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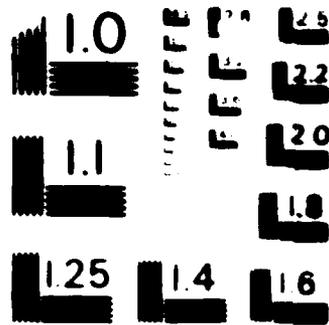
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Final Scientific Report

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by

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I INTRODUCTION

Over the past ten years, it has become increasingly apparent that vortex motions play an important and apparently dominant role in many of the flow fields of critical concern to aerodynamics and hydrodynamics. Turbulence and separation phenomena are two particular areas in which the role of vortex behavior has been recognized and is just beginning to be understood. As research on the flow structure of turbulence and separation phenomena has progressed, it has become increasingly clear that many of the complexities inherent in these flows are a consequence of three-dimensional vortex motions. Unfortunately, our intuitive grasp of the dynamics and intricacies of three-dimensional vortex dynamics is relatively primitive, which severely limits our ability to (1) properly interpret and understand the role and significance of vortices in complex flows, and (2) utilize this subsequent understanding in establishing a priori prediction techniques.

The above limitations arise from the methods and techniques required to study three-dimensional, time-dependent vortex flow structures. Since such flow structures develop in a Lagrangian sense, experimental approaches employing the use of single-point measurement techniques such as probes and LDV are of only limited utility. It is clear that our future success in experimentally understanding and interpreting the three-dimensional behavior of such phenomena lies in the appropriate use of computer imaging techniques for quantitative visualization approaches, most likely employing multi-view or stereoscopic viewing techniques. However, the extraction and synthesis of the massive amounts of data from the visualized flow field, whatever the mode of visualization, requires appropriate computer analysis of extensive frame sequences.

From a computational point of view, it is also clear that to understand the complexities of the motion and deformation of three-dimensional flow structures, such as vortex loops, requires not only the numerical calculation and static presentation of the data, but presentation in a manner which will clearly reveal the dynamics of the actual behavior, i.e. animation of the computed results in multi-perspective or quasi three-dimensional views. In regard to the melding of analytical and numerical predictions with experimental imaging results, methods and techniques are necessitated which allow for efficient three-dimensional cross-correlation of analysis with experiment. In line with this, methods are needed which allow three-dimensional pattern recognition searches within the imaged experimental flow field using the analytically developed flow structure results as the signature pattern. These latter

methods are felt to be particularly necessary in attempting to rationally detect and identify coherent, three-dimensional vortex structures within visualized turbulent flow fields.

To properly develop the above techniques requires (1) substantial dedicated computational data storage with immediate accessibility to the host computer, and (2) the capability for rapid image processing, enhancement, and evaluation. The instrumentation purchased under the present DOD grant has allowed, and will continue to allow, the development of techniques to address a number of key areas of three-dimensional vortex dynamics. The following sections describe the equipment acquired under the grant and the utilization of the equipment for enhancement of present and future research on three-dimensional vortex behavior, and its applicability for understanding and modeling turbulence processes.

II. EQUIPMENT PURCHASED AND INCORPORATION

The combined funds from the DOD Equipment Grant (\$90,300) and the Lehigh University matching funding (\$15,000) were utilized to purchase the following equipment.

- 1 Two DEC Model RA81-AA, 456 MB Disk Drives
- 2 A Gould Model 8500 Digitizing and Image Processing System
- 3 A Video Logic video format converter
- 4 A Gould Microverter Interface Board for a DEC MicroVAX II

Descriptions of the function of each of these equipment items and their incorporation within the overall experimental/numerical system are presented in the following sections.

A. Disk Drives

The two RA81-AA disk drives have been incorporated into an integrated computational system located in the Lehigh University Computer-Aided Design (CAD) Laboratory. One disk is dedicated to a DEC MicroVAX II computer purchased under an ongoing AFOSR contract. This disk is used primarily for mass data storage for the experimental image processing work. The second disk is dedicated as a private mass storage device for the numerical work which is done on a DEC 8300 computer (operated by the CAD laboratory and partially purchased with other AFOSR funds). The Disks now act as the sole data storage devices for our ongoing

AFOSR-supported research on turbulent boundary layers and three-dimensional vortex interactions. Note that an Ethernet link-up between the DEC MicroVAX and the DEC 8300 computers facilitates rapid access of data from either disk.

B. Digitizing and Image Processing System

The Gould system is comprised of hardware for (1) rapid digitization of images from standard video input, and (2) subsequent manipulation and display of the images for scene enhancement and/or quantification. The digitizer is employed for digitization of selected, pre-recorded scenes (from the high-speed video system utilized in our experimental work) to the image processor. The image manipulation capabilities of the image processor are employed to extract quantitative characteristics from the digitized scenes, such as time-of-flight velocity profiles, boundary shapes, etc. In addition, the image manipulation capability can be employed to create "images" from either experimental or numerical/analytical data sets, which allows rapid visual examination and detection of the "structure" and patterns within the data sets.

C. Video Format Converter

The Video Logic video format converter is used to convert the non-standard format video of our high-speed video system to conventional RS 170 video format. This allows the images to be digitized by the standard format digitizer employed by the Gould image processing system. In addition, the converter allows the documentation of selected research scenes to be stored in standard video format such that they can be sent to other researchers and presented at technical conferences.

D. Interface Board for DEC MicroVAX II

This plug-in board for the Gould image processor allows communication between the image processor and the DEC MicroVAX II. The MicroVAX, purchased under funds from an AFOSR contract, functions as the support computer for the image processing work, and as the interface computer between the numerical work performed on the DEC 8300 and the image processing system.

III. IMPROVED CAPABILITIES

A. Experimental Program

The enhancements to our experimental program which the purchased equipment provide us fall basically in four categories: 1) scene enhancements, 2) three-dimensional flow reconstruction, 3) velocity data extraction, and 4) pattern recognition techniques. Each of these enhanced capabilities provided by the requested instrumentation is discussed in the remainder of this section.

1) Scene Enhancement. The image processor provides greatly increased scene digitization rates and rapid hardware enhancement of the initial data, which allows single-scene edge analysis, background subtraction, multiple scene averaging, multi-scene differencing, and pseudo-color display. These capabilities allow deletion of extraneous scene information, extraction of significant scene details, and equalization for irregular lighting effects. These capabilities are particularly useful for visualization techniques which use more than one visual medium, such as the combined dye-hydrogen bubble studies which are part of the current research effort.

2) Three-Dimensional Reconstruction. The capability to rapidly digitize, enhance, and off-store to the host computer allows rapid three-dimensional flow reconstruction techniques. In addition, the system provides the capacity and enhancement required to allow stereoscopic reconstruction of a flow visualization event from two simultaneous video views (obtained at the proper viewing angle).

3) Velocity Data Extraction. The enhancement capabilities of the image processor coupled with the computing power of the host MicroVAX II allows velocity flow field data to be obtained using hydrogen bubble time-lines. Utilizing the digitizing and enhancement speed of the image processor and the disk storage capabilities, extensive bubble time-line scenes are rapidly stored and analyzed to yield a velocity flow-field data record using time-of-flight techniques. This data record is then analyzed in the same manner as is done with probe rakes, but with essentially continuous experimental velocity field data, which can be directly related to a series of visual images (see Figure 1). This latter aspect allows, for example, turbulence burst detection techniques, such as VITA techniques, to be closely correlated with the visual bubble time-line pictures in order to establish the actual flow structure(s) which these techniques detect.

4) Pattern Recognition Techniques: Two-dimensional pattern recognition or identification is one of the key imaging techniques employed to establish the presence of a particular pattern or sub-image within a broader field picture. In essence, this employs the same approach as is applied to one-dimensional velocity signals in turbulent boundary layers in an attempt to detect turbulent bursts. With the acquired equipment, this two-dimensional pattern recognition technique is applied to visualization sequences obtained for turbulent boundary layers to allow computer identification of characteristic bursting patterns, vortex patterns, or any flow structure or behavior with a specific definable visualization pattern.

B. Analytical Studies

In the present analytical studies, the numerical calculations are carried out on a DEC 8300 computer, which is the main computer for the CAD Laboratory in Mechanical Engineering at Lehigh. The graphics activity associated with CAD utilizes only a portion of the resources of the 8300, providing adequate central processor time for our present research program, which helped fund the computer. Since the 8300 is a virtual memory machine, it is capable of processing large arrays of numbers via immediate data accessibility on disk storage. Until the present equipment was acquired, the limiting feature of the system was the lack of available disk space.

The addition of the two dedicated disks has considerably expanded the nature and scope of the vortex calculations that we can perform; in addition, it makes the process of carrying out the computations much more efficient. The types of phenomena that are presently under investigation are Lagrangian in character and the availability of a large storage medium linked to the image processor greatly facilitates the dynamic display of the computed results, which is crucial to its proper interpretation. The addition of the image processing system also facilitates the cross-comparison of the experimental flow visualization results with the analytical predictions, which as pointed out in the introduction is key to the understanding of three-dimensional vortex behavior.

In the previous analytical studies, a variety of physical situations corresponding to vortex flows in two dimensions have been investigated; the results indicate that two-dimensional vortices in motion above a wall induce an unsteady separation effect in the viscous flow near the wall, which ultimately leads to an eruption of the boundary layer flow near the wall and the production of new vorticity in the outer flow.

Although the two-dimensional results are very suggestive it is clear that the vortex motions in a turbulent boundary layer are very highly three-dimensional. In this environment, the process of vortex stretching (which is absent in two-dimensional flows) is significant. Unfortunately vortex motions in three-dimensions are considerably harder to analyze than two-dimensional flows, not only because of the extra dimension but also because the calculation procedures required to compute the vortex trajectories are much more complicated. Thus, the greatly augmented data storage capability provided by the acquired disks have facilitated both manifold increases in mesh point analyses and expanded time-step analyses employing much smaller time-steps.

The second and most important analytical use of the large disk storage is associated with our computations of the effects of a convected vortex on the rest of the flow field. Implementation of the requested disk storage has allowed the expansion of our present studies to address the following areas:

- 1) Computation of the effect of convected three-dimensional vortices on the viscous flow near the wall - The types of calculations which are carried out in this study involve the three-dimensional unsteady boundary layer equations which produce more than an order of magnitude more numerical data than two-dimensional studies.
- 2) Simulation of vortex effects on simulated hydrogen bubble wires or dye markers in the flow - An important part of flow visualization is the proper interpretation of the results. The improved system has allowed the development of capabilities to demonstrate the effects of known vortex configurations on simulated flow markers. These analytical simulations may then be compared with the experimental flow visualizations as an aid in interpreting the flow physics. Note that even for the simulation of a small number of bubble lines (e.g. 15) relatively large disk storage requirements are incurred.
- 3) The interaction of several vortex loops and/or filaments - The experimental work suggests that the interaction of several vortices is an important phenomena. The storage requirements needed to compute multiple interactions escalates dramatically as more vortices are considered. The present system has greatly facilitated the implementation of such studies.

IV ASSOCIATED PUBLICATIONS

(Employing acquired equipment)

- 1) Ersoy, S and Walker, J.D.A., "The boundary layer due to a three-dimensional vortex loop", in review, J. Fluid Mech.
- 2) Lu, L.J. and Smith, C.R., "Application of Image processing of hydrogen bubble flow visualization for evaluation of turbulence characteristics and flow structure", to appear, Pro. of 4th Int. Symp. on Flow Visualization, C. Veret, ed., Hemisphere Press.
- 3) Walker, J.D.A., Smith, C.R., Cerra, A.W., and Doligalski, T.L., "The viscous flow due to an impacting vortex ring", in press, J. Fluid Mech.
- 4) Ersoy, S. and Walker, J.D.A., "The flow induced at a wall by a vortex pair", AIAA paper 85-1583, to appear in AIAA J.
- 5) Lu, L.J. and Smith, C.R., "Image processing of hydrogen bubble flow visualization for determination of turbulence statistics and bursting characteristics", Exp. in Fluids, vol. 3, p.349, (1985).

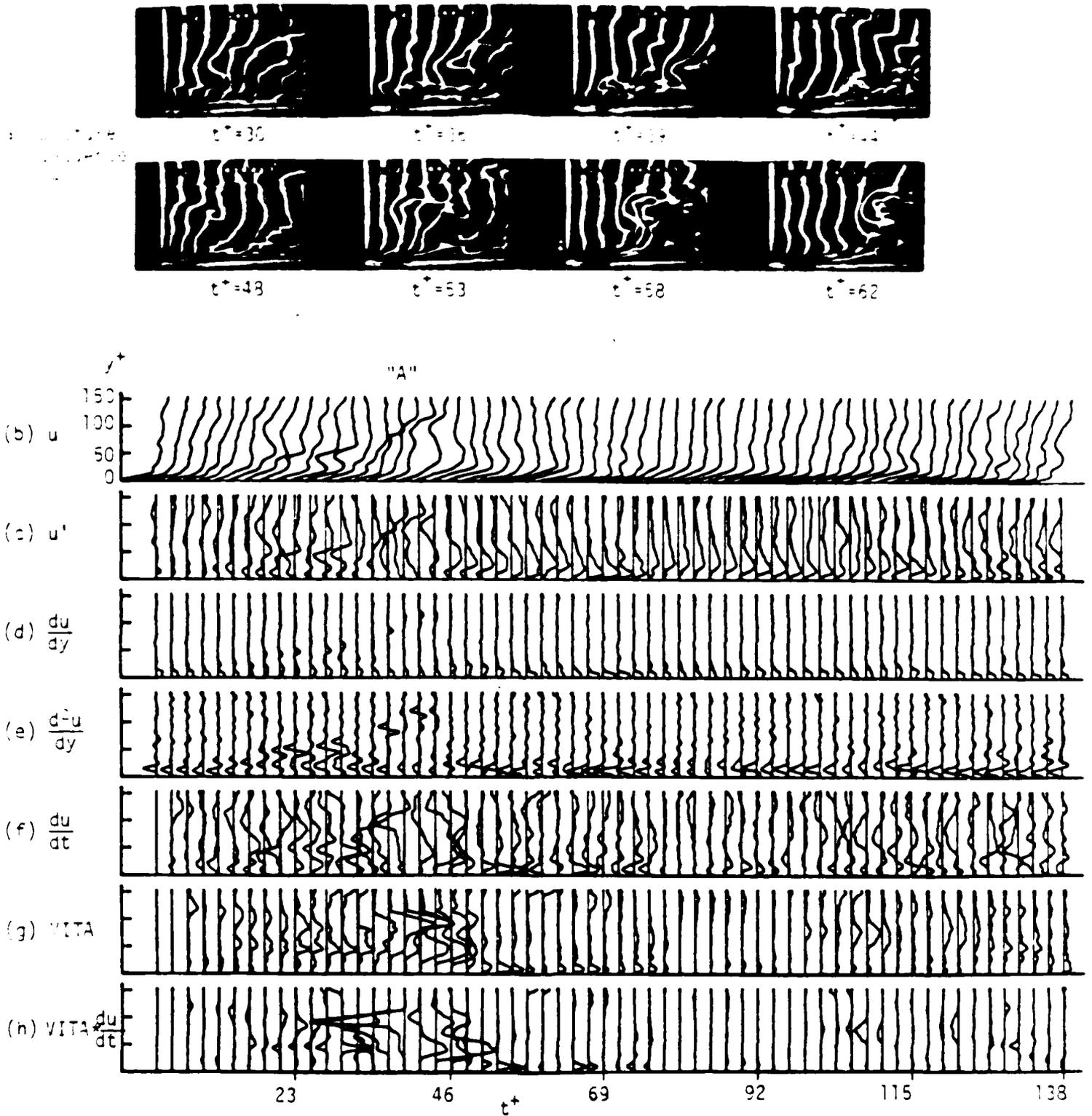


Figure 1 Profiles of velocity and velocity derived properties obtained from hydrogen bubble flow visualization pictures. Flow visualization sequence spans bursting contour "A" indicated above velocity profile (b) and in Figure 3.

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