The effects of stabilizing and destabilizing longitudinal curvature on the structure of turbulent, two-stream mixing layers

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1. Introduction

1.1 Background

The topic of the research program is mixing and turbulence transport in parallel, co-flowing, two-stream shear or mixing layers. In particular the effects of streamwise (longitudinal) curvature on the growth and development of the shear layer were investigated. The preliminary results of the present research program are reported in Plesniak and Johnston (1987), where results are presented for stable and unstable (in the Taylor-Görtler (T-G) sense) mildly curved two-stream mixing layers. These results are compared to a plane mixing layer studied in the same facility under nearly identical initial and boundary conditions. At typical operating conditions, a nominal speed ratio of 0.5 with flow speeds of 12 and 24 cm/s was employed. The ratio of the shear layer thickness to the radius of curvature is less than 5%. Reynolds numbers based on ΔU and momentum thickness ranged from 1000 to 2000 (5000 to 10000 based on vorticity thickness) over the region in which measurements were made. Laminar flow exists at the splitter plate trailing edge due to the low operating velocities. The average momentum thickness Reynolds number in the trailing edge boundary layers is estimated to be 190, too low for a trip to be effective. The mixing layer was not artificially forced and often exhibited more than one frequency of roll up. Dye flow visualization along with single component LDV results are presented for all three cases.

Flow visualization indicated that for stabilizing curvature vortex mergings (pairings and triple interactions) are common, but there is little mixing of the dye across the layer and fine-scale three-dimensionality does not occur in the region studied. Conversely, destabilizing curvature promotes mixing at all scales and the layer is characterized by complex three-dimensional structures. Vortex interactions are also less prevalent for the unstable case than for the stable or plane layers.

The LDV measurements showed that the unstable layer exhibits a greater growth than the plane or the stable layer of nearly the same velocity ratio (growth rate was determined from the maximum slope thickness). The mean (U) and fluctuating (u') streamwise velocity profiles exhibited self-similarity for all three cases studied. However the fluctuating normal (v') profiles were not self-similar for either the stable or unstable layer. Peak fluctuation levels in both components were greatest for the unstable layer.

1.2 Current Research

The main goal of the research program is to gain a fundamental understanding of the physics of curved, turbulent, unforced free mixing layers and to provide a data base for turbulence modelers. Since the facility was previously instrumented only with a one-component LDV system, the major objective was to construct a two-component LDV system to allow the measurement of Reynolds stresses and examine turbulence transport in the mixing layers.

2. Approach

2.1 Documentation of Initial Conditions

It is well known that the scatter in data from various sources regarding free shear layers is large. This is due to the mixing layer's extreme sensitivity to initial conditions. A number of studies have been undertaken to examine the effects of initial conditions and side-wall confinement effects on the growth of free shear layers. These studies attempted to resolve the discrepancies in the literature concerning spreading rates and other characteristics of mixing layers. However conflicts regarding the effects of laminar vs. turbulent boundary layers at separation, initial fluctuation level, initial momentum thickness and influence of splitter-plate trailing-edge thickness on the streamwise evolution of the shear layer still exist. Some groups report confinement effects of boundaries while others do not.

In view of many unresolved issues concerning initial and boundary condition effects it is considered important to document the initial conditions of the present study. The two-component LDV system described below is being used to investigate the boundary layers on the high and low speed sides of the splitter plate. Determination of the momentum thicknesses will allow us to predict the most unstable frequency and compare to the results in Ho and Huerre (1984). The levels of free stream turbulence in the nozzle will also be measured with this system.

Another issue which has recently been addressed in the literature is spanwise nonuniformity in the mixing layer and the formation of small-scale streamwise vortical structures due to natural disturbances. Jimenez (1983), Lasheras et al (1986, 1988), Bernal and Roshko (1986), Mehta; Ho (private communications), and others have reported on the presence of these structures in plane mixing layers. They are easily detectable in spanwise variations of the mean streamwise (U) velocity profiles. Since these structures have never been studied in curved mixing layers, it is unknown whether there is any interaction with the T-G structures resulting in their suppression or enhancement.

2.2 Flow Visualization Studies

Previous results obtained with vegetable dye visualization were able to show diffusion of the dye across the layer and also the entrainment of ambient fluid into the layer. VHS format videotape movies showed large-scale structures which transported dye across to opposite sides of the shear layer in the case of destabilizing curvature. However the dye visualization technique had several limitations: the major being the rapid diffusion of dye in the fully turbulent regimes restricting the operating velocities lower than those used in acquiring the quantitative data.

Thus, for the present study a hydrogen bubble technique with portable laser sheet illumination was employed. The wire may be positioned at any location in the mixing layer along the entire length of the test section. Using existing equipment, timelines can be generated by pulsing the wire. This technique will enable us to visualize the transport of turbulence (and of mass if the Schmidt number of the bubbles is low enough) by the structures of various scales. In particular, the large scale motions associated with the T-G rollers in the unstable layer can be studied. A suitable lighting source is currently being sought to illuminate a 2-D grid of hydrogen bubble wire used to visualize an entire plane across the mixing layer.

2.3 Velocity Data

After unexpected delays in delivery of the necessary components the two/three-component LDV system has been constructed, optically aligned and calibrated. Preliminary two-component velocity profiles have been obtained for the stable and unstable layers. However, these data suffer convergence problems in the mixed (uv) moments due to insufficient numbers of samples. More complete data being presently acquired correct this problem. In addition the third component capability (w measured with an immersible fiber optics probe) has recently been added to the system so that the entire 3-D velocity field may simultaneously be acquired and the full Reynolds stress tensor computed.

2.3.1 Description of the 2-Component LDV

A three-color, two-component LDV system powered by a 3-Watt Argon-ion Lexel laser was constructed for turbulence studies in the curved mixing layers. The system employs frequency shifting on both channels and is configured to operate in the backscatter mode. The entire system is mounted on an optical breadboard which may be traversed in a rectilinear X-Y global coordinate system.

An aluminum traversing cart made of 2×4 inch square tubing (1/8 inch wall thickness) chosen for its light weight and stiffness was constructed to traverse the optical system. The traverse rides on pillow block linear bearings over a 1 inch diameter ground stainless steel shaft. Positioning in the global streamwise direction (X) is performed manually over a travel of 12 feet (3.66 m). The direction normal to this (Y) has a travel of 4 feet (1.22 m). Thus, any point across the entire outer channel may be accessed.

In order to traverse along a radial line in the inner curved test section, programmable computer controlled stepper motors are used. The stepper motors are driven by Superior 430-TH translator modules operating in a chopped mode. An Anaheim Automation CL1605 programmable controller board is used to control the translator modules. Parameters such as motor speed, acceleration, and limit switch condition are controlled by the board. A serial RS-232 interface is used to communicate to the CL1605 with the data acquisition computer system.

A ball nut/screw assembly with a lead of 0.250 in (6.35 mm) is used for positioning in the Y direction while a lead screw unislide assembly with a lead of 0.100 in (2.54 mm) is employed for fine positioning over 10 inches (0.254 m) of travel in the global X direction. The stepper motors are driven in a half-step mode which produces a resolution of 400 steps/revolution. This allows a positioning resolution of 0.00025 in/step (0.00635 mm/step) in the X direction and 0.000625 in/step (0.015875 mm/step) in the Y direction. Backlash in X was measured to be 0.001 in (0.0254 mm) and in Y, 0.003 in (0.0762 mm).

A radial move in the local x-y coordinate system of the curved shear layer consists of two moves in the global X-Y coordinate system. The angle between a radial line in the local coordinates and the global coordinate system is determined experimentally. Considering spatial resolution in X and Y, backlash and uncertainty in determining the angle, the resolution in positioning accuracy is less than half of the LDV measuring volume diameter (100 microns).

One limitation of this traversing system is that no automated spanwise traversing is possible due to design constraints resulting from lack of funding. However, the He-Ne based fiber optics probe traverse does have spanwise capability and can be used when such measurements are dictated.

2.3.2 Present LDV Measurements

The two-component LDV system described above is being used to make measurements in the curved mixing layer for three different configurations: straight (reference), stable and unstable with a velocity ratio of 2:1. Measurements of complete profiles (20 to 30 spatial points) at approximately 8 streamwise stations will allow accurate determination of the mean growth rate and evolution of the shear layers' turbulence fields. In conjunction with the fiber optics probe, three components of velocity (u, v, w) can be measured. Acquisition of all three velocity components simultaneously allows the entire Reynolds stress tensor to be computed and estimates of the turbulent energy budget can be made. Complete time records are saved at each position for post-processing. Mean and rms velocities, Reynolds stresses, higher order moments (skewness and kurtosis), and velocity probability density functions will be calculated.

Separate runs with much longer record lengths necessary to resolve the lowest frequencies will be made for spectral and autocorrelation data acquisition at several points in the mixing layer. Since we have two independent LDV systems (1-component probe and 2-component system), it will be possible to obtain two-point spatial correlations by positioning the probes at different points in the mixing layer. This kind of data may be particularly useful in tracking the large T-G rollers in the unstable layers.

3. Summary

A major portion of the period covered under CTR funding was spent on the construction and development of the multi-component traversing system and associated control hardware and software. Delays in delivery of necessary components delayed construction by several months. The system was first used to make measurements in October, 1988.

In addition to acquiring the two-component measurement capability, a hydrogen bubble/laser sheet flow visualization technique was developed to visually study the characteristics of the mixing layers. With this new technique we can look for evidence of the large-scale rollers arising from the Taylor-Görtler instability and study its interaction with the primary Kelvin-Helmholtz structures.

In general, the recently acquired data confirm the results reported in our preliminary paper (Plesniak and Johnston, 1987). At this stage we are making two and three-component measurements and will be able to report information regarding the transport of turbulence and full Reynolds stress data in several months.

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