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The effect of boundary layer fluctuations on the streamwise vortex structure in simulated plane turbulent mixing layers

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A R T I C L E I N F O

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A B S T R A C T

This paper details the influence of the magnitude of imposed inflow fluctuations on Large Eddy Simulations of a spatially developing turbulent mixing layer originating from laminar boundary layers. The fluctuations are physically-correlated, and produced by an inflow generation technique. The imposed high-speed side boundary layer fluctuation magnitude is varied from a low-level, up to a magnitude sufficiently high that the boundary layer can be considered, in a mean sense, as nominally laminar. Cross-plane flow visualisation shows that each simulation contains streamwise vortices in the laminar and turbulent regions of the mixing layer. Statistical analysis of the secondary shear stress reveals that mixing layers originating from boundary layers with low-level fluctuations contain a spatially stationary streamwise structure. Increasing the high-speed side boundary layer fluctuation magnitude leads to a weakening of this stationary streamwise structure, or its removal from the flow entirely. The mixing layer growth rate reduces with increasing initial fluctuation level. These findings are discussed in terms of the available experimental data on mixing layers, and recommendations for both future experimental and numerical research into the mixing layer are made.

1. Introduction

The use of numerical simulation techniques such as Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) to compute turbulent flows is becoming more widespread thanks to ever increasing computing power. Extremely well-resolved simulations of turbulent flows to reasonably high Reynolds numbers are now attainable. For the spatially-developing mixing layer flow, it is expected that these simulation methods will assist in solving the outstanding problems that persist in the field, in spite of seventy years of extensive research. Over this period of time, the mixing layer that forms between two merging parallel streams of fluid has proven to be a remarkably challenging flow configuration. A large spread in the growth rates of mixing layers has been reported, as reviewed by Yoder et al. (2015). Explanations for the discrepancies in observed growth rates include the laminar or turbulent state of the separating high-speed side boundary layer (Batt, 1975; Slessor et al., 1998), and even whether the measured flows could be considered as truly fully-developed (D'Ovidio and Coats, 2013). Regardless of the root cause, the above investigations show that the mixing layer displays a hypersensitivity to its initial conditions, and their effects persist to Reynolds numbers (based on the mixing layer visual thickness and velocity difference across it) that are in excess of those found in flows of practical engineering interest.

The presence of organised structures in the plane turbulent mixing layer has been acknowledged for over forty years. Large-scale, spanwise-orientated structures were observed in contemporary studies of the low Reynolds number flow (Winant and Browand, 1974), and its high Reynolds number counterpart (Brown and Roshko, 1974). Since their discovery, these large-scale coherent structures have been the subject of intensive study, both experimentally (Konrad, 1976; Hernan and Jimenez, 1982; Jimenez et al., 1985; Bernal and Roshko, 1986), and computationally (Moser and Rogers, 1991; 1993; Rogers and Moser, 1992; 1994; Balaras et al., 2001; Wang et al., 2007; Attili and Bisetti, 2012; McMullan et al., 2009; 2015). Growth and entrainment models of the mixing layer have been developed from these observations (McMullan et al., 2015; Dimotakis, 1986), but doubt remains as to whether such structures are ubiquitous for non-idealised initial conditions (Chandrsuda et al., 1978).

In addition to the spanwise structure a secondary, streamwise-orientated vortex structure has been observed in the mixing layer. Discovered through flow visualisation as 'streaks' (Konrad, 1976), subsequent experiments revealed that the streaks are manifestations of a statistically-stationary streamwise vortex structure (Bernal and Roshko, 1986). First postulated as an unstable response of the layer to three-dimensional perturbations in the flow up-

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stream of the mixing layer (Lasheras et al., 1986), it was later shown that the formation of streamwise vortices is linked to residual streamwise vortices in the upstream separating high-speed side boundary layer (Bell and Mehta, 1992). The evolution of these streamwise vortices does appear to be somewhat facility dependent. It has been observed that changes in the flow smoothing screens upstream of the mixing layer can affect the spanwise locations of the streamwise vortices (Bernal and Roshko, 1986), and that small surface imperfections in the splitter plate can provide anchor points for them (Jimenez, 1983). Further experiments have shown that small changes in the initial conditions caused by switching the freestreams between legs in a wind tunnel can produce measurable differences in the streamwise vortex properties (Plesniak et al., 1993). In some experiments the streamwise structure spacing changed in a stepwise fashion, in conjunction with the interactions that occurred between the primary spanwise structures (Konrad, 1976; Jimenez, 1983; Huang and Ho, 1990). Other experiments, however, have shown no evidence of changes in streamwise structure spacing with increasing streamwise distance (Lasheras et al., 1986; Breidenthal, 1978). It is not clear if a spatially stationary streamwise structure is ubiquitous for all initial conditions, as a two-stream mixing layer that originated from a turbulent high-speed side boundary layer did not contain a spatially stationary streamwise structure (Bell and Mehta, 1990).

Eddy-resolving simulations of spatially-developing mixing layers should be able to capture the features described above. There are some examples of DNS studies in the literature (Wang et al., 2007; Attili and Bisetti, 2012), with reasonably high Reynolds numbers attained. Large Eddy Simulation is an attractive numerical method for the simulation of mixing layers, as the large-scale structures which dictate the flow evolution are explicitly resolved by LES. Published research into the use of LES for mixing layer simulations has largely focused on idealised flows, rather than direct comparisons with reference experimental data (Wang et al., 2007; Attili and Bisetti, 2012; Comte et al., 1998). In these studies the flow originates from what can be considered as idealised inflow conditions (in this paper the terms ‘initial conditions’ and ‘inflow conditions’ are used interchangably), where a base mean velocity profile is perturbed through a white noise disturbance field. Where simulations with this type of inflow condition have been performed against a reference experiment, reasonable agreement with the mean flow statistics has been obtained (McMullan et al., 2009; 2015). The continuous linear growth mechanism, reported in experiments (D’Ovidio and Coats, 2013), has also been captured in numerical simulation (McMullan et al., 2015). In spatially developing mixing layer simulations originating from a white-noise disturbance environment, evidence for a spatially developing streamwise structure is lacking (Comte et al., 1998; McMullan and Garrett, 2016b).

Numerical white noise is, of course, not a physically realistic representation of the fluctuations found in real flows. In order to produce inflow fluctuations that are both spatially- and temporally-correlated, an inflow generation technique must be used. Application of an inflow generation method to produce physically-correlated, low-level fluctuations in the upstream laminar boundary layers of a mixing layer simulation has resulted in a mixing layer that contained a spatially stationary streamwise vortex structure (McMullan and Garrett, 2016b). The statistical properties of this streamwise structure compared extremely well with experimental data (McMullan and Garrett, 2016a). The streamwise structure originated from residual streamwise vorticity contained in the upstream boundary layer, and the structure evolved in a stepwise fashion with downstream distance in the mixing layer. The growth rate of the mixing layer originating from these physically correlated initial conditions was also observed to increase by 15% when compared to a simulation originating from a white noise fluctuation environment of the same disturbance magnitude; the physically correlated simulation producing better agreement with reference data.

In order to produce an accurate numerical simulation of any mixing layer experiment, detailed information on the initial conditions of the flow is essential. This includes the mean streamwise velocity profile of each boundary layer, and the associated velocity fluctuations for all three velocity components. This complete set of mixing layer initial conditions has not been recorded for any experimental study available in the literature. Where boundary layer velocity fluctuation data has been recorded, only the streamwise component has been reported (Browand and Latigo, 1979; Pickett and Ghandhi, 2002). All reported simulations of plane mixing layers are therefore a representation of the real conditions, and it is not clear how the magnitude of the imposed fluctuations influences the development of the mixing layer. The simulation studies of McMullan and Garrett (2016a) have shown that low-level, physically-correlated boundary layer fluctuations produced a spatially stationary streamwise structure. That study, however, only considered one particular set of boundary layer fluctuation profiles; the connection between the magnitude of the fluctuations in the upstream separating boundary layers, and the formation and evolution of the streamwise vortices, has not been fully established.

The aim of this study is to quantify the effects of the magnitude of the upstream boundary layer fluctuations on the streamwise structure in simulations of the spatially developing mixing layer. The initially-laminar experiments of Browand and Latigo (1979) provide the reference data for this study. An inflow generation technique is used to provide these physically-correlated inflow conditions. Three distinct simulations are performed, where the fluctuations in the high-speed boundary layer are successively increased. These simulations represent a range of initial fluctuations from being ‘clean’ (or two-dimensional in the mean), up to where the initial conditions are, in a statistical sense, highly three-dimensional (or nominally laminar). To maintain consistency all three simulations do, however, originate from the same mean inflow velocity profiles. The effects of the initial conditions on the simulated mixing layers will be assessed through mean flow statistics, flow visualisation, and cross-plane samples of the flow field at several streamwise locations. Section 2 provides a brief description of the research code. A brief summary of the reference experiment, and the simulation set up are described in Section 3. The results obtained from the simulations are presented in Section 4. A discussion of the results and their significance is provided in Section 5, and concluding remarks are drawn in Section 6.

2. Numerical methods

A brief description of the research code is provided here; a more complete description can be found in a previous study (McMullan et al., 2009). The code solves the spatially-filtered equations for conservation of mass and momentum for a uniform density flow. A finite volume method is employed, with the primitive variables discretised using a staggered cell approach. The momentum equation is solved using a second-order, central differencing method. Time advancement is performed by the second-order accurate Adams–Bashforth method. The pressure equation is solved by a multi-grid method which ameliorates the convergence of the equation solution. The outflow condition is the commonly-used standard convective outflow condition (Voke and Potamitis, 1994). The unresolved scales of motion are modelled using the WALE model (Nicoud and Ducros, 1999). A previous study has shown that this choice of subgrid-scale model is advantageous over the standard Smagorinsky, owing to the fact that the WALE model predicts