6th Australasian Hydraulics and
Fluid Mechanics Conference
Adelaide, Australia, 5-9 December 1977

Interactions Between Adjacent Turbulent Flows

P. BRADSHAW
Reader in Fluid Dynamics, Imperial College of Science and Technology, London University, U.K.

SUMMARY A review is presented of the three main types of interaction between a turbulent boundary layer (or other shear layers) and another field of turbulence. These types are (i) interaction with another shear layer having its mean shear in the opposite sense (or even in a different plane), as in the merging of two boundary layers at the end of the entry region in a high-aspect- ratio rectangular duct, (ii) interaction with another shear layer with the same sign of mean shear, as in the internal boundary layer that grows below an existing boundary layer after an abrupt change in surface roughness (iii) interaction with an essentially-unsheared region of "free stream" turbulence. Turbulent flows in streamwise corners (two shear layers at roughly 90 deg.) are included in class (i) but present difficulties not found in two-dimensional or mildly-three-dimensional cases. Both physical understanding and predictive ability are discussed, and a few practical examples are given to illustrate the frequent occurrence of the turbulence-turbulence interactions in engineering.

1 INTRODUCTION

The academic-sounding subject of this paper comprises a very large number of practical problems. There are many flows in which two or more turbulent regions join up after initially developing separately, for example the merging of the boundary layers on the walls of a duct. There are also many cases in which a new turbulent region grows within an old one, such as the development of an axial turbomachine blade boundary layer beneath a turbulent stream composed of the wakes of all the upstream blades. In cases of practical interest at least one of the turbulent regions is a shear layer (a boundary layer or a free mixing layer for example); it is helpful to think of a plane jet as the result of two merging mixing layers, and a plane wake - or a plane duct flow - as the result of two merging boundary layers. The flow along a streamwise corner represents the interaction between two boundary layers in planes at right angles, and the flow in a rectangular duct develops from four boundary layers (or four streamwise-corner flows).

If the equations of motion were linear, these interacting flows could be replaced by superpositions of their constituent regions. If, on the other hand we had a universally-valid method of calculating turbulent flows we could treat multiple regions in the same way as a single shear layer without explicitly acknowledging the presence of an interaction, just as one would do in laminar flow. However the only method of calculating turbulent flows that is generally accepted as universally-valid is the solution of the time-dependent Navier-Stokes equations for the fluctuating motion, and this is too time-consuming for engineering purposes at present. Therefore it is worth studying the physics of interacting turbulent flows to test and improve the range of validity of our approximate calculation method. In some cases, at least, it will be helpful to represent the interaction explicitly in the calculation method, for example by altering the eddy viscosity in a boundary layer by an amount proportional to the free-stream turbulence intensity. The alternative in this case would be to trust the same calculation method, with the same empirical data, in two flows with entirely different histories and boundary conditions, namely the boundary layer and the turbulent free stream.

This paper is a discussion of the three main classes of interacting turbulent flows, of which simple examples are sketched in Figure 1

(i) interacting shear layers (Figure 1(a))
(ii) internal layers (Figure 1(b))
(iii) shear layers beneath turbulent - but essentially unsheared - external streams (Figure 1(c))

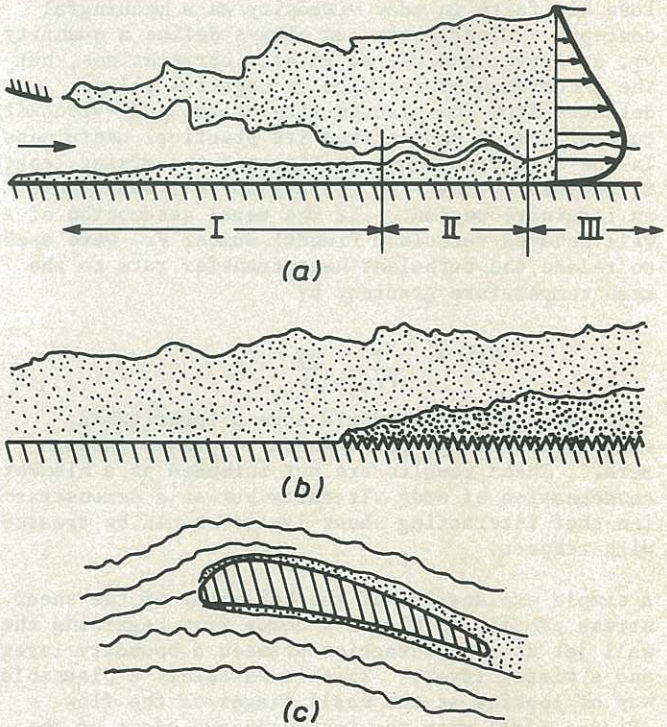

Figure 1 Interacting turbulence fields
(a) shear layers of opposite sign (wall jet)
(b) internal layer (roughness change)
(c) free-stream turbulence

The distinction between (i) and (ii) is that the two layers in (i) have opposite signs of shear while an internal layer has the same sense of shear as its parent. There are of course borderline cases: should the flow behind an obstacle in a boundary layer - such as a tower block in the atmospheric wind - count as (i) or (ii)? However we are not trying to erect a rigid system of taxonomy but just an aid to understanding. Interacting turbulent flows form one of the two main classes of what we at Imperial College call "complex turbulent flows" - as opposed to the simple turbulent flows like unperturbed boundary layers and mixing layers, which are commoner in textbooks than in real life. The other main class is composed of shear layers subjected to extra rates of strain in addition to the basic simple shear $\partial U/\partial y$: examples include shear layers with longitudinal curvature - extra strain rate $\partial V/\partial x$ - or lateral divergence - extra strain rate $\partial W/\partial z$. A general introduction to both classes was given by Bradshaw (1975) and a summary of work on complex flows at Imperial College by Bradshaw (1976). The present paper concentrates on interactions, and is intended for engineers as well as academics. It is largely descriptive - quantitative results are to be found in the papers quoted below and in other papers in preparation (references to authors by initials and name but without a date denote current work by my colleagues). The object of studying interactions is to improve prediction methods but here only the qualitative implications for prediction methods will be discussed since there is insufficient space to treat the different types of calculation method in detail.

2 INTERACTING SHEAR LAYERS

Figure 2 shows the velocity profile U(y), the shear-stress profile $-\overline{uv}(y)$ and the profile of eddy viscosity $\nu_T \equiv -\overline{uv}/(\partial U/\partial y)$ in a wall jet (Figure 1 (a)). The measurements were made by Bradshaw and Gee (1960), and caused this author permanently to lose his faith in eddy viscosity as a meaningful concept. Clearly one can always define a quantity ν_T, as above, and use it in data correlations, but the occurrence of infinite or negative values detracts from the plausibility of the eddy-viscosity concept and of course from its practical usefulness. In the situation shown in Figure 2 the mixing length ℓ, defined by $-\overline{uv} = \ell^2 (\partial U/\partial y)|\partial U/\partial y|$, would have an imaginary region. If the usual assumption of a well-behaved turbulent Prandtl number Pr_T were used to relate the turbulent heat-transfer rate to the mean temperature gradient by

$$-\overline{\theta v} = \frac{\nu_T}{Pr_T} \frac{\partial T}{\partial y}$$

then the temperature would have a logarithmic singularity at the point where ν_T passes through zero. These results are not intended as a blanket condemnation of eddy viscosity but as a demonstration that interacting shear layers should be treated with respect.

A simple explanation of the behaviour of the shear stress profile in Figure 2 comes from regarding the wall jet as an interaction between a boundary layer and a mixing layer. This is certainly a plausible way of looking at the early stages of the flow (Figure 1(a)) when the instantaneous edges of the boundary layer and mixing layer are still distinct, though perhaps occasionally overlapping as in region II of Figure 1(a). It also turns out to be useful, qualitatively at least, in region III which can be thought of as an overlapping boundary layer and mixing layer - two different turbulence fields

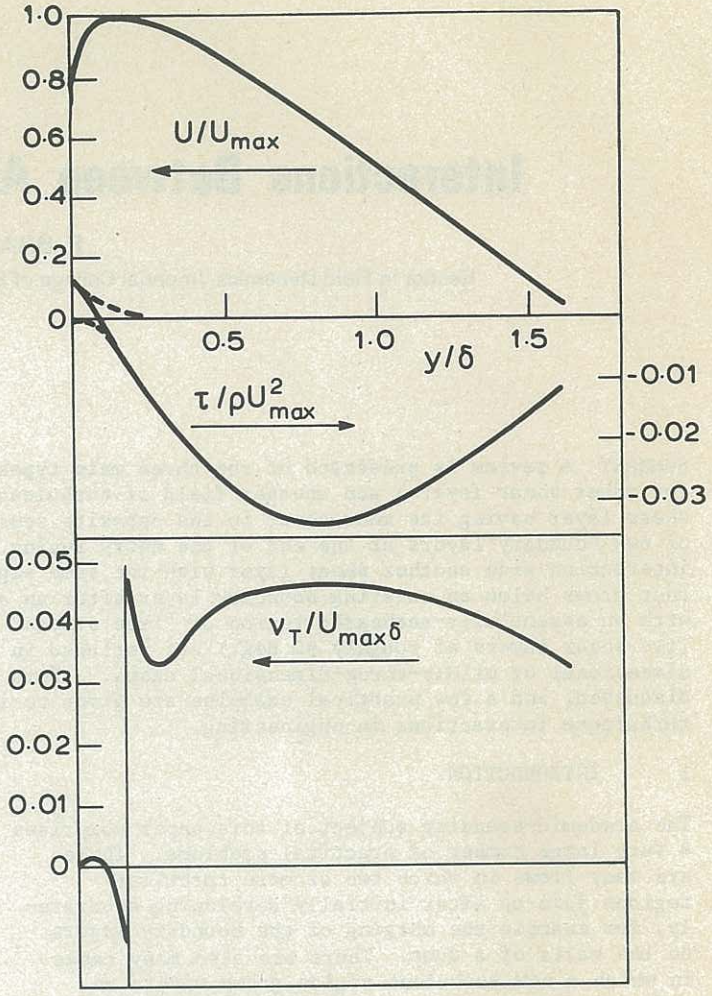

Figure 2 Profiles of velocity U, shear stress τ and eddy viscosity $\nu_T \equiv \tau/(\rho\partial U/\partial y)$ in wall jet in still air

sharing the same mean velocity profile. If the two shear-stress profiles could be distinguished they would look like the dotted curves in Figure 2, and there is clearly no reason why the net shear stress should be zero exactly at the point of zero velocity gradient.

In a symmetrical interaction between two boundary layers, in the entrance region of a two-dimensional duct, say, the net shear stress and velocity gradient both pass linearly through zero on the centre line, and the eddy viscosity is well behaved although the instantaneous eddy processes are no simpler qualitatively than in the asymmetrical case. If the turbulent intensity or shear-stress profiles of the two overlapping boundary layers could be distinguished they would look like the dotted curves in Figure 3. In fact they can be distinguished and Figure 3 shows experimental results presented by Dean (1974) at the 4th Conference in this series and published in full by Dean and Bradshaw (1976). The technique used was "temperature-conditioned sampling". One boundary layer was heated near its origin so that fluid which entered that boundary layer acquired enthalpy at the same time as vorticity: the concept is the same as in flow visualization of a smoke-filled boundary layer. By adding a temperature sensor (resistance-thermometer wire) to the hot-wire probe and digitally analysing the signals, the "hot zone" contributions to the turbulence statistics can be distinguished from the "cold-zone" contributions. Just as the users of a time-sharing computer get the impression that their programs are being run

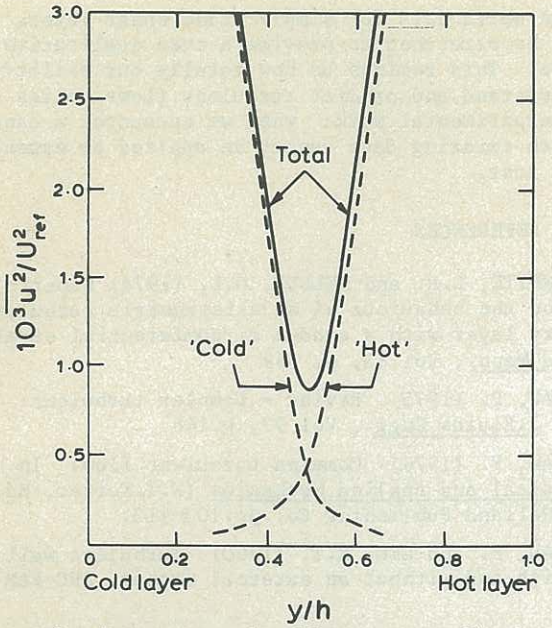

Figure 3 Hot-zone and cold-zone contributions to total mean-square longitudinal-component intensity in a high-aspect-ratio duct with one boundary layer heated at entry. Measurements at 38.7 duct heights from entry. Hot and cold $-\overline{uv}$ would be antisymmetric

simultaneously, so the time-averages in Figure 3 give the qualitative impression of superposition. Bradshaw, Dean and McEligot (1973) obtained good predictions of fully-developed duct flow by using the superposition principle quantitatively with a boundary layer calculation method whose empirical data were unaltered. Dean's experimental work confirmed that the turbulence structure parameters (broadly equivalent to the empirical constants or functions used in calculation methods) were virtually unaltered by the interaction.

In the interaction region of a wall jet (Figure 1(a)) or a free jet formed from the merging of two mixing layers the turbulence intensity is higher than in a duct and there are some changes in turbulence structure so that the empirical content of calculation methods for isolated shear layers may have to be made dependent on a suitable interaction parameter. Weir and Bradshaw (1977) presented preliminary results of an experiment on two merging mixing layers in a two-dimensional jet, as a belated justification of the ad hoc adjustments of empirical content made by Morel and Torda (1973). The main reason for the structural changes is crudely speaking - that high-intensity large-eddy eruptions across a centre line are less likely to attain peaceful co-existence than the weaker eddies in, say, a duct flow. The ultimate in large-eddy incompatibility is reached when the centre line is replaced by a solid surface. The boundary condition of zero normal velocity is equivalent to the presence of an instantaneously-identical image shear layers whose large eddies collide head-on with those of the real mixing layer. Measurements by Chandrsuda (1976) in the reattaching mixing layer behind a step, by Castro and Bradshaw (1976) at the downstream end of a rig which fortuitously approximated the entry region of a wall jet, and by D.H.Wood (unpublished work at Imperial College) in a purpose-built wall-jet-like rig, all show large changes in large-eddy statistics, even before the turbulent region has reached the solid surface.

The interaction of two boundary layers in the near-wake of an aerofoil is a rather different case from the above. Here the change in (removal of) constraint by a solid surface again alters the pressure fluctuations, but the eddies that interact directly are very small (relative to the shear-layer thickness) since they are the former occupants of the inner layers of the two boundary layers. The concept of large-eddy time-sharing is therefore not very useful. Measurements using temperature-conditioned sampling in a flat-plate wake by J.Andreopoulos show that the probability that the fluid on the centre line is "cold" is only 0.1, rather than the probability of 0.5 to be expected if the hot/cold interface remained sharp instead of being smeared into a "warm" region by fine-grained mixing.

Flows in streamwise corners are the commonest example of a strongly three-dimensional interaction between two-dimensional or mildly-three-dimensional shear layers. The two types of corner flow must be clearly distinguished. In the first type, found in wing-body or blade-annulus junctions, skew-induced secondary flow results in the formation of a "horse-shoe" vortex round the leading edge with one leg of the vortex trailing downstream on each side of the wing, blade or other obstacle. This kind of secondary flow can occur in laminar or turbulent shear layers: in either case it decays very slowly. In the second type of corner flow, found only in turbulent flow and mainly in long, straight polygonal ducts, turbulent stress gradients in the cross-sectional plane generate secondary flow in the form of a pair of contra-rotating vortices in each corner. For a more detailed review see Cebeci and Bradshaw (1977). Measurements in a simplified wing-body junction by I.M.Shabaka show large regions of negative eddy viscosity and suggest that even the decay of skew-induced secondary flow may be a severe test for any calculation method.

3 INTERNAL LAYERS

The commonest example of interaction between two shear layers with the same sign of shear is the internal boundary layer formed downstream of a change in surface roughness or transpiration rate and growing into an existing boundary layer. A large proportion of our current knowledge of change of roughness flows comes from work by Australian engineers and meteorologists. Except in the region near a roughness discontinuity where the internal layer is not much thicker than the roughness elements and therefore depends on their detailed geometry, changes in turbulence structure seem to be small. An indirect but satisfying demonstration of this is the finding by Wood (1977) that a simple boundary layer transport-equation calculation method (Bradshaw and Unsworth 1976) sufficed to predict the effect of large roughness changes (roughness-length ratios up to 100-200 in either direction) without altering the empirical closure approximations for the method.

Another type of internal boundary layer is formed by relative motion of two surfaces. Examples where the relative motion is in the stream direction are rare, but relative transverse motion occurs between the hub surfaces in the rotor rows and stator rows of axial turbomachines and the resulting internal layer is of course three-dimensional. Experiments on a single fixed-to-rotating discontinuity have been reported by Bissonnette and Mellor (1974) and Lohmann (1976).

4 FREE-STREAM TURBULENCE

Many shear layers in engineering situations develop in external streams which are turbulent but not significantly sheared, perhaps because the turbulence results from the interaction and mixing of many shear layers. Examples include axial turbomachine blade boundary layers whose external stream consists of the well-mixed but still turbulent wakes of many

blades (Walker 1974), and the favourite laboratory experiment of a boundary layer in the nearly-isotropic turbulent stream generated by a grid for upstream. In the latter case, the skin friction and growth rate increase by 2 to 4 percent for one percent rms free-stream turbulence. Even the response of a simple, constant-pressure boundary layer to grid-generated isotropic turbulence is neither well understood nor even well documented. Recent analyses of existing data, and some new measurements, by P.E. Hancock show that the ratio of the free-stream turbulence length scale to the boundary layer thickness significantly effects the response to free-stream turbulence. Previous measurements covered only a rather small range of this parameter; it can be shown that requiring a high turbulence level and a reasonably high boundary-layer Reynolds number severely restricts the available range of length-scale ratios in typical low-speed tunnels. However a combined plot of previous data and our new results explains some of the scatter in correlations based on turbulence intensity alone and shows that for a given turbulence intensity the skin friction and growth rate increase as the length scale decreases. The smallest length scale attainable is of the same order as the turbulence length scale of the boundary layer itself. Most certainly the effect of free-stream turbulence of given intensity would eventually decrease if the scale could be further reduced because eddies of the same order of size as those in the boundary layer are likely to have the greatest effect on the latter. However this last point is academic because small-scale turbulence in an unsheared stream will almost always decay too rapidly to be a problem.

The effect of free-stream turbulence on heat transfer has been claimed, by several experiments, to be small. Simonich (1976) performed an experiment on an electrically-heated flat plate constructed so that the heat transfer from the top surface should be (a) spatially uniform (b) half the total heat input. The results showed that heat transfer did increase in the presence of free stream turbulence, in fact by rather more than the surface shear stress although we would not claim the latter as a general result.

5 CONCLUSIONS

Of the three problems in turbulence-turbulence interactions discussed above, the change-of-roughness type of internal layer seems to be in a fairly satisfactory state, the effect of nearly-isotropic free-stream turbulence on boundary layers - at least - is becoming clearer, while the simpler forms of interaction between opposed shear layers are understood conceptually even if the number of well-documented cases is still too small. The practising engineer who demands numbers may sometimes be disappointed (by their absence or by their inaccuracy) but a qualitative understanding is often of almost equal value to the engineer and is an essential prerequisite for the assessment and use of limited quantitative data in the development of calculation methods.

The one type of problem discussed where fundamental understanding seems to be lacking is the streamwise corner flow together with other forms of shear layers with discrete longitudinal vortices imbedded in them. It is significant that this is the only case in which data for simple plane shear layers cannot be stretched to provide a even qualitative picture. This reminds us how totally our ability to understand and predict turbulent flows relies on basic experimental work: when we encounter a case to which existing data cannot be applied or extended we are lost.

6 REFERENCES

BISSONNETTE, L.R. and MELLOR, G.L. (1974) Experiments on the behaviour of an axisymmetric turbulent boundary layer with a sudden circumferential strain. J.Fluid Mech., Vol 63, p. 369

BRADSHAW, P. (1975) Review - Complex turbulent flows. J.Fluids Engg., Vol 97, p.146

BRADSHAW, P. (1976) Complex turbulent flow. In Theoretical and Applied Mechanics (W.T.Koiter, Ed.) North-Holland Publishing Co. pp.103-113.

BRADSHAW, P. and GEE, M.T. (1960) Turbulent wall jets with and without an external stream. ARC R&M 3252.

BRADSHAW, P. and UNSWORTH, K. (1976) Computation of complex turbulent flows. In Reviews in Viscous Flows, Lockhead-Georgia Co. LG 77 ER 0044.

BRADSHAW, P., DEAN, R.B. and McELIGOT, D.M. (1973) Calculation of interacting turbulent shear layers. Duct flow. J. Fluids Engg., Vol.95, p.214.

CASTRO, I.P. and BRADSHAW, P. (1976). The turbulence structure of a highly-curved mixing layer. J.Fluid Mech. Vol.73, p.265.

CEBECI, T. and BRADSHAW, P. (1977) Momentum Transfer in Boundary Layers. McGraw-Hill/Hemisphere.

CHANDRSUDA, C. (1976) The reattachment and relaxation of a turbulent shear layer. Ph.D Thesis Imperial College, London.

DEAN, R.B. (1974) The application of a conditional sampling technique to the understanding of turbulent interacting shear layers in duct flow. Proceedings, 5th Australasian Conf. on Hydraulics and Fluid Mech. Canterbury, N.Z.

DEAN, R.B. and BRADSHAW, P. (1976) Measurements of interacting turbulent shear layers in a duct. J. Fluid Mech. Vol.78, pp. 641-676.

LOHMANN, R.P. (1976) The response of a developed turbulent boundary layer to local transverse surface motion. J. Fluids Engg. Vol. 98, p.354.

MOREL, T. and TORDA, T.P. (1974) Calculation of free turbulent mixing by the interaction approach. AIAA J., Vol.12, p.533.

SIMONICH, J.C. (1976) Heat transfer from a turbulent boundary layer in zero pressure gradient. M.Sc project report, Imperial College, London (submitted to J. Heat Transf.)

WALKER, G.J. (1974) The unsteady nature of boundary layer transition on an axial flow compressor blade. ASME paper 74-GT-135.

WEIR, A.D. and BRADSHAW, P. (1977) The interaction of two parallel free shear layers. Proceedings, Symposium on Turbulent Shear Flow, Penn.State University.

WOOD, D.H. (1977) Calculation of the Neutral Wind Profile following a large Step Change in Surface Roughness. Submitted to Quart.J.Roy.Met. Soc.