe position were ±0.5, ±0.02, and ±0.1 mm in X, Y, and Z, respectively. Spot celerities are uncertain within ±5%.

Results

Periodic turbulent strips were produced upstream of the baseline boundary-layer transition by two side-by-side spot generators. Figure 1 presents the phase-locked-average of the measured near-wall intermittency in the form of an X-t diagram ($Z = 0.04$ m). Trajectories that denote spot interface celerities of $U_{le} = 0.88$, $U_{te} = 0.53$, and $U_{cr} = 0.27$ are also shown. The termination of the calmed region was identified where the near-wall velocity perturbation diminished to within 2% of the steady-state value (laminar, transitional, or turbulent). Data were also acquired[6] at $Z = 0.06$ m, showing similar results and confirming that spanwise uniform turbulent strips were obtained. The turbulent spots are identified in Fig. 1 as regions of high intermittency ($\gamma \cong 1$) at the first measurement station. The spots have a duration of $w = 10.5$ ms ($w/\tau = 0.07$) at the source location. This compares favorably with the duration of

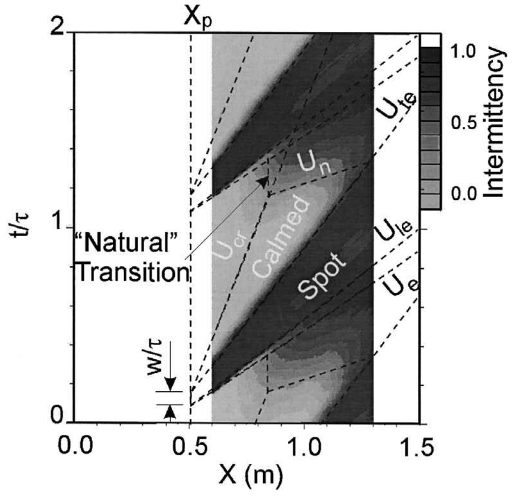

Fig. 1 Space-time diagram of intermittency in a forced boundary layer: $U_r = 8.6$ m/s, $X_p = 0.5$ m, $X_{tr} = 0.85$ m, $Z_p = 0.04$ and 0.08 m, $Z = 0.04$ m, and $\tau = 150$ ms.

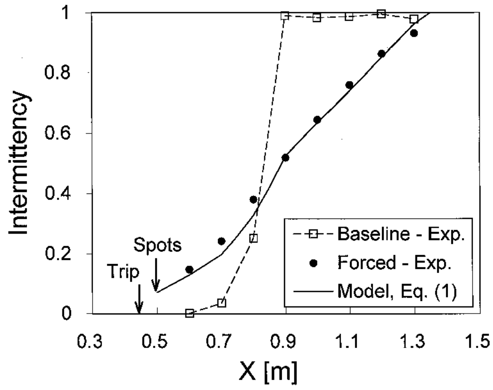

Fig. 2 Intermittency caused by a train of two side-by-side spots; conditions as in Fig. 1.

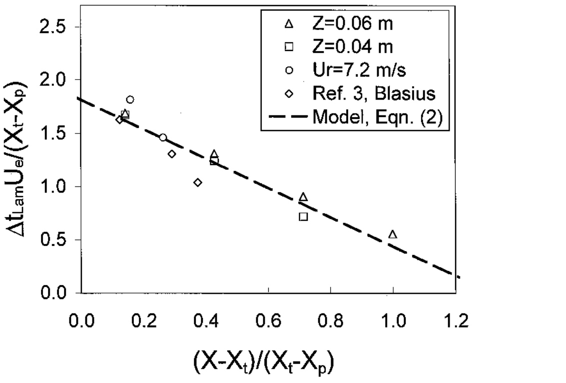

Fig. 3 Duration of the calmed region in a turbulent boundary layer.

the spot generating pulse, 10 ms. In Fig. 1 steady flow transition can be seen in the vertical contours centered on $X = 0.85$ m between $t/\tau = 1.0$ and 1.35. The contours show that the baseline flow transition would end near $X = 0.90$ m having begun near $X = 0.70$ m. The calming effect of the forced spots causes a significant increase in the transition length. The rear of the calmed region is not truncated by the turbulent spots that originate at the location of steady-state transition. Instead, it seems to be truncated by the creation of new turbulent spots inside the calmed region. These additional spots form along a line that appears to have a celerity $U_n \approx 2U_e$. This accelerated truncation reduces the gains afforded by the periodic strips of turbulence and calmed regions.[9]

Figure 2 presents the averaged (in both the spanwise direction and in time) near-wall intermittency for the steady and the forced boundary layer. Steady-state transition is centered around $X = 0.85$ m. The averaged intermittency of the forced boundary layer is somewhat higher than that of the steady boundary layer for $X < 0.85$ m, because of the periodic triggering of spots in a laminar boundary layer, but is lower for $X > 0.85$ m because a fraction of the cycle was maintained laminar in an otherwise turbulent environment. Indeed, the unforced transition is completed at $X = 0.9$ m, whereas the forced boundary layer is only 50% intermittent. Because of the spots' calming effect, transition is not complete until $X = 1.3$ m. Figure 2 also presents results of a model of the forced-flow time-averaged intermittency. This calculation is based on the schematic interpretation of Fig. 1 and extends beyond previous work.[5,10] In this simple model the interface celerities that have just been indicated are used, and the spots have a finite duration ($w = 10$ ms) at the source. The flow within the spots is assumed to be fully turbulent, as observed for artificially triggered spots. The flow that still undergoes steady flow transition may be transitional, and its intermittency is given by the measured $\gamma_{\text{std}}(X)$. If this is not known, $\gamma_{\text{std}}(X)$ may be calculated using conventional methods. The time mean intermittency is derived by examination of the areas bounded by the lines drawn in Fig. 1. It is given by

$$\bar{\gamma} = \frac{X - X_p}{\tau}\left(\frac{1}{U_{\text{te}}} - \frac{1}{U_{\text{le}}}\right) + \frac{w}{\tau} + \left[1 - \frac{w}{\tau} - \frac{X_{\text{tr}} - X_p}{\tau}\left(\frac{1}{U_{\text{cr}}} - \frac{1}{U_{\text{le}}}\right)\right]\gamma_{\text{std}}(X) + \left[\frac{X - X_{\text{tr}}}{\tau}\left(\frac{1}{U_{\text{le}}} - \frac{1}{U_n}\right)\right]\gamma_{\text{std}}(X) \tag{1}$$

The first term in Eq. (1) represents the contribution from the turbulent strips. It includes the effects of the chordwise elongation of the turbulent strips caused by the differing leading- and trailing-edge celerities and the finite duration of the strips at inception. The second term in Eq. (1) represents the contribution caused by natural, steady flow transition and exists downstream of X_{tr}. It represents the opportunity that natural transition would occur between the termination of one calming region and the appearance of the next spot leading interface. The last term in Eq. (1) represents the erosion of the calmed region by spots that appear to be generated inside it. The agreement between the experiment and the model is within ±3% (Fig. 2).

Erosion of the Calming Effect

The same assumptions that lead to Eq. (1) can be used to find the duration of the calmed (laminar) region inside the turbulent boundary layer [i.e., where $\gamma_{\text{std}}(X) \geq 50\%$]:

$$\Delta t_{\text{lam}} = (X_{\text{tr}} - X_p)(1/U_{\text{cr}} - 1/U_{\text{te}}) - (X - X_{\text{tr}})(1/U_{\text{cr}} - 1/U_n) \tag{2}$$

The first term on the right-hand side represents the maximum calmed duration within the transitional boundary layer. The second term represents the erosion caused by new spots generated inside the calmed region.

Measured duration of calmed regions, normalized accordingly, is presented in Fig. 3. These data were obtained at $Z = 0.04$ and 0.06 m with periodic side-by-side spots (see Figs. 1 and 2) together with data from experiments carried out with trains of single spots[6] ($U_r = 7.2$ m/s, $X_p = 30$ cm, and natural boundary-layer transition) and earlier measurements made in Blasius flow.[3] Figure 3 also presents the calculations based on Eq. (2), showing reasonable agreement with experiment. These calculations were made by assuming that the rear of the calmed region, inside the turbulent boundary layer, actually has a celerity of $U_n \approx 2U_e$. Further experiments and physical interpretation are necessary to explain these observations.

Optimization of the Spots Production Rate

The optimum frequency, in terms of intermittency, occurs when the end of one calmed zone is just truncated by the arrival of the next turbulent strip at the X location where $\gamma_{\text{std}}(X) = 50\%$. From Eq. (2) this corresponds to the period given by

$$\tau_{\text{opt}} = 1/f_{\text{opt}} = (X_{\text{tr}} - X_p)(1/U_{\text{cr}} - 1/U_{\text{le}}) \tag{3}$$

if the spots are formed with no initial duration. This frequency does not depend on the location in question.

To test the preceding, the spot production rate was altered, and the ensemble average of the near-wall intermittency was determined at one location inside the otherwise turbulent environment. The experimental and calculated intermittency factors for the two test conditions are presented in Fig. 4. The calculation for generation frequencies below the optimum is made using all of the terms in Eq. (1), which allows natural transition after the termination of the calming effect. At frequencies greater than the optimum, natural transition does not occur, and the time mean intermittency is given by the first part of Eq. (1) alone. In both cases the optimum frequency and the minimum intermittency of the model appears to match that of the experiment (Fig. 4). The rate of change in the off-optimum intermittency is not accurately predicted, but the range of τ that were tested is small. The discrepancies between the measured and calculated intermittency for the higher reference velocity are probably because the calmed region was not fully developed as the spots entered the turbulent boundary layer.

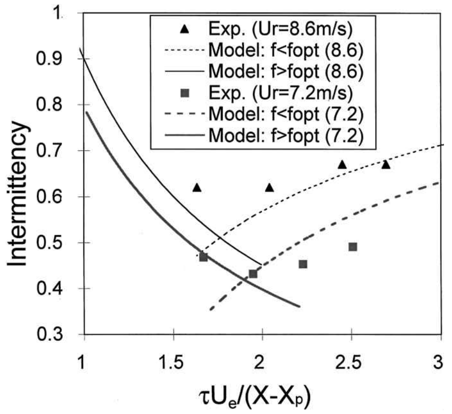

Fig. 4 Measured time-average intermittency factors of the boundary layer forced at different periods compared with calculations based on all the terms of Eq. (1) (- - - -) and Eq. (1a) (——) for $U_r = 7.2$ m/s, $X_p = 0.3$ m, $X_{tr} = 1.25$ m, $X = 1.5$ m, $Z = Z_p$, and for $U_r = 8.6$ m/s, $X_p = 0.5$ m, $X_{tr} = 0.85$ m, $Z_p = 0.04$ and 0.08 m, and $Z = 0.04$ m.

Conclusions

A train of turbulent strips generated upstream of a steady flow transition region can reduce the average intermittency to about half its value downstream of the steady transition location. Periods of laminar flow were maintained in an otherwise turbulent environment. However, the calmed region is eroded inside the turbulent boundary layer, probably by the generation of new spots inside it. Simple kinematic modeling of the described phenomena is capable of reproducing most of the measured events that are relevant to transition delay in turbomachines. Further experiments are needed to explore the creation of new spots inside the calmed region.

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References

[1]Pfeil, H., Herbst, R., and Schröder, T., "Investigation of Laminar-Turbulent Transition of Boundary-Layers Disturbed by Wakes," American Society of Mechanical Engineers, ASME Paper 82-GT-124, June 1982.

[2]Halstead, D. E., Wisler, D. C., Okiishi, T. H., Walker, G. J., Hodson, H. P., and Shin, H. W., "Boundary-Layer Development in Axial Compressors and Turbines. Part 1 of 4: Composite Picture," *Journal of Turbomachinery*, Vol. 119, No. 1, 1997, pp. 114–127.

[3]Schubauer, G. B., and Klebanoff, P. S., "Contributions to the Mechanics of Boundary-Layer Transition," NACA Rept. 1289, Feb. 1956.

[4]Cumpsty, N. A., Dong, Y., and Li, Y. S., "Compressor Blade Boundary Layers in the Presence of Wakes," American Society of Mechanical Engineers, ASME Paper 95-GT-443, June 1995.

[5]Schulte, V. S., and Hodson, H. P., "Unsteady Wake Induced Boundary-Layer Transition in Highly Loaded LP Turbines," American Society of Mechanical Engineers, ASME Paper 96-GT-486, June 1996.

[6]Seifert, A., and Wygnanski, I. J., "On Turbulent Spots in a Laminar Boundary-Layer Subjected to a Self-Similar Adverse Pressure Gradient," *Journal of Fluid Mechanics*, Vol. 296, Aug. 1995, pp. 185–209.

[7]Seifert, A., "Spot Calming Effect on Boundary-Layer Transition," *1997 Minnowbrook II Workshop on Boundary Layer Transition in Turbomachines*, edited by J. E. LaGraff and D. E. Ashpiz, NASA CP-1998-206958, 1998, pp. 99–110.

[8]Glezer, A., Katz, Y., and Wygnanski, I., "On the Breakdown of the Wave Packet Trailing Turbulent Spots in a Laminar Boundary-Layer," *Journal of Fluid Mechanics*, Vol. 198, 1989, pp. 1–26.

[9]Gostelow, J. P., Walker, G. J., Solomon, W. J., Hong, G., and Melwani, N., "Investigation of the Calmed Region Behind a Turbulent Spot," American Society of Mechanical Engineers, ASME Paper 96-GT-489, June 1996.

[10]Hodson, H. P., "Modelling Unsteady Transition and Its Effects on Profile Loss," *Propulsion and Energetics Panel 74th(A) Specialists' Meeting*, CP-486, AGARD, 1989.

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Grid Adaption for Shock/Turbulent Boundary-Layer Interaction

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Introduction

FOR shock/turbulent boundary-layer interaction problems common to aeronautical applications, the severe adverse pressure gradient at the foot of the shock wave makes the turbulence modeling a very challenging task. While concentrating on the physical modeling, one should also be aware of numerical errors introduced from the discretization of the physical modeling and from the computational solution of the discretized equations. The variation of solutions for different grids or different numerical schemes can be as significant as that from different turbulence models. The merit of different models not only depends on the appropriate level of the physical modeling but also on the numerical accuracy and robustness in the computation. Both the discretization scheme and the computational grid play important roles in the numerical accuracy. Ideally one should choose discretization schemes that produce less numerical dissipation so that the numerical results will be less sensitive to the grid used. Furthermore, turbulence models, their implementation, and the related boundary conditions may also introduce a strong dependency on the grid quality. For a given physical model and a given discretization scheme, grid sensitivity study is a very useful way to eliminate numerical uncertainties in computational simulations. However, for multidimensional problems, the process of doubling grid points in each direction, a common practice for grid sensitivity studies for a structured grid approach, can soon exhaust the resources of an available computer system.

Based on equidistribution algorithms, a structured grid adaption[1,2] aims to distribute the numerical errors more evenly by redistributing the grid points along a grid line according to solution activities. Here an assumption has been made that the solution activity is properly measured to reflect the errors between the discretized computational solution and the solution of the governing partial differential equations. For the present study, a structured anisotropic grid adaption approach is adopted to resolve the λ-shock wave, the turbulent boundary layer, and the strong shock/boundary-layer interaction involving boundary-layer separation. The effects of the grid adaption on the flowfield solution, in particular, the turbulent boundary-layer profiles, are studied. This provides a more reasonable and efficient means to carry out grid sensitivity studies through which we can make a fair judgement of a particular turbulence model.

Methodology

The governing equations are the two-dimensional Reynolds averaged Navier–Stokes equations strongly coupled with the two turbulence equations. The shear stress transport (SST) model[3] has exhibited a better capability in dealing with the strong adverse pressure gradient that occurs in shock/boundary-layer interaction problems among a number of two-equation models tested.[4]

The convective numerical flux at the cell interface is evaluated using the Osher approximate Riemann solver with a MUSCL interpolation for a higher-order accuracy. The viscous fluxes and the turbulent source terms are discretized by using central differences through the use of Gauss's theorem. The time discretization

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