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Technical Notes

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Scaling of the Bursting Frequency for Turbulent Boundary Layers Approaching Separation

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Nomenclature

f_b = bursting frequency, Hz
f^+ = nondimensional bursting frequency, $f_b\nu/u^{*2}$
K = pressure gradient parameter, $(\nu/U_0^2)(dU_0/dx)$
P = static pressure
Re_θ = momentum thickness Reynolds number, $U_0\theta/\nu$
U_0 = wind tunnel local freestream velocity
u^* = friction velocity
x = axial coordinate
β = pressure gradient parameter, $(\delta^*/\tau_w)(dP/dx)$
δ = boundary-layer thickness
δ^* = boundary-layer-displacement thickness
θ = boundary-layer-momentum thickness
ν = fluid kinematic viscosity
τ_w = local wall shear stress

Introduction

THERE have been many attempts by investigators to scale the frequency of bursting events within turbulent boundary layers. Scaling with inner (wall-region) variables,[1–5] outer-boundary-layer variables,[6–9] and mixed scaling[10] have all been attempted. These efforts have not managed to give a universal scaling method applicable to all turbulent boundary layers.

Evidence in recent years seems to support the inner-variable scaling argument. Bandyopadhyay[11] showed that the outer-scaled bursting frequency $U_0/\delta f_b$ should vary as a function of the flowfield and not possess a universally constant value. Blackwelder and Haritonidis[5] found that some of the early data sets that were used to support the conclusion of outer-variable scaling contained errors resulting from spatial averaging effects of the hot wire sensors. They found that an inner-variable scaling solution resulted in f^+ as only a mild function of Reynolds number for momentum thickness Reynolds numbers in the range of 1000–10,000. When scaled with outer variables, the Blackwelder data displayed a large variation with Reynolds number. Inner-variable scaling has been largely corroborated by many investigators for values of Re_θ as low as about 200 and up to 10,000.[1–4]

White and Tiederman[12] conducted a recent experimental study of the effect of adverse pressure gradient on the bursting frequency. Their study was limited to relatively mild adverse pressure gradients for which the turbulent boundary layer was fully attached at all times. A key finding of their work was that the inner-scaled bursting frequency for adverse-pressure-gradient flows was increased relative to the zero-pressure-gradient case.

In the present study, scaling of the bursting frequency is addressed for turbulent boundary layers approaching separation. Detailed boundary-layer measurements were performed upstream of and within regions of strong pressure gradient prior to the onset of intermittent backflow. Under these conditions, the boundary-layer bursting behavior was found to be strongly influenced by the pressure distribution, with increases in f^+ relative to the case of zero pressure gradient. However, boundary layers with intermittent backflow were not found to display the high augmented levels of nondimensional bursting rates that have been observed for fully attached boundary layers developing in an adverse pressure gradient.

Results

The frequency of burst events for a two-dimensional, turbulent boundary layer depends on several flow elements, including the Reynolds number, the pressure gradient, the history of the pressure gradient, and appropriate flowfield length and velocity scales. In addition, the appearance of intermittent reverse flow near the wall is likely important. The current study focuses attention on effects associated with the pressure gradient. These effects have been isolated to some extent and thus highlighted by conducting the study in such a manner as to minimize the influence of the other parameters. Reynolds number effects have been minimized by performing measurements over a restricted range of Re_θ from roughly 2000 to 4000. The influence of near-wall intermittent reverse flow was eliminated

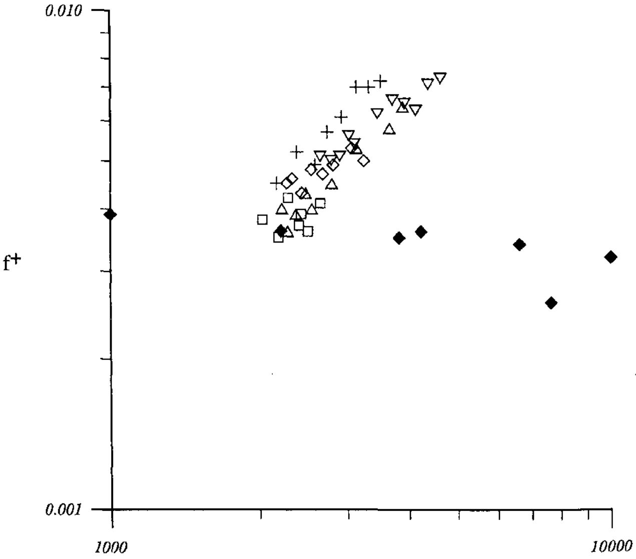

Fig. 1 Scaling of the bursting frequency with inner, wall-region flow variables: □, empty tunnel; +, diffusing wall; ◇, strong backflow; △, mild backflow; ▽, backflow aerodynamic blockage; and ◆, Ref. 5.

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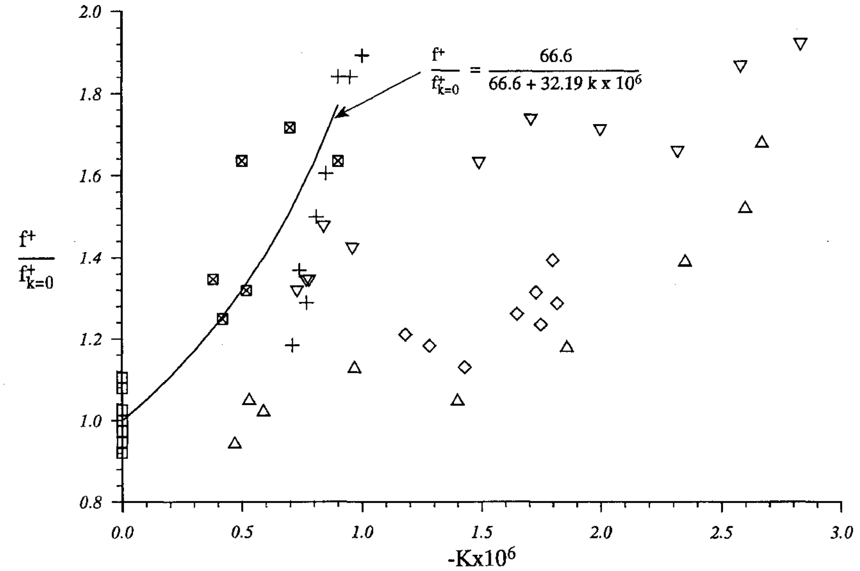

Fig. 2 Nondimensional bursting frequency increase as a function of pressure gradient parameter K: □, empty tunnel; +, diffusing wall; ◇, strong backflow; △, mild backflow; ▽, backflow aerodynamic blockage; ——, Ref. 12 equation; and ⊠, Ref. 12.

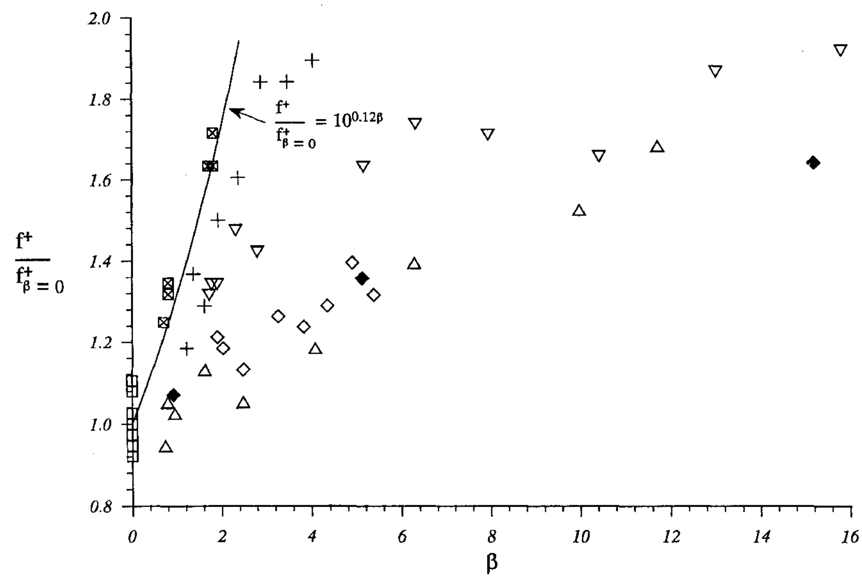

Fig. 3 Nondimensional bursting frequency increase as a function of pressure gradient parameter β: □, empty tunnel; +, diffusing wall; ◇, strong backflow; △, mild backflow; ▽, backflow aerodynamic blockage; ⊠, Ref. 12; ——, Ref. 12 equation; and ◆, Ref. 7.

by confining the study of the boundary-layer bursting frequency to the region upstream of the onset of intermittent backflow. Finally, the effects of pressure gradient history were minimized by generating separation without forcing the boundary layer to flow first through a long upstream region of developing adverse pressure gradient.

The present experimental study was carried out in airflow for a low-speed, flat-plate turbulent boundary layer. The boundary layer was forced to separate by injection of a thin layer of external fluid in the upstream direction through a slot adjacent to the test wall. Separations from two different injected flow speeds were investigated. A third separation was generated by placing on the wall a raised contour whose shape approximated the blockage of the injected slot fluid. Measurements were also performed for a fully attached turbulent boundary layer flowing through a more mild adverse pressure gradient. In all cases the boundary-layer bursting frequency was measured near the wall with a crossed-wire hot wire and the uv-quadrant-2 burst detection technique. Wall shear stress was obtained with the same hot wire. The uv-quadrant-2 burst measurement technique involves the acquisition of a long time record of simultaneously measured u and v signals. The signs of u and v are used to sort the instantaneous uv product into quadrants. After this the uv-quadrant-2 average is calculated, and a burst detection threshold is defined relative to this average. The uv points from the time record are then compared with the threshold, and those that exceed it are identified as belonging to a burst event. The process of counting and grouping these events and calculating the bursting frequency is described in Refs. 2 and 9. The details of the present experiment and the instrumentation and measurement technique are described by Tillman.[13]

A plot of the current bursting frequency data scaled upon inner variables is shown in Fig. 1, along with the data of Blackwelder and Haritonidis.[5] The data for the case of the empty tunnel are devoid of pressure gradient effects and are reasonably close to the Blackwelder results. The data for the three cases approaching separation show completely different behavior, with f^+ rising steeply with Reynolds number. The diffusing wall configuration, which produces a fully attached boundary layer developing within an adverse pressure gradient, shows the scaled bursting frequency values rising even more rapidly and steeply than those of the separation cases.

It was found that to fully understand the behavior of the nondimensional bursting frequency, the results had to be examined relative to the boundary-layer pressure distributions. The data from the current investigation and from White and Tiederman[12] are shown as a function of the nondimensional pressure gradient in Figs. 2 and 3. In Fig. 2 the data are plotted as a function of the pressure gradient parameter K, and in Fig. 3 the term β is used (both common forms of expressing the nondimensional pressure gradient). Recall that all of the data presented are devoid of near-wall reverse-flow effects, because measurements were made upstream of the onset of intermittent backflow.

In Figs. 2 and 3, the bursting frequency f^+ has been normalized to the zero-pressure-gradient case (calculated from the average of the empty tunnel values for the current results) to highlight changes in f^+ from this baseline condition. Note the close match in trends between the data of White and Tiederman[12] and the data for the diffusing wall of the current study. Recall that the diffusing wall case, like that of White and Tiederman,[12] represents a boundary layer that is fully attached yet developing in an adverse pressure gradient. Both of these cases show a sharp rise in f^+ with increasing pressure gradient. The data for the cases approaching separation clearly do not display this feature. The increases in f^+ are more modest, and there is in general a more mild increasing trend with pressure gradient. There are few data sets in the open literature documenting boundary-layer bursting behavior for separating flows. Strickland and Simpson[7] present results that may be used for comparison, and these data (taken from the tables in Ref. 7) are plotted in Fig. 3. The data agree well with those of the strong- and mild-backflow-separation cases of the present study.

Whereas the Blackwelder data of Fig. 1 show that a mild f^+ dependence on Reynolds number exists, the data of the current experiment presented in Figs. 2 and 3 are meant to highlight the additional important effect of the pressure gradient. The pressure gradient appears to cause different responses for fully attached and separating boundary layers. Of the three separation cases presented, note the reasonably good agreement between those of the strong and mild backflows. These two cases possessed pressure distributions that were similar in character. The pressure distribution for the case of the backflow aerodynamic blockage differed in that changes in the pressure gradient were stronger and occurred farther along in the pressure field development. This may be responsible for some of the differences observed between this and the other separation cases.

Note that the findings of this study were unaltered upon recalculation of the bursting frequencies with the threshold detection parameter doubled. Along with the obvious result of lowering the absolute levels of f_b, the relative trends among the various flow cases were found to be unchanged. This result provides good confidence in the measured data and in the findings presented thus far.

Conclusions

It is concluded that while inner-variable scaling is a proper nondimensionalization of the turbulent-boundary-layer bursting frequency, Reynolds number alone is not sufficient to adequately describe the behavior of this parameter. The pressure distribution is necessary to aid in the interpretation of scaled-bursting-frequency results. In addition, turbulent boundary layers approaching separation exhibit a marked reduction in bursting frequency augmentation relative to fully attached boundary layers developing within an adverse pressure gradient. While the scaled bursting frequency is increased relative to zero-pressure-gradient cases, the increases are more gradual and modest than corresponding increases for the fully attached adverse-pressure-gradient boundary layers. This indicates the existence of a less active condition of the boundary layer for flows approaching separation.

References

[1]Kim, J., and Spalart, P. R., "Scaling of the Bursting Frequency in Turbulent Boundary Layers at Low Reynolds Numbers," *Physics of Fluids*, Vol. 30, No. 11, 1987, pp. 3326–3328.

[2]Luchik, T. S., and Tiederman, W. G., "Timescale and Structure of Ejections and Bursts in Turbulent Channel Flows," *Journal of Fluid Mechanics*, Vol. 174, Jan. 1987, pp. 529–552.

[3]Shiau, B. S., and Lu, S. S., "Detection of Burst-Events in the Turbulent Boundary Layer," *Journal of the Chinese Institute of Engineers*, Vol. 11, No. 2, 1988, pp. 147–153.

[4]Wei, S., and Ning, T., "Bursting Frequency in Turbulent Boundary Layer," *ACTA Mechanica Sinica*, Vol. 4, No. 4, 1988, pp. 291–296.

[5]Blackwelder, R. F., and Haritonidis, J. H., "Scaling of the Bursting Frequency in Turbulent Boundary Layers," *Journal of Fluid Mechanics*, Vol. 132, July 1983, pp. 87–103.

[6]Rao, K. N., Narasimha, R., and Narayanan, M. A. B., "The 'Bursting' Phenomenon in a Turbulent Boundary Layer," *Journal of Fluid Mechanics*, Vol. 48, Pt. 2, 1971, pp. 339–352.

[7]Strickland, J. H., and Simpson, R. L., "The 'Bursting' Frequencies Obtained from Wall Shear Stress Fluctuations in a Turbulent Boundary Layer," *Physics of Fluids*, Vol. 18, No. 3, 1975, pp. 306–308.

[8]Simpson, R. L., Strickland, J. H., and Barr, P. W., "Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation," *Journal of Fluid Mechanics*, Vol. 79, Jan.–March 1977, pp. 553–594.

[9]Lu, S. S., and Willmarth, W. W., "Measurements of the Structure of the Reynolds Stress in a Turbulent Boundary Layer," *Journal of Fluid Mechanics*, Vol. 60, Pt. 3, 1973, pp. 481–511.

[10]Shah, D. A., and Antonia, R. A., "Scaling of the 'Bursting' Period in Turbulent Boundary Layer and Duct Flows," *Physics of Fluids*, Vol. 1, No. 2, 1989, pp. 318–325.

[11]Bandyopadhyay, P. R., "Period Between Bursting in Turbulent Boundary Layers," *Physics of Fluids*, Vol. 25, No. 10, 1982, pp. 1751–1754.

[12]White, J. B., and Tiederman, W. G., "The Effects of Adverse Pressure Gradient on Turbulent Burst Structure in Low-Reynolds Number Equilibrium Boundary Layers," Office of Naval Research, ONR Rept. PME-FM-90-2, Purdue Univ., West Lafayette, IN, Jan. 1990.

[13]Tillman, G., "An Experimental Study of Two-Dimensional Turbulent Boundary Layer Separation," Ph.D. Thesis, Dept. of Mechanical Engineering, Northwestern Univ., Evanston, IL, June 1994.

Drag Reduction with the Slip Wall

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Introduction

FOR rigid surfaces immersed in a flow, the no-slip condition on the wall holds. In simplistic terms, the basic idea of our slip wall is to release the no-slip condition to reduce drag. This is achieved with a belt that replaces the rigid wall. The moving belt, driven by the flow shear stress itself, reduces the velocity difference between mean flow and the wall, and thus it reduces the skin friction. Our device should not be confused with an actively driven belt surface like the one of a moving floor in a wind tunnel. We deal with a purely passive device. Simplified theoretical predictions show an impressive drag reduction potential. In our oil channel, we have experimentally demonstrated the feasibility of the concept. These first trials have shown a 9% net drag reduction, which is probably much less than can be achieved with a careful optimization of the system.

The idea of reducing drag by releasing the no-slip condition in some way is actually not so new. For instance, the following two drag reduction concepts are based on this idea. 1) The pressure loss in pipelines carrying highly viscous crude oil can be decreased dramatically by the injection of water.[1] The water remains close to the wall and, by its low viscosity, practically removes the no-slip condition of the crude oil at the wall. 2) Air can be ejected through the hulls of ships to reduce their drag in water.[2]

At first glance, it is not obvious that a passively moving belt can indeed reduce the wall shear stress. Therefore, to demonstrate the drag reduction capability of our slip wall we will discuss here a model that, admittedly, is at the verge of oversimplification. However, it exhibits clearly the physics of the slip wall system as well as its possible limits (Fig. 1). As a first (crude) approximation, we assume that the turbulent shear stress on the belt is proportional to

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