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FINAL REPORT

NASA Grant NCC 2-294

EXPERIMENTAL STUDIES OF VORTEX FLOWS

Report covering the period March 1984 - May 1988

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(NASA-CR-182874) EXPERIMENTAL STUDIES OF VORTEX FLOWS Final Report, Mar. 1984 - May 1988 (Stanford Univ.) 8 p CSCL 20D

N88-23171

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G3/34 0142320

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June 1988

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Investigators: L. Roberts, R.D. Mehta and J.H. Bell

Summary

This final report describes the research work completed in the period of just over four years starting in March 1984 and funded by NASA Grant NCC-2-294 from the Fluid Dynamics Research Branch, NASA Ames Research Center. After a brief introduction of the main topics addressed by the completed research, the accomplishments are summarized in chronological order. Since most of the described work has been published in the open literature, individual results are not presented in this report.

Introduction

Vortex flows have always been an intrinsic part of practical aerodynamics. Over the years, the problems due to the slow decay of trailing vortices from aircraft wing-tips have received particular attention due to their direct importance to airport traffic control. In addition, the principle of boundary layer separation control by vortex generators has been known and used on aircraft wings since the 1940s. It involves the generation of discrete longitudinal vortices near the surface so that mixing between the higher momentum external stream and the boundary layer is increased. However, with higher demands on aircraft performance in recent years, attention has also been focused on the interaction between a single, relatively strong vortex and the wing boundary layer and wake. One situation of particular interest is when the longitudinal vortex interacts with a separated boundary layer. Such interactions are becoming increasingly important in advanced aircraft technology: highly maneuverable fighter aircraft utilize the vortex from a canard or strake to suppress or control boundary layer separation on the wing so that the necessary stability is sustained. Another example is in rotorcraft, where the blade goes through phases when the boundary layer is separated and this is then acted upon by the tip vortex shed from the blade ahead.

Vortices are also an important part of many fundamental types of shear flows, such as mixing layers. The important role played by turbulent mixing layers in practical aerodynamics is now well recognized. Mixing layers govern the rate of mixing in combustion chambers and flow reactors, and are also responsible for most of the broadband noise generated in propulsion systems. The structure of a plane mixing layer is dominated by the presence of quasi-two-dimensional vortical structures. The formation of these spanwise structures is primarily caused by the inviscid Kelvin-Helmholtz instability. However, recent studies have also indicated the presence of distinct streamwise streaks which in cross-sectional views turned out to be pairs of counter-rotating vortices. The origin and development of the streamwise vorticity has been investigated in some low Reynolds numbers water channel experiments. However, it is not clear if these structures exist in the same form, and if they do, what role they play in the development of fully turbulent mixing layers at higher Reynolds numbers, such as those more commonly encountered in practice. Also, there is a distinct lack of *quantitative* data on the detailed spanwise structure of plane mixing layers.

Despite the obvious importance of vortex interactions in practical aerodynamics, there is a definite lack of experimental information detailed enough to guide the development of calculation methods. It is essential to obtain detailed and accurate measurements in such complex interactions if our basic understanding is to be improved so that new turbulence models and hence calculation methods may be developed. At present, our understanding and predictive capability for such complex flows, where the turbulence is no longer in equilibrium, is very limited. The present research program was instigated to obtain detailed measurements of mean and turbulence properties in vortex/turbulent shear layer interactions.

Accomplishments in the First Year

The majority of the time in the first year of the grant was spent on the development of the hardware and software for a 3-component Laser Doppler Velocimeter (LDV). This system was developed for the measurement of the three components of velocity simulatneously, thus yielding all three components of mean velocity, all six components of the Reynolds stress tensor and higher order products.

The 3-D LDV system utilized the blue and green lines from an argon-ion laser. A four beam matrix was obtained using a standard TSI optical system. The green line was then split in half using a dichroic filter, thus giving a third set of beams which was directed over the top of the traversing mechanism and focused to intersect the main set of beams at an angle of about 45 degrees. Two velocities were hence measured directly, while the third channel contained a combination of the crossflow velocities. The scattered light was collected in the off-axis forward scatter mode using two collection lenses and three phtomultiplier tubes. Signal processing was accomplished with single-particle burst counters and the validated data was multiplexed through a NASA interface to a HP9845 computer. All the software for this system was developed in Basic and Assembley languauges and included on-line data reduction and graphics capabilities. The accuracy of the data obtained with this system was assessed by comparing the measurements with those given by a cross-wire system in a vortex/mixing layer interaction set-up in the Shear Layer Wind Tunnel. It was found that while the mean velocities and normal stresses were adequately measured with the 3-D LDV system, one of the shear stresses contained relatively large errors. The sources of the errors were identified and attempts were made to resolve them. The full description of the system, together with recommended operating procedures, were published in an internal report (Ref. 1) and the comparisons of the measurements were presented at the ICIASF meeting (Ref. 2).

A 2-D version of this system was used by Laura Rodman (Stanford University Graduate Student) for measurements in an axisymmetric wall jet. The instrumentation and supervision were provided for these experiments which were performed at NASA Ames. This work formed a part of Laura's Ph.D. Thesis.

Accomplishments in the Second Year

A detailed experimental study of forced plane mixing layers for conducted in the first part of this time period. A flap consisitng of an internal hinge and driven by a linear oscillator was used to excite the mixing layer at various frequencies. Flow visualization studies were conducted using the laser/smoke technique and included some real time video recordings. The results confirmed previous observations that the mixing layer growth rate and structure could be affected significantly by varying the forcing frequency (Ref. 3). Velocity measurements in forced and unforced mixing layers were also obtained using a 2-D LDV system. The results for the unforced case were compared to previously obtained cross-wire data and reasonable agreement was found. The cross-wire data were also used to validate some Reynolds averaged Navier Stokes computations performed by Dr. L.S. King. The computations were particularly successful at predicting the near-field evolution of the mixing layer which included the splitter plate wake effects. Quantitative results from a 2-D discrete vortex simulation performed by Dr. O. Inoue were also compared to the measurements. The simulations were in excellent agreement with the experimental data for the forced cases. A unique paper was prepared which compared the two experimental and the two computational techniques (Refs. 4 and 5).

An experimental study designed to investigate the main vortex and secondary flows produced by a double-branched vortex generator was conducted in the Unsteady Boundary Layer Wind Tunnel. Measurements were made on cross-plane grids at one streamwise location using a five-hole pressure probe. The most optimum configuration, consisting of end-plates and profiled extensions near the wing root, produced a single round primary vortex with higher circulation than typical delta-wing configurations (Refs. 6 and 7).

The effects due to vortex meander in a vortex/boundary layer interaction were investigated experimentally in the Boundary Layer Wind Tunnel (Ref. 8). Vortex meander was simulated by forcing a periodic lateral translation of the vortex generator at a very low frequency of 1 Hz and a half-amplitude of 0.5 cm. The effect of the forced meander was characterized by measurement of the apparent mean velocities and Reynolds stresses at two streamwise locations, for cases with and without forcing. The results showed that the effect of meander was to flatten the vorticity contours at a station where they were originally round. However, the Reynolds stresses, especially $\overline{u'w'}$, were also affected, mainly through contributions from the individual production terms. Further downstream, where the vortex had diffused substantially, the additional stresses were much smaller.

Accomplishments in the Third Year

A subsonic experimental study was conducted to examine the mean and turbulent properties of a single longitudinal vortex generated by a half-delta wing (Refs. 9 and 10). Measurements were made on fine cross-plane grids at seven streamwise locations using hot cross-wires. The evaluated streamwise vorticity contours indicated that the initially distorted vortex at a streamwise station equivalent to a half wing height became round by about three wing heights. In this initial "transition" region, where the vortex was still rolling-up, the peak vorticity dropped by about 50% following a $X^{-1/2}$ decay. In this region, the generator wake remained distinct from the region of maximum vorticity, although the two regions were seen to slowly merge together. The Reynolds stress contours were also distorted initially with the maximum values occuring in the generator wake region, rather than in the vortex core, but these also decayed rapidly. Downstream of the transition region, the vortex appeared to reach an equilibrium state with the regions of maximum vorticity and turbulent kinetic energy coincident and the levels approximately constant with increasing streamwise distance. Comparison with previous data on vortices produced by double-branched generators further confirmed that the present vortex had achieved a fully developed state, and in a relatively short streamwise distance.

As part of the overall design of a new mixing layer wind tunnel, an iterative design procedure was developed for two- or three-dimensional contractions installed on small, low-speed wind tunnels (Refs. 11, 12 and 13). The procedure consists of first computing the potential flow field and hence the pressure distributions along the walls of a contraction of given size and shape using a three-dimensional numerical panel method. The pressure or velocity distributions are then fed into two-dimensional boundary layer codes to predict the behavior of the boundary layers along the walls. For small, low-speed contractions it is shown that the assumption of a laminar boundary layer originating from stagnation conditions at the contraction entry and remaining laminar throughout passage through the "successful" designs is justified. This hypothesis was confirmed by comparing the predicted boundary layer data at the contraction exit with measured data in existing wind tunnels. The measured boundary layer momentum thicknesses at the exit of four existing contractions, two of which were 3-D, were found to lie within 10% of the predicted values, with the predicted values generally lower. From the contraction wall shapes investigated, the one based on a fifth-order polynomial was selected for installation on the mixing layer wind tunnel.

The detailed design of the mixing layer wind tunnel was completed in this time period and the blue prints were submitted to the contractors responsible for the tunnel construction. The Shear Layer Wind Tunnel was moved to the Fluid Mechanics Laboratory and the data acquisiton and reduction hardware was upgraded to run on a MicroVax II computer.

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Accomplishments in the Fourth Year

Two major tasks were completed in this time period. The vortex/mixing layer experiment was completed in the old shear layer facilty and the new mixing layer tunnel was assembled and calibrated.

An experiment was completed on the interaction of a single streamwise vortex embedded in a single-stream plane, turbulent mixing layer. The vortex was generated by placing a half-delta wing vortex generator on the floor of the tunnel settling chamber, downstream of the last screen. The single-stream mixing layer was generated at the top lip of the extended contraction section. Measurements were made on fine cross-plane grids at ten streamwise stations. All three components of mean velocity and the six components of the Reynolds stress tensor were measured using a hot cross-wire probe linked to a fully automated system driven by a Microvax II computer. The data show that initially the effect of the vortex is to induce strong three-dimensionality in the mixing layer which leads to the generation of significant secondary shear stresses. Further downstream, where the vortex has diffused, the secondary motions and stresses also tend to be diminished. The vortex had diffused completely by the end of the test section (X = 25 in) following a X^{-2} decay. Some preliminary results were presented at the APS meeting in November, 1987 (Ref. 14) and a more detailed paper will be presented at the First Fluid National Dynamics Congress in July, 1988 (Refs. 15 and 16).

Final construction and assembly of the new mixing layer wind tunnel was completed in this year and the data acquisition and reduction systems were adapted to the new tunnel. The flow quality in the new tunnel has been fully investigated and a report describing the results is in preparation (Ref. 17). Measurements of the velocities, spectra and flow angles were obtained with pitot probes and hot-wires. The measured turbulence level (u'/U_e) was about 0.15% with the mean flow uniform to within 0.5% and the crossflow angles less than 0.25 degrees. The splitter plate boundary layers were surveyed with a total pressure probe. Results indicate that the boundary layer remains laminar and two-dimensional on both sides of the splitter plate at velocities up to 15 m/s. The measured boundary layer properties agree to within 10% with predictions made using the new contraction layer design scheme.

An experimental study, designed to investigate the spanwise (3-D) structure of a two-stream plane mixing layer, is being conducted in the new mixing layer wind tunnel. The main objective was to investigate the presence of streamwise structures (in counter-rotating vortex pairs) in this relatively high Reynolds number mixing layer. If present, the origin, development and persistence of these structures was to be investigated. The mixing layer (velocity ratio = 0.6) originates from laminar boundary layers and measurements are made on fine cross-plane grids at several streamwise stations with a pitot tube and a single rotatable cross-wire probe. The results obtained so far indicate that the instability, leading to the formation of streamwise vortices, is triggered at random spanwise locations at some distance downstream of the splitter plate edge. Further downstream, the vortices re-align to form pairs of counter-rotating vortices. The vortices are found to grow in size, scaling with the mixing layer thickness, and the maximum vorticity diffuses with downstream distance. There is some evidence that the stuctures persist through to the self-similar region, although they are very weak and large scale by this point. The results from this first phase of the experiment are being written up in Ref. 18. In the next phase of the study, spanwise disturbances will be introduced at the splitter plate edge so that the structures have a definite origin to lock-onto.

To complement the experimental study, a 3-D discrete vortex filament simulation is being run on the Cray-XMP (Ref. 19). The program simulates a forced 3-D mixing layer using the Biot-Savart law. An initial spanwise disturbance is introduced in each vortex filament to induce the three-dimensionality. A 2-D forcing is also imposed on the filaments in an effort to control the mixing layer growth rate. Initial results show that the 2-D forcing has indeed increased the initial growth rate (as per design) and the 3-D stretching of the spanwise disturbance has also increased as a consequence.

References

(1) "A Three-Component Laser-Doppler Velocimeter Data Acquisition and Reduction System" by L.C. Rodman, J.H. Bell and R.D. Mehta. Dept. of Aeronautics and Astronautics, Stanford University, JIAA Report TR-63, 1985. Also, NASA-CR 177390, January 1986.

(2) "Aspects of the Design and Performance of a 3- Component LDV System" by J.H. Bell, L.C. Rodman and R.D. Mehta. Proceedings of the 11th ICIASF Congress on Instrumentation, Stanford University, California, Aug. 26-28 1985.

(3) "Perturbed Mixing Layers" by J.H. Bell and R.D. Mehta. Presented at the 38th APS Meeting and abstract published in the Bulletin of the American Physical Society, Vol. 30, No. 10, p. 1744, 1985.

(4) "Experimental and Computational Studies of Plane Mixing Layers" by R.D. Mehta, O. Inoue, L.S. King and J.H. Bell. Paper presented at the 10th Symposium on Turbulence, University of Missouri-Rolla, Sept. 22-24th 1986.

(5) "Comparison of Experimental and Computational Techniques for Plane Mixing Layers" by R.D. Mehta, O. Inoue, L.S. King and J.H. Bell. *Physics of Fluids*, Vol. 30, No. 7, pp. 2054-2062, July 1987.

(6) "Double-Branched Vortex Generator" by E.R. Cantwell, R.D. Mehta and R.V. Westphal. Presented at the 38th APS Meeting and abstract published in the Bulletin of the American Physical Society, Vol. 30, No. 10, p. 1758, 1985.

(7) "Double-Branched Vortex Generator" by E.R. Cantwell, R.D. Mehta and R.V. Westphal. NASA-TM 88201, November 1985.

(8) "Interaction of an Oscillating Vortex With a Turbulent Boundary Layer" by R.V. Westphal and R.D. Mehta. AIAA Paper 87-1246. Paper presented at the 19th AIAA Fluid Dynamics and Plasma Dynamics and Lasers Meeting, Honolulu, Hawaii, June 8-10th 1987. Submitted to *Experiments in Fluids*, April 1988.

(9) "Properties of a Half-Delta Wing Vortex" by E.R. Cantwell and R.D. Mehta. Presented at the 39th APS Meeting and abstract published in the Bulletin of the American Physical Society, Vol. 31, No. 11, 1986. Paper presented at the 6th Symposium on Turbulent Shear Flows, Toulouse, France, September 7-9th 1987.

(10) "Mean Flow and Turbulence Measurments In a Half-Delta Wing Vortex" by R.D. Mehta and E.R. Cantwell. *Fluid Dynamics Research*, in press, May 1988.

(11) "Contraction Aerodynamics" by J.H. Bell and R.D. Mehta. Presented at the 40th APS Meeting and abstract published in the Bulletin of the American Physical Society, Vol. 32, No. 12, 1987.

(12) "Contraction Design for Small Low-Speed Wind Tunnels" by J.H. Bell and R.D. Mehta. JIAA Report TR-64, Department of Aeronautics and Astronautics, Stanford University, April 1988. Also NASA CR, in publication.

(13) "Boundary Layer Predictions For Small Low-Speed Contractions" by J.H. Bell and R.D. Mehta. Accepted for publication in *AIAA J.*, May 1988.

(14) "Vortex/Mixing Layer Interaction" by R.D. Mehta and J.H. Bell. Presented at the 40th APS Meeting and abstract published in the Bulletin of the American Physical Society, Vol. 32, No. 12, 1987.

(15) "A Streamwise Vortex Embedded in a Plane Mixing Layer" R.D. Mehta and J.H. Bell. AIAA Paper 88-3607. Presented at the First Fluid Dynamics Congress, Cincinnati, Ohio, July 24-28, 1988.

(16) "A Single Longitudinal Vortex Interacting With a Plane Turbulent Mixing Layer" by J.H. Bell and R.D. Mehta. Journal Article in progress.

(17) "Design and Calibration of the Mixing Layer Wind Tunnel" by J.H. Bell and R.D. Mehta. JIAA Report and NASA CR in progress.

(18) "Three-dimensional Structure of a Plane Mixing Layer" by J.H. Bell and R.D. Mehta. Paper in progress.

(19) "3-D Vortex Simulation of a Forced Plane Mixing Layer" by J.H. Bell, O. Inoue and R.D. Mehta. Paper in progress.