Whole Field Measurements of Vorticity in Turbulent and Unsteady Flows

by

R. E. Falco, PI
C. P. Gendrich
C. C. Chu

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Turbulence Structure Laboratory
Department of Mechanical Engineering
Michigan State University
East Lansing, MI 48824
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**Title:** Whole Field Measurements of Vorticity in Turbulent and Unsteady Flows

**Abstract:***
Measurements of cross-stream and streamwise vorticity have been made over important regions of an experimental simulation of the bursting process of turbulent boundary layers. Vorticity measurements have also been made of the starting vortex of an airfoil, in a vortex ring, and in a Stokes' layer. Using a new technique developed under this contract, these measurements have been made at approximately fifty simultaneous positions over the flow structures of interest. The technique can accurately measure vorticity and strain rate, as well as instantaneous Reynolds stress and velocities over a field. It requires only a clock and a ruler for calibration. Furthermore, it directly measures these quantities, avoiding indirect interpretations. It employs long time persistence of irradiation of a photo-chemical to mark fluid particles. The technique has been named LIPA, an acronym for Laser Induced Photochemical Anemometry. Its accuracy has been measured by comparing it to an exact solution of the Navier-Stokes equations. This indicated an absolute accuracy of cross-

(Continued on following page)
stream vorticity of $\pm 3/\sec$. Data reduction procedures have been developed which utilize high resolution digitization and image processing. Algorithms have been written and tested which allow almost complete automation of the data reduction procedure.
INTRODUCTION

There is a need for measurements of flow quantities such as vorticity and strain rate as well as instantaneous Reynolds stress over and area in turbulent and unsteady flows. Examples include all aspects turbulence structure and entrainment studies, external and internal aerodynamics, studies of turbulence control, of mixing and combustion. In many cases there is a need to obtain more detailed information about these flows, but our understanding of a large number of simpler flows would also be increased. Existing probe techniques are at best able to provide single point estimates of gradient information. Of particular importance is the need to develop instrumentation to extend these capabilities to high speed flow studies. Another need is for instrumentation techniques that can enable quantitative Lagrangian information to be obtained. Evidence of these needs is the very high level of activity both in the US and in Europe aimed at developing quantitative field measurement techniques. It is well known that measurements of vorticity using a hot-wire probe at a single location are very difficult, but significantly less difficult than use of LDA to perform the same task. Thus, the goal of obtaining a large number of simultaneous vorticity measurements over an area (that may include an evolving coherent motion, for example) requires a different approach.

The technological transfer between physicists, plasma physicists, chemists, computer scientists and fluid dynamicists, has been the basis for the application of new techniques to measure these quantities at single or multiple points. Several new techniques for turbulence measurements in fluids have thus been adapted from physics and chemistry. They are based on atomic or molecular properties of the medium and changes in these properties. The techniques have rapidly become useful tools because of advances in laser and computer technology. Typical examples of the diagnostics are: Laser Induced Fluorescence (LIF), Forced Rayleigh Scattering (FRS), Anti-Stokes Raman Diffusion (ASRD), Fourier
Densitometry, and Laser Speckle. These advanced techniques can lead to information of a new kind, or may enable measurements to be performed in currently difficult flows. To this list we are now able to add Laser Induced Photochemical Anemometry (hereafter call LIPA). It has specific advantages over many of the others, which are discussed below.

Although many of the new optical techniques are essentially single point measurement techniques, LIPA is a field measurement technique, as is PV (Particle Velocimetry, which includes LPV, Laser Particle Velocimetry). Of those above which are field measurement techniques, all require optical data acquisition, and thus they have in common several advantages and disadvantages. Advantages include either no intrusion or very little intrusion on the flow to be measured, and very fast response. Many of these new techniques can be used in compressible, supersonic or hypersonic flows, where the conventional techniques (hot-wires, laser doppler anemometry) are difficult to use. LIPA can also be used in high speed flows, although these applications were not part of the current work. Common disadvantages include the need for optical interrogation of the results making conversion to digital form expensive.

Most of these new field techniques suffer from limitations of interpretation (for example fourier densitometry provides wave vectors), or from limitations to low speed liquid flows (particle velocimetry), or from inherent inaccuracies (for example the spatial ambiguities of speckle), or from inaccurate data reduction potential (holographic particle velocimetry). LIPA can surmount almost all of these difficulties. The outline of this report will first include a discussion of the technique and its variations, then a discussion of results from the present investigation, and finally an overview of new applications and the specific advantages and disadvantages of using LIPA to study them.
RESULTS

A) The LIPA technique

LIPA depends essentially upon marking specific fluid particles so that they can be tracked as they move in a flow. We must record the tagged particles' motion. We have restricted our data acquisition to the visible range of wavelengths, but the technique is not, in principle, confined to this range. In the visible range we have two types of photochemical tagging available, either color change or emitted light. Color change upon irradiation is called photochromism, while light emission is broadly called florescence. Both types have been used in experiments reported herein, and thus a review of the pros and cons of each are now presented.

At this stage in the development of LIPA, a limiting factor is the number of chemicals that are available to be irradiated with lifetimes long enough to allow the flow to move appreciably. This limitation has made the lifetime of the chemical govern the experiments that have been performed. The chemicals have also often been the determining factor in the choice of fluid that has been used for the experiments. In general photochromic chemicals have a lifetime of 1 ms to several seconds. This lifetime is long enough so that they are suitable for almost all experiments, from very low speed to very high speed. However, these chemicals can only be dissolved in organic liquids. Thus, the range of fluid dynamic experiments with photochromic chemicals is limited to those in liquids. On the other hand, photoluminescent chemicals tend to have very short lifetimes. Typical florescent lifetimes are the order of nanoseconds, far too short for the radiation to last long enough for all but hypersonic flows to appreciably move the tagged fluid particles. Thus, special photoluminescent chemicals are needed which have longer lifetimes. These tend to be specially constructed molecules which have a 'shield' of other atoms surrounding them that prevent collisional quenching, but are transparent to the incident and emitted radiation. One of
these is the proprietary product called Flowlite I from Flowmod Corp. This chemical can be dissolved in water and has a 1.5ms lifetime. We have used it in preliminary experiments in water and in a water droplet aerosol. Another chemical we have used is $K_2Pt_2(POP)_4$. This was synthesized at Michigan State University by professor D. Nocera. It has a 10μs lifetime, and has been used successfully as a water droplet aerosol in $N_2$. We envision a rapid growth of the number of chemicals synthesized for use in LIPA as the value of the technique becomes apparent.

For the experiments described herein, tagging has been performed in a plane. This is not an inherent constraint; three-dimensional tagging and stereo recording is certainly possible, and is seen as an evolutionary step in the use of LIPA. Tagging in a plane, combined with stereo viewing will enable all three components of velocity in the neighborhood of a chosen plane to be obtained. Furthermore, creation of two closely spaced grids, combined with stereo data acquisition will enable all three components of the vorticity vector in the neighborhood of the bisecting plane to be obtained.

In the current version of the technique, we have chosen to develop passive beam splitting and steering devices, which divide the laser beam into 'n' beams (we have used $n = 7$, and 10) and cause these beams to cross within the fluid. It has the advantages that no incident light is lost, and that the line widths and spacings can be specified by the facet design. The devices are similar in appearance to an oversized diffraction grating (see Appendix B, Fig. 1 and 2), but it gives specular reflection. The subsequent excitation of the chemical along the multiple intersecting laser lines creates a grid of 'n' lines of marked fluid. At each of the intersections of the laser gridlines a 'fluid particle' is unambiguously tagged. This results in $n^2$ simultaneous measurements over the area of the grid. The distortion of the grid in a known time provides us with all of the kinematic information obtainable in a fluid in the plane of the grid. The
resolution of this information is equal to the applied grid mesh. For flows where
differential resolution is natural, the grid can be set to match the needs of the
flow.

Details of the use of the technique have been published (see Falco and Chu
(1987); Falco, Chu, Hetherington and Gendrich (1988)) and are included in
appendix B and C. Further description is given in Chu (1988) and Falco and Chu
(1988). It is important to emphasize that the technique used requires only a
known length and a known time between exciting the chemical with a laser and
imaging the marked fluid particles. Precision placement of measurement points is
another advantage of the technique. Because the laser excitation is in a plane,
our information will be at selected points in (or very close to) selected planes
in the flow. This ability to choose to have the measurement points near a center
line or at y* = 5, for example, is extremely helpful.

B) Automated data reduction

The success of the development of LIPA into a tool that can be widely used
for detailed fluid dynamic measurements will most probably depend upon the ease
of data reduction. Thus, we have put considerable effort into automating the data
reduction. Key to our success has been the use of the lines of radiation from the
chemicals in the grids to provide redundant information for the determination of
the points of intersection of the laser lines. This has made imperfections in the
film or optics, film grain, dirt acquired in developing, etc. unimportant. The
fact that two independent pieces of film are used further decouples the problems
with parasitic images, and as a result we have a robust data reduction technique.

The algorithms used are included in the Appendix A. They are written in
FORTRAN and have been run on a Silicon Graphics IRIS 3120, under Unix System V.
Briefly, it allows the velocity, gradients, vorticity and instantaneous Reynolds
stress to be calculated from four randomly spaced points. The field may have ‘p’
groups of points, where 'p' is only limited by available computer memory. The algorithm will calculate the vorticity in contiguous polygons, if points are within distances that are less than a specified fluid mechanically determined limit, such as a Kolmogoroff scale. It requires that each of four points be identified in two photographs, separated by an arbitrary time interval.

C) Determination of the accuracy of the technique

We have calibrated the technique by making measurements in a flow in which we have an exact solution (a Stokes' layer). Results are presented in the papers in the Appendix B and C (also see Falco and Chu 1988). Essentially, we can obtain cross-stream vorticity to ±1 sec^{-1} accuracy. This compared very well with estimates made using classical error analysis techniques. Since we can very accurately measure both a clock and a ruler, we should be able to maintain this accuracy over a wide range of flow speeds.

D) Cross-stream vorticity measurements:

Cross-stream vorticity measurements have been made in the Stokes' layer for calibration as mentioned above, in a vortex ring, and in the starting vortex of an airfoil. The Stokes' layer measurements are discussed in Appendix B and C.

The measurements in a vortex ring Falco and Chu (1987), show for the first time the distribution of vorticity in a single ring and its changes as we move circumferentially. Previous measurements with LDA have required averaging over many rings, and suggested greater symmetry. These changes in a real ring that was very carefully produced and very stable, indicate the insensitivity of the stability of the ring to the detailed shape of the vorticity distribution or of its circumferential symmetry. The other point of interest is that the circulation for our low Reynolds number ring is quite close to that found for a Hill's spherical vortex.

The measurements of the starting vortex formed when an airfoil is
impulsively started have also shown significant surprises. This study, described in Appendix C, indicated that only about $1/3$ of the vorticity was in the starting vortex, which means that the remaining vorticity is in a shear layer between the wing trailing edge and the vortex. As a result, the Kutta condition can not be established. This has interesting implications for non-steady airfoil work and for calculations that depend on the Kutta condition being established. Since it has not been possible to make measurements of this type before, unsteady phenomena which require vorticity measurements over an area have received no experimental attention.

E) Streamwise vorticity measurements of a simulation of the production process in turbulent boundary layers

Streamwise vorticity measurements have been made in streamwise vortices created above a wall, similar to those found in turbulent boundary layers. These results have been reported by Chu (1988) and by Falco and Chu (1988). Briefly, we have observed this sequence in the turbulent boundary layer, and have subsequently been able to model it, in all its detail, by passing a vortex ring over a laminar shear layer (either a Stoke’s or Blasius layer). It is true that the complete event is rarely seen in the turbulent boundary layer. However, a significant part of it was apparent during each of the bursts we have observed (and it must be noted that our techniques don’t result in observation of the entire picture at all times). We are presently doing this in the turbulent boundary layer using either multiple dye slits, or the LIPA technique (it will be reported on later), which is allowing whole field real time measurements of vorticity and instantaneous Reynolds stress in the marked fluid.

In experiments designed to examine only the wall region, we observed that the production sequence starts with the formation of a pair of long streaks. Using two dye slits in series, we observed that subsequently a pocket forms
between the streak pair; often after streaks of several hundred \( x^* \) have formed. It appears to us that the dye marks a strong vortex which forms in the pocket. Use of the LIPA technique, in simulations, has clearly showed that the pocket vortex is present and that it is the most intense vortex found in the wall region.

The other aspect that has been quantified, is that the long streaks are observed to undergo an instability that results in the formation of one or more hairpin vortices over each streak. Using LIPA, we have measured the streamwise vorticity in these vortices and found it to be weak with respect to the streamwise vorticity in the pocket vortex. Left to evolve on their own, these hairpin vortices would not contribute much to the production of turbulence.

However, this is not the case. The experiment shows that as the pocket vortex is stretched, these secondary hairpins are convected past it. Because the pocket vortex, which now has a primarily streamwise component, is much stronger, it induces the hairpin vortices around it. Our two-dimensional instantaneous vorticity maps of these features and their interactions gave us a detailed quantitative account of the ensuing interaction. We found that the pocket vortex was more than twice as strong as the hairpins, and that it lifted them completely around it leading to the breakup. Furthermore, practically all of the Reynolds stress associated with the streak...secondary hairpin...pocket vortex interaction is due to the pocket vortex and the motion it induces.

In addition, our observations have indicated that the streaks do not form as a result of a 'pumping' action by long streamwise vortices, and that evidence of vortices associated with the streaks is only found when the secondary hairpins form. LIPA unequivocally shows no concentration of streamwise vorticity during the time when streaks first appear.
DISCUSSION

There are two additional aspects that use of the LIPA technique can uniquely provide for researchers in turbulent and unsteady flows. They are 1) quantitative Lagrangian information and 2) quantification of the kinematics of high speed flows.

Since high speed movies can be taken (synchronized in combination with a high repetition rate Excimer laser) we can gain an understanding of the evolution of the dynamics of unsteady fluctuating flows, i.e. obtain quantitative Lagrangian information. This is of great importance in the study of control of turbulence, for the details of how the control interacts with the coherent structures is the essential design information. Experiments of this type are currently underway at the Turbulence Structure Laboratory to help understand turbulent boundary layer inner-outer interactions, and their role in the production process.

Another range of insights will come from far more detailed measurements of the dynamics of high speed flows. The capability of LIPA to obtain whole field measurements in gas flows (which are seeded with submicron water droplets containing one of the chemicals), makes possible measurements in high speed flows. Most uv lasers pulse in nanoseconds, and the reactions occur in even shorter time scales. Since this is a non-intrusive measurement technique, and since it requires only a clock and a ruler for calibration, it potentially can provide high accuracy results for flows at any speeds currently obtainable in wind tunnels. Recording the signals with image converter cameras appears entirely possible. Thus, potentially, transonic and supersonic flow studies could be performed. An interesting sidelight is that LIPA may prove to be a practical tool for aircraft development. Since many high Reynolds number experiments are now being performed in cryogenic tunnels, and since N₂ essentially prevents quenching, construction of an optical setup that would provide, say 100 to 1000
data points over a body, might prove very cost effective when compared to the tunnel
time required for a similar number of LDA measurements.

Finally, LIPA using a gaseous phase chemical in a gas flow (this is
contextually possible, but has not been attempted), has the potential to give
whole field measurements in high temperature, combusting or hypersonic flows.

Summarizing, the **advantages** of the LIPA technique are:

- Instantaneous measurements of velocity gradients, vorticity,
  strain rate, instantaneous Reynolds stresses and
  velocities can be made over an area
- Can be setup to give highly accurate space and time resolved
  measurements over a large range of velocities
- Non-intrusive
- Measurements can be made at chosen locations
- Simple calibration depends only on a clock and a ruler
- Simple data acquisition
- Not limited by interferometric quality access
- Data reduction can be automated
- Can be used in gases (currently in aerosol form) or liquids
- Can be used in non-Newtonian fluids and in two-phase flows
- Three-dimensional measurements are possible
- Standard wavelengths of uv lasers can be used
- Can be combined with flow visualization
- Mixing can be studied by using more than one chemical
- Potentially can be combined with LIF to give concentration
  information along with the kinematic data.

The chief **disadvantage** of LIPA is:

- Specific chemicals must be found for flow velocities and
  fluids of interest.
CONCLUSIONS AND FUTURE WORK

LIPA has been developed and used to measure derivative information at multiple points in complex flows. An algorithm has been written that essentially automates data reduction. The study of a model of the production process has shown that the pocket vortex is the strongest, easily overwhelming the hairpin vortices that develop over the streaks. Our study of the starting vortex indicates that significant vorticity exists in a shear layer between it and the airfoil at low Reynolds numbers.

Quantification of this kind has here-to-fore been impossible. LIPA enables quantitative measurements of velocity, vorticity, strain rate, and instantaneous Reynolds stress over an area in turbulent flows. Only two successive pictures are needed to calculate the distortion of the marked fluid. Calibration requires only a clock and a ruler. It works in reversed flows. The technique has been used in kerosene, water, nitrogen and air (with seeding). As such, it should be able to measure flows into the supersonic range. It can also be extended so as to make three-dimensional measurements of all kinematic quantities over an area. The potential for the use of LIPA in many other flows and particularly at high Reynolds numbers has been discussed.

Future work will include:

a) Measurement of coherent motions; their formation, evolutions and interactions in turbulent water flows.
b) Development of technique in gases.
c) Use of the technique in water to develop its three-dimensional capability for both velocity and vorticity fields.
d) Development of simultaneous LIPA and LIF measurements.
e) Use of the technique in high speed flows.
PAPERS resulting from this work to date:


Students trained in the development of this technique during the contract period

1. Mike Hetherington (currently working on his M.S.)
2. Sean Hilbert (currently working on his M.S.)
3. Chuck Gendrich (currently working on his M.S.)
4. Dan Chu, received the Ph.D. 1987, currently associate professor National Taiwan University
5. Dan Hamilton (currently working on his MS)
6. Harry Haufbauer (currently working on his MS)
7. Todd Parr (undergraduate)
This appendix contains the command files which run the image processing equipment, converting the visual information into digital form. The program which interrogates the visual information and calculates the fluid kinematic quantities is also included. The programs which are run on the image processor to perform standard operations like averaging and edge enhancement are too lengthy to include here.

The data flow is as follows. Either film or video tape is used to record an experiment. The image processor is required to digitize all of these frames and then individually reduce each image to a set of intersection points. A model command file can be applied to each image to perform this data reduction, but since our image processor does not allow one command file to call another, a large command file must be generated to automatically process many frames without personal intervention.

The first command file (TapeCrunch) is a UNIX shell script which generates this large image processing command file. In this example it is setup to acquire up to 40 sequential frames from a video tape, store them, and then process them using a model command file. The second command file (TapeCrunch.csm) is suitable for use on the Megavision 1024X1 image processor. Although up to 40 frames may be processed at once, we show how only five are done in the interests of brevity. The third command file (auto.csm) contains the commands to reduce the digitized images to two sets of intersecting lines.

The program VORTICITY and all of its subroutines comprise the remainder of this appendix. It must be run after the intersections have been obtained. It takes the output of the image processing programs and converts that into velocity, velocity derivative, and vorticity information.
#!/bin/sh

Description:
This Unix shell script generates a large MegaVision command file to crunch many frames from a video tape. It is necessary to generate one large MegaVision command file since the image processing software doesn't permit nesting from one command to another then back again.

Use of Arguments $0, $1, $2, ...
- The command file ($FILE) created will have the name $0.cxm.
  NOTE: Any previous contents of $FILE are wiped out by this shell script.
- The root filename used to store the video data frames is take from $1. If $1 is not set (or null), the string 'VidFram' is used.
- The root filename used to store the intersection data will be $2 or 'Intersect'.
- The model command file to crunch the data will be $3 or 'auto.cxm'.

History:
<cp> 6 oct 88 -- 1st version. Always did it by hand before...

FILE=$0.cxm
FRAMES=5
arg=$1, VROOT=pwd/${arg:=VidFram}
arg=$2, IROOT=pwd/${arg:=Intersect}
arg=$3, COMND=${arg:=auto.cxm}

echo "!
Video tape crunch command file."
!
read in $FRAMES frames, store them, and then recall and crunch each individually using COMND as the command file template.
!
This file was created on "date".
!
First read the video tape
ERALL
INIT
TVPACK t 525,$FRAMES,0
!
Then store the data" > $FILE

we need to look at A1, A2, A3, A4, B1, ..., 2 | 1
until we've stored as many frames as were --------
scanned in. The frames are stored like this: 4 | 3
(See the MegaVision TVPACK help.) This determines the values for Xoff and Yoff and the order in which they change...

FRM_RUN=0

for MEMORY in A1 A2 A3 A4 L1 L2 B3 B4 C D E F
do
for Yoff in 0 512
do
for Xoff in 512 0
do
    FR1NUM= expr $FRNNUM + 10
    if test $FR1NUM -gt $FRAMES then
        break 3
    fi
    FNAME=$VROOT$FR1LN"-echo -NSTORE SMEMORY $FNAME 1,512,512.$Xoff.$Yoff,1,1" >> $FILE
done
done
done

echo "! DATA STORED. !" >> $FILE

FR1NUM=1

while test $FR1NUM -le $FRAMES
do

VNAME=$VROOT$FR1NUM
INAME=$VROOT.$FR1NUM
echo "!
! Now processing frame number $FR1NUM !
!RECALL SVNAME B 0,0,2,2
!AVERAGE B A4 3,5,0,1
!*cat $SCOMND*
!
! Calculate and store the intersections
LOTS 3,A4 C,$INAME
!" >> $FILL

FR1NUM= expr $FR1NUM + 10
done
Video tape crunch command file.
Read in 5 frames, store them, and then recall and crunch
individuality using model.cxm as the command file template.

This file was created on Thu Oct 6 11:01:36 EDT 1988.

First read the video tape

ERALL

INIT

TVPACK t 525,5,0

Then store the data

NSTORE A1 /usr/thor/gendrich/vision/Video1 1,512,512,512,0,1,1
NSTORE A1 /usr/thor/gendrich/vision/Video2 1,512,512,0,0,1,1
NSTORE A1 /usr/thor/gendrich/vision/Video3 1,512,512,512,512,1,1
NSTORE A1 /usr/thor/gendrich/vision/Video4 1,512,512,0,512,1,1
NSTORE A2 /usr/thor/gendrich/vision/Video5 1,512,512,512,0,1,1

DATA STORED.

Now processing frame number 1

RECALL /usr/thor/gendrich/vision/Video1 B 0,0,2,2
AVERAGE b A4 3,5,0,1

model command file is inserted here
processing data from memory A4 and
depositing the intersections in Bl.

Calculate and store the intersections

DOTS 3,A4 C,/usr/thor/gendrich/vision/Intersect.1

Now processing frame number 2

RECALL /usr/thor/gendrich/vision/Video2 B 0,0,2,2
AVERAGE B A4 3,5,0,1

model command file is inserted here
processing data from memory A4 and
depositing the intersections in Bl.

Calculate and store the intersections

DOTS 5,A4 C,/usr/thor/gendrich/vision/Intersect.2

Now processing frame number 3

RECALL /usr/thor/gendrich/vision/Video3 3 0,0,2,2
AVERAGE 3 A4 3,5,0,1
model command file is inserted here
processing data from memory A4 and
depositing the intersections in El.

! Calculate and store the intersections
DOTS B,A4 C,/usr/thor/gendrich/vision/Intersect.3
!
!
! Now processing frame number 4
!
RECALL /usr/thor/gendrich/vision/Video4 B 0,0,2,2
AVERAGE B A4 3,5,0,1
!
!
model command file is inserted here
processing data from memory A4 and
depositing the intersections in El.

! Calculate and store the intersections
DOTS 5,A4 C,/usr/thor/gendrich/vision/Intersect.4
!
!
! Now processing frame number 5
!
RECALL /usr/thor/gendrich/vision/Video5 B 0,0,2,2
AVERAGE B A4 3,5,0,1
!
!
model command file is inserted here
processing data from memory A4 and
depositing the intersections in El.

! Calculate and store the intersections
DOTS 5,A4 C,/usr/thor/gendrich/vision/Intersect.5
!
Image processing command file

Works with all:
- Ektachrome wing images
- ASA 1000 wing images

NOTE: The angles through which the picture is rotated are dependent on the setup of the beam dividers. These values will change from one setup to the next, requiring modification of the 'ROTATE' angle at the start and end of processing each half frame.

History:
- <cpg> 1 Jan 88 -- comments
- <cpg> 21 Jan 88 -- Instead of subtracting the background level, differ and HEQ are used.

PRELIMINARIES

First, subtract the background level to get a more even grey level across the entire screen.
average a4 b4 1,37,3,0,1
subtract b4,a4 c
threshold c a3 0,143,2,2,2,2

To eliminate the noise at the edges, crop A3.
erase b3
block a3 b3 64,64,959,959,64,64
move b3 a3

START PROCESSING THE FIRST HALF FRAME:

Rotate the image so the first set of lines is vertical
rotate j3 b3 -25

Emphasize the vertical lines -- their average within a vertical kernel is greater than the surroundings (and the other lines).
average b3 a2 1,1,130,0,1
threshold a2 b2 0,168,2,2,2,2
not b2 a1

Fill in gaps from thresholding.
_range a1 b1 1,1,256,100,255,255

Eliminate the thin noise spikes.
minimum b1 a3 3,5

Fatten up the lines a bit -- it helps for filling in the gaps.
roller j3 b3 3

Now fill in the gaps.
_range b3 a2 1,1,256,110,255,255
roller a2 b2 5

Eliminate any stray high order bits...
threshold b2 a2
Shrink lines to one pixel wide, being careful to eliminate any
open circles and line stubs. (ERODEC erodes everything but Contiguous
objects.)
move a1 b1
erodec b1 a3 20
(This fills in holes for any points that might not want to go away...)
roller a3 b3 3
! Now finish up the job...
erodec b3 a3 36
!
Put these lines into their original frame of reference.
rotate a3 b3 25
!
NOTE -- the origin wasn't moved in our cropping above (although it
could have been). If the origin *is* moved, use ELOCK here
to put it back where it belongs.

Next, fatten up the lines so that intersections won't be missed by one line zigging while
the other is zagging. See illustration =>
The intersection between lines "1" and "2" is a <NULL> instead of a point.
roller b3 a2 3
END OF PROCESSING FIRST HALF FRAME.

... now do it all over with the lines in the other direction
threshold a2 b2 0,150,2,2,2,2
not b2 a1
subtract b4,a4 c
move a1 b4
!
threshold c a3 0,125,2,2,2,2
erase b3
block a3 b3 64,64,959,959,64,64
move b3 a3
!
START OF PROCESSING THE 2na HALF FRAME
rotate a3 b3 27
average b3 a2 1,1,100,0,1
threshold a2 b2 0,166,2,2,2,2
not b2 a1
_range a1 b1 1,1,256,110,255,255
minimum b1 a3 3,5
roller a3 b3 3
_range b3 a2 1,1,256,110,255,255
roller a2 b2 7
threshold b2 a1 0,150,2,2,2,2
not a1 b1
erodec b1 a3 20
roller a3 b3 3
erodec b3 a3 36
rotate a3 b3 -27
roller b3 a2 3
END OF PROCESSING THE 2nd HALF FRAME

Here are the other lines.

threshold a2  b2 0,150,2,2,1,2
not    b2  a1

A logical AND is the intersection of the two sets of lines (literally). :-)

and   a1,b4 c

The system uses C as a working memory. Put our intersections somewhere safer. :-|

move    c    bl

Let's overlay the points on the original image.

White objects in the graphics memory (F) are what we need to do that.

move    c    f

Look at the original image...

view    a4

...and turn on the graphics display.

...on
program VORTICITY

Description:
This program reads two data files produced by the
"object" function of the MegaVision 1024XN. The labelled and
filtered objects are the points within the flow which we are
tracking.

This program performs a number of tasks:
1) reads the data
2) sorts it by increasing X and Y values
3) matches points in frame 1 to points in frame 2
4) interpolates in space and time to construct a velocity field
   throughout the frame
5) connects the dots to form polygons,
6) uses the velocity information to determine derivatives,
   stress and strain values, vorticity, etc.

Author: Chuck Gendric (Give me unix or ...)

History:
August, 1987 -- 1st version -- written on freyja, an IRIS 312C
running unix System V.

December, 1987 -- 1.1 <cpp> Added graphics display of the
calculations (velocities, vorticity, etc.)

Added TURB3D-formatted output.

include "vorticity.h"

logical Again, UnDim
integer NumPts, NumPoly
external Again, NumPts, NumPoly
Again is the error handler -- prints diagnostics and asks
if the user wants to quit or re-run the preceding section.

UnDim comes back TRUE when output will be non-dim'd

open unit=1, file='/dev/tty'
unit1 -- ctty input
open unit=2, file='/dev/tty'
unit2 -- tty output

step 1 -- get the data

include "graphics.h"
continue

if getfrm(frame1, frame2, UnDim, ierr)
if ierr.ne.0 then
 error handle
endif

endif
c c c step 2 -- sort the points. this is necessary when using more
c sophisticated matching algorithms.
c
c call sortfrm(framel)
c call sortfrm(frame2)

ifdef DEBUG
 n = NumPts(framel, 2)
 write(*, 1000) 'frame 1', n, (i, frameli(i,X), frameli(i,Y), i=1,n)
 n = NumPts(frame2, 2)
 write(*, 1000) 'frame 2', n, (i, frame2i(i,X), frame2i(i,Y), i=1,n)
1000 format(/' X-Y data for ',a7,'.',i2,' points:'/ + '(',i2,:(',f8.3,1,',f8.3,1))
endif

c c c step 3 -- define the correspondence between the two frames (match)
c 20 continue
c call color(GREEN)
c call Matches(framel, frame2, match, ierr)
 if( ierr.ne.0 ) then
   if( Again(ierr) ) goto 20
 endif
endif DEBUG
 write(*, 1010) match
1010 format('/ Here is the match array:'/(i3))
endif

c c c step 4 -- interpolate the velocity vectors
 c
c call Velocities(framel, frame2, match, vel)

ifdef DEBUG
 n = NumPts(vel, 4)
 write(*, 1020) i, vel(i,X), vel(i,Y), vel(i,Vx), vel(i,Vy), i=1,n,
1020 format(/' Here are the velocity components and their', + 'locations:'/(i3) + 'X Y Vx Vy'/ + '(lx,12.',',4(lx,f7.2))'
endif

c c c step 5 -- define the polygons
 c
c continue
c call Polygons(vel, poly, ierr)
 if( ierr.ne.0 ) then
   if( Again(ierr) ) goto 30
 endif
endif DEBUG
 write(*, 1030)
1030 format('/ Here are the polygons which have been defined:'// + 'ULH URH LRH LLH')
 n = NumPoly(poly)
 write(*, 1040, (poly(i,1),poly(i,2),poly(i,3),poly(i,4), + i=1,n)
1040 format(4(2x,12,1x))
endif

c
c step 6 -- calculate fluid kinematic quantities
c call fluids( vel, poly, UnDim, ierr)
c end
data declarations for the vorticity program

integer MaxPts, MaxPoly
parameter( MaxPts = 100 )
the maximum number of points per frame

parameter( MaxPoly = MaxPts )
the maximum number of polygons

real BIGRAD, SMALLRAD
parameter( BIGRAD = 3.0 )
parameter( SMALLRAD = 1.5 )
large and small radii for outer- and inner-circle drawing

real (4,4), scale
transformation matrix for sizing, things correctly
and the value to put on the diagonal

integer X, Y
parameter( X = 1 )
parameter( Y = 2 )
pointers to XY coords

integer Vx, Vy
parameter( Vx = 3 )
parameter( Vy = 4 )
pointers to velocity components

integer BAD
parameter( BAD = 0 )
when 'look' returns a BAD point, it didn't find a
corner in the indicated direction at the correct
distance.

integer ddx, ddy
parameter( ddx = X )
parameter( ddy = Y )
pointers so that subprograms agree whether the
derivative wrt X or wrt Y should be taken.

real frame( MaxPts, 2 )
real frame1( MaxPts, 2 )
real frame2( MaxPts, 2 )
XY coords of each point in frames 1 and 2

integer match( MaxPts )
frame1( i ) <-> frame2( match(i) )

integer poly( MaxPoly, 4 )
making four-sided polynomials
poly( i, 0 ) is the upper-LH corner of the polygon
poly( i, 1 ) is the upper-RH corner
poly( i, 2 ) is the lower-RH corner
poly( i, 3 ) lower-LH
real vei( MaxPts, 4)
velocity field --- Vx a Vy ⊆ X,Y

integer MatchDim
parameter( MatchDim = 10); integer matches( MatchDim)
  watch the spelling!!!
  Hopefully, no more than 10 points will match...

character*30 title
  for titling output

real UP, DOWN, RIGHT, LEFT
parameter( UP    = 90.0); parameter( DOWN  = 270.0);
parameter( RIGHT = 0.0); parameter( LEFT  = 180.0);

integer Xsize, Ysize
  size of the window port opened up.

logical GoOn
  external GoOn
  a logical function which types <RET> to continue, then
  returns .TRUE.

integer ierr
  returns 0 when there is no error, otherwise...

integer i, j, k, n, n1, n2, p
  counters
call foregr

c the job in the textport needs to run in the foreground

call KeepAs(1024,767)
c
the window needs to have an aspect ratio of a:b
i = winope('Vorticity Tool',14)
call wininit('Vorticity Tool',14)
c
get a window and title it

call getsiz(Xsize, Ysize)
c
find out how large it is, then make the transformation
c matrix which will scale everything appropriately.
c
if(Ysize.eq.1024.0) Ysize = 767.
c
mex isn't running. Ysize is really 767...
scale = 1024./Ysize

c 1024. is the largest x or y value my data will ever have.
c
do 77777 i=1,4
    do 77777 j=1,4
        if(i.eq.j), then
            m(i,i) = 1.0
        else
            m(i,j) = 0.0
        endif
    enddo
77777 continue

m(4,4) = scale

c m(2,2) = -m(2,2)
c m(4,2) = Ysize

c this should flip the image vertically

c call wininit(i,i)
c call color(WHITE)
c call clear
    do 77778 i=8,64
        call mapcol(i, i*4, j, 150-(2*i))
    enddo
77778 continue

c Here are the predefined colors 1-7 (defined in 'fgl.n')
c
BLACK RED GREEN YELLOW

BLUE MAGENT CYAN WHITE
define UPSIDE_DOWN
define MFRC
define YYMIN 70.0
  actually -YYMIN .. Y = Y - YYMIN
define XXMIN 30.0
define YSPLIT 5.217881548
define XSPLIT 5.217881548
The conversion is:
Y = (Ymfrc + YYMIN) * YSPLIT  and similarly for X.

subroutine getfrm( frame1, frame2, UnDim, ierr)
  Description:
  Read in the data files, storing the points in FRAME1 and FRAME2.
  Return Values:
  X,Y points in frame1 and frame2
  ierr = 0 if no error occurred
  History:
  <cpg> aug 87 --- v1.0
  
  include "vorticity.h"
  character*80 filnam1, filnam2
  real Xoffset, Yoffset
  integer NumPts
  external NumPts
  logical UnDim

  initialize both frame1 and frame2

  do 1 i=1, MaxPts
     frame1( i,X) = 0.0
     frame1( i,Y) = 0.0
     frame2( i,X) = 0.0
     frame2( i,Y) = 0.0
 1 continue

  frame1
  1000 format(' Please enter the name of the file which contains '/
           + ' the data for frame 1.')
  1010 format(' Error opening the data file ' ,a30//' Please try again./')
  10 continue
  return here on error 11
  filnam1 = 'frame1.dat'
  write( *, 1000)
  call getline( filnam1)
c

call makefrm( framel, filnam1, ierr)

n = NumPts( framel, 2)
call color( BLUE)
do 15 i = 1, n
    call circ( framel(i,X), framel(i,Y), BIGRAD)
15 continue
if( ierr.eq.1) then
    try again if error opening the frame data file
    write( *, 1010) filnam1
    goto 10
else if( ierr.ne.0) then
    calling routine will have to deal with the error
    return
endif

c
C FRAME2
1020 format( ' Please enter the name of the file which contains'/
+ ' the data for frame 2.',
continue
filnam2 = 'frame2.dat'
write( *, 1020)
call getline( filnam2)
c

call makefrm( frame2, filnam2, ierr)
if( ierr.eq.1) then
    write( *, 1010) filnam2
    goto 20
else if( ierr.eq.0) then
    get the X- and Y-offsets for this frame
    write( *, 1030)
    read( *, *) Xoffset, Yoffset
    n = NumPts( frame2, 2,
do 30 i = 1, n
        frame2( i,X) = frame2(i,X) - Xoffset
        frame2( i,Y) = frame2(i,Y) - Yoffset
30 continue
    call color( CYAN)
do 40 i = 1, n
    call circ( frame2(i,X), frame2(i,Y), BIGRAD)
40 continue

c
    call convert( 1.0, 0.0, 0.0, 0.0, UnDim)
    return
endif
1030 format( ' Please enter the X- and Y-offsets for frame 2.'/
+ ' They should be chosen such that (0,0) in frame 1 is the'/
+ ' point (Xoffset, Yoffset) in frame 2.'
end

subroutine makefrm( frame, filnam, ierr)

c
open the frame data file
c
throw away the first (descriptor) line
c
while not EOF
c
find out how many points are in the next set
read X values
read Y values
convert X and Y to a std coord system
end while

The following is an example of the data contained in the file:

ORIGINAL OBJECTS

OBJECT LABEL 1 2 3 4 5
X-CENTROID 225.75 662.50 497.44 861.73 705.30
Y-CENTROID 109.25 115.00 133.78 185.91 234.30

OBJECT LABEL 36 37 38
X-CENTROID 445.78 570.09 685.25
Y-CENTROID 916.00 922.36 940.25

include "vorticity.h"

integer set, start
character*80 filnara
character*80 linel, line2, line3, junk
integer HowMany
external HowMany

open( 3, err = 2000, file=filnara, status = 'old')
print*, 'Reading data from ',filnara

1000 format( a80)
1010 format( 17x, 5(4x, f7.2))
1020 format(' Zero objects found in coordinate set ',i2,'.')
read( 3, 1000, end=2010) junk

start = 0
start stores the current number of points that have
been read in.
set = 0
continue
read( 3, 1000, end=2020) junk
read( 3, 1000, end=2050) line1
read( 3, 1000, end=2050) line2
read( 3, 1000, end=2050) line3

set = set + 1
n = HowMany( line1)

if( n.gt.0) then
read( line2, 1010) (frame(i,X), i=start+1, start+n)
read( line3, 1010) (frame(i,Y), i=start+1, start+n)
start = start + n
else
write( *, 1020) set
endif

c

go to 100

c

2000 continue
c error opening the frame data file
ierr = 1
return
c

2010 continue
c empty file
ierr = 2
close( 3)
return
c

2020 continue
c end of file --- OK
close( 3)
ierr = 0
endif

ifdef MFRC

oo 2025 i=1,start
frame(i,Y) = (frame(i,Y) + YYMIN) * YSPLIT
frame(i,X) = (frame(i,X) + XXMIN) * XSPLIT

2025 continue
endif

ifdef UPSIDE_DOWN

do 2030 i=1,start
frame(i,Y) = -frame(i,Y) + 1024.

2030 continue
endif
return

c

2050 continue
c wrong number of lines. three should appear at once --
c OBJ NUMBER / X-COORDS / Y-COORDS --- Frame probably incorrect
ierr = 3
close( 3)
return
end

integer function HowMany( line)

c Check that the first word is OBJECT.
c Then count to see how many \ signs there are.
c
We're parsing this line:
c OBJECT LABEL  \  36 \ 37 \ 38
c123456789 123456789 123456789 123456789 123456789 123456789 123456789 12345

c so we'll only look every 11 places for the \.
c
character*80 line
integer pos
character*6 word, obj
character*1 lb
parameter( obj='OBJECT')
parameter( lb='[]')

c
c 1000 format( lx, a6)
read( line, 1000) word
if( word.ne.obj) then
  HowMany = 0
  return
endif
n = 0
c Use n as a counter for the number of objects
do 100 i= 1,5
c 5 is the maximum number of points possible
  pos = 11*i + 12
  if( line(pos:pos).eq.lb) then
    n = n+1
  endif
100 continue
HowMany = n
return
end
integer function NumPts(points, dim)

#include "vorticity.h"

integer dim
real points(MaxPts, dim)

n = 0
10 continue

if(points(n+1, X).eq.0.0.and.points(n+1, Y).eq.0.0) goto 20
n = n+1
if(n.eq.MaxPts) goto 20
goto 10

20 continue

"n" now contains the number of points

NumPts = n
return
end

integer function NumPoly(poly)

#include "vorticity.h"

n = 0
100 continue

if(poly(n+1,1).eq.0) goto 200
n = n+1
if(n.eq.MaxPoly) goto 200
goto 100

200 continue

"n" now contains the number of polygons

NumPoly = n
return
end
subroutine sortfrm(frame)

Description: Uses a simple exchange sort to order FRAME on decreasing Y. Ignores (0,0) pairs.

This sort should be efficient enough given the small number of points which can be in a frame. If MaxPts goes above 200, someone should consider exchanging this for a shell sort or something else more efficient.

Author: Chuck Gendrich

History:
August, 1987 v1.0

Procedure:
Determine how many points there are
For all points except the last
  check this point against all subsequent
    if X > Xsubsequent,
      swap X's and Y's
    if X == Xsubsequent
      check Y's and swap if appropriate
  end for

ccc

include "vorticity.h"

n = NumPts(frame, 2)
find out how many points there are in this frame

do 100 i=1,n-1
check all points but the last
do 75 j=i+1, n 
  compare it against all remaining points
  if( frame(i,Y).lt.frame(j,Y)) then
    call swap( frame(i,X), frame( j,X))
    call swap( frame(i,Y), frame( j,Y))
  else if (frame(i,Y).eq.frame(j,Y)) then
    compare X's
    if( frame(i,X).lt.frame(j,X)) then
      call swap( frame(i,X), frame( j,X))
      call swap( frame(i,Y), frame( j,Y))
    endif
  endif
75 continue
100 continue
return
end

subroutine swap( a, b)
real a, b, tmp

tmp = b
b = a
a = tmp

c
    return
end
subroutine Matches( framel, frame2, match, ierr)

Description: Establishes a correspondence between points in {framel and frame2}. Match is setup such that

\[ \text{framel}(i) \leftrightarrow \text{frame2}(\text{match}(i)) \]

Algorithm: (What algorithm? Huh? Who? Where? :-( ) We'll be looking for points within a certain neighborhood of the original point. At the moment, we'll assume there's only one point which will fall into the neighborhood, but that may not be the case.

We'll error-check. If more than one point matches, this routine will return an error. If no point matches, a zero will be put in the appropriate place in Match.

Author: Chuck Gendrich ("I wish I knew how to do this one better.")

History:
August, 1987 v1.0

#include "vorticity.h"

real close, close2
parameter( close = 23)
parameter( close2 = close*close)

half the distance in pixels between the two closest points in the original image (FENCE1)

real dist
integer NumPts
external dist, NumPts

integer found

how many matches have we found

initialize Match

do 10 i=1, MaxPts

match(i) = 0

continue

OK, we'll do it the hard way. Compare every point in {framel}
with every point in frame2. Tally all the distances less than
CLOSE. If there's only one point, wonderful. Otherwise, oops.

n1 = NumPts( framel, 2)
n2 = NumPts( frame2, 2)

do 100 i=1, n1
found = 0
xl = framel(i,X)
yl = framel(i,Y)
do 75 j=1, n2
   x2 = frame2(j,X)
   y2 = frame2(j,Y)
   dx = x2-xl
   dy = y2-yl
   if( (dx*dx + dy*dy).lt.close2) then
      found = found+1
      if( found.gt.MatchDim) then
         ierr = 6
         return
      endif
      matches( found) = j
   endif
75 continue
if( found.eq.0) then
   match(i) = 0
else if( found.eq.1) then
   match(i) = matches( 1)
else
   Of course this should be made more sophisticated so that
   it can conflict-resolve any problems. But for now, just
   chalk up an error and return.
   ierr = 7
   return
endif
100 continue
ierr = 0
return
end
subroutine Velocities( framel, frame2, match, vel)

Description: vel-maker computes the position and both components of the velocity vector between matching points in frame1 and frame2.

The position is assumed to be at the midpoint between the two matching points. If there is no matching point in FRAME2 for some point in FRAME1 (match(i) == 0), the position and velocity components are left 0.

The initial "velocity" is in dPixels. A conversion for pixels to real units of measure, and knowledge of dTime between frames is required so that we can calculate the real velocity. This will be done in a subsequent routine.

Author: Chuck Gendrich

History:
August, 1987 v1.0

include "vorticity.h"

character*80 line
integer NumPts
real avg, getreal
external avg, NumPts, getreal

initialize the velocity descriptor array

do 10 i=1, NumPts
   vel(i,X) = 0.0
   vel(i,Y) = 0.0
   vel(i,Vx) = 0.0
   vel(i,Vy) = 0.0
10 continue

write( *, 1000)
1000 format(' Please enter now many pixels a point moving at: /
   the free stream velocity will move between frames:/
   (Vx) = (deltaX) + baseV')
   line = ' -36.1655 pixels/frame'
   baseV = getreal( line)
   scale = 4.0 * exp( -abs(baseV) / 28.0);

n = NumPts( framel, 2)
1 = 0

do 100 j=1, n
   make a corresponding entry in vel for each point in frame1
   if( match(j) .ne. 0) then
      we have something to work with
i = i+1
vel(i,X) = avg(frame1(j,X), frame2(match(j,X))
vel(i,Y) = avg(frame1(j,Y), frame2(match(j,Y))
vel(i,Vx) = frame2(match(j,X)) - frame1(j,X) + baseV
vel(i,Vy) = frame2(match(j,Y)) - frame1(j,Y)
call move2(vel(i,X), vel(i,Y))
call vector(vel(i,Vy), vel(i,Vx), scale)

c endif

100 continue

c Now construct the TURB3d output files.
c
open( unit=3, file='vel.xyz')
unit3 -- flow field point locations
open( unit=4, file='vel.q')
unit4 -- flow field information

c write( 3, 1010) 1
write out the X and Y locations
write( 3, 1020) vel(j,X), j=1,i,
write( 3, 1020) vel(j,Y), j=1,i,

c write( 4, 1030) 1
write out the Vx and Vy velocities
write( 4, 1020) vel(j,Vx), j=1,i,
write( 4, 1020) vel(j,Vy), j=1,i,
do 110 j=1,i
write out a fictitious pressure value
write( 4, 1040)
110 continue

do 120 j=1,i
write out a fictitious vorticity value (for now)
write( 4, 1040)
120 continue
1010 format( i3, 'l')
1020 format( 5(f10.5,1x))
1030 format( i3, 'l'/'1 1 1 1')
1040 format( 'l')
c return
end
real function dist( xl, yl, x2, y2)
    real xl, yl, x2, y2, sqrd
    sqrd = (xl-x2)**2 - (yl-y2)**2
    dist = sqrt( sqrd)
    return
end

real function avg( a, b)
    real a, b
    avg = (a+b)/2.0
    return
end

real function tanl( dy, dx)
    returns the arctan in degrees given dx and dy
    real dx, dy, angle, pil80, small
    parameter( small = 0.0001)
    to keep from dividing by zero
    parameter( pil80 = 57.29579513)
    180/pi for converting to degrees
    if( abs( dx),it.small) then
        let's not divide by zero, shall we?
        if( dy gt 0) then
            tanl = 90.0
        else if( dy lt 0) then
            tanl = 270.0
        else
            tanl = 0.0
            ??? punt ???
    endif
    else
        angle = atan( dy/dx) * pil80
        if( dx gt 0) then
            first or fourth quadrant -- atan is OK
            if( angle lt 0) then
                angle = angle + 360.0
            endif
            make sure angle is > 0
        endif
    else
        angle = atan( dy/dx) * pil80
        if( dx gt 0) then
            first or fourth quadrant -- atan is OK
            if( angle lt 0) then
                angle = angle + 360.0
            endif
            make sure angle is > 0
        endif
    endif
real function interp( xx0, ffx0, xx2, ffx2, xl, ierr)

ccccccclccccc2ccccccccccc3cccccccc4cccccccccc5cccccccccc6cccccccccc7cc

returns the interpolated value for \( f(x) \) given the function
value at boundaries \( x_0 \) and \( x_2 \). \( x_l \) has to lie between \( x_0 \) and \( x_1 \).

real \( x_0, f(x_0), x_2, f(x_2), x_1, x(x_0), f(x_0), x_2, f(x_2) \)
integer ierr

real small
parameter( small = 0.00001,)

real \( dx_0, dfx \)

\( x_0 = xx_0 \)
\( f(x_0) = f(x_0) \)
\( x_2 = xx_2 \)
\( f(x_2) = f(x_2) \)

since we don't want to change the original values for \( x_0 \) and \( x_2 \),
etc., we make our own copies which we can switch around if
necessary.

interp = \( f(x_0) \)

\( \text{junk answer just in case they don't check ierr and interp's} \)
\( \text{value isn't changed because of some error...} \)

\( dx_0 = x_2 - x_0 \)

if( abs( \( dx_0 \)) < small) then
  \( \text{let's avoid division by zero, eh?} \)
  ierr = 16
  return
else if( \( dx_0 \lt 0 \)) then
  \( x_0 > x_2 \) \( \rightarrow \) we have to switch them around
  call swap( \( x_0, x_2 \))
  call swap( \( f(x_0, f(x_2) \))
  \( dx_0 = -dx_0 \)
else
  \( \text{they're already in the right order and plenty far apart} \)
endif

if( \( x_1 \lt x_2 \) or \( x_1 \lt x_0 \)) then
  \( \text{out of bounds (oops)} \)
  ierr = 17
  return
endif

dxl = xl - x0
dfx = fx2 - fx0

c interp = fx0 + ( dfx * dxl / dx0)
return
end

subroutine centroid( poly, vel, i, x0, y0, ierr)

C Description: The centroid of a four-sided figure is calculated. This is located at the intersection of the two lines which join the midpoints of opposing sides.

Author: Chuck Genorich

C History:
August, 1987

C integer a,b,c,d
real Ax, Ay, Bx, By, Cx, Cy, Dx, Dy

real ml, m2, b1, b2

real deltaY, deltaX, y1, x1, y2, x2
d = poly( i,4)

Ax = vel(a,X)
Ay = vel(a,Y)
Bx = vel(b,X)
By = vel(b,Y)
Cx = vel(c,X)
Cy = vel(c,Y)
Dx = vel(d,X)
Dy = vel(d,Y)

ifdef DEBUG
write(*,990) a,Ax,Ay,b,Bx,By,c,Cx,Cy,d,Dx,Dy
990 format(/' centroid: finding the centroid with these corners --'/
+ (4x,i2,: ('f8.3','f8.3')))
1000 format(' Wierd centroid (no dx or dy) at ('f8.3','f8.3')')
1010 format(' centroid; neither line vertical. m1: 'f8.3,
+ ' m2: 'f8.3/ b1: 'f8.2/ b2: 'f8.2 --> ('f8.3','
+ f8.3')/)
1020 format(' centroid: ',a6,' vertical. m: 'f8.3/ b: ',
+ f8.3/ --> ('f8.3','f8.3')/)
endif

--- initialize x0 and ierr (x0 must be known later)

x0 = -99999.0
ierr = 0

--- line 1 first

yl = avg(Ay,By)
x1 = avg(Ax,Bx)

deltaY = avg(Cy,Cy) - yl
deltaX = avg(Dx,Cx) - x1

if( abs(deltaX).lt.small) then
  let's see if we'll be dividing by zero
  if( abs(deltaY).lt.small) then
    midpt(AB) = midpt(CD) (?) and the centroid is there
    y0 = yl
    x0 = x1
    ifdef DEBUG
    write(*,1000) x0, y0
    endif
    return
  else if( abs(deltaX/deltaY).lt.small) then
    midpt(AB) --> midpt(CD) is a vertical line
    ml = x0
    x0 = x1
    endif
  else
    ml = deltaY / deltaX
    ol = y1 - ml*x1
  endif
c --- line 2 next
c  
y2 = avg( Ay, Dy)
x2 = avg( Ax, Dx)
c
deltaY = avg( By, Cy) - y2
deltaX = avg( Bx, Cx) - x2
c
if( abs( deltaX).lt.small) then
  if( abs( deltaY).lt.small) then
    midpt(BC) = midpt(DA) (?) and the centroid is there
    y0 = y2
    x0 = x2
    ifdef DEBUG
    write( *, 1000) x0, y0
    endif
    return
  else if( abs( deltaX/deltaY).lt.small) then
    midpt(BC) --- midpt(DA) is a vertical line
    if( x0.ne.-99999.0) then
      ierr = 4
      return
    else
      m2 = x0
      x0 = x2
    endif
  endif
else
  m2 = deltaY / deltaX
  b2 = y2 - m2*x2
endif

c --- now for the intersection (i.e., the centroid)
c
c -- calculate x0 if we still need to
if( x0.eq.-99999.0) then
  neither line was vertical
  x0 = -(b2 - b1) / (m2 - m1)
y0 = m2 * x0 + b2
  ifdef DEBUG
  write( *, 1010) m1, m2, b1, b2, x0, y0
  endif
  return
endif

c -- calculate y0 using the appropriate slope and intercept.
if( m1.eq.-99999.0) then
  line 1 is vertical so use m2 and b2
  ifdef DEBUG
  write( *, 1020) 'line 1', m2, b2, x0, y0
  endif
  y0 = m2 * x0 + b2
else
  use m1 and b1
y0 = ml * x0 + bl

ifeff DEBUG
write( *, 1020) 'line 2', ml, bl, x0, y0
endif

return
end
subroutine Polygons( vel, poly, ierr)

Description: Establishes a polygon descriptor array. Each element in poly(i) describes a corner of the polygon according to the following scheme:

```
poly( i,1) --> upper LH corner
poly( i,2) --> upper RH corner
poly( i,3) --> lower LH corner
poly( i,4) --> lower RH corner
```

Procedure: Try to make roughly rhomboidal-shaped polygons. Try to use each point in VEL as an upper LH corner. If it doesn't work, move on to the next point.

Author: Chuck Genurich ("SCORPIO: all scorpio's are assassinated.")

History:
15 Aug 87 <cpg> v1.1 -- removed the triangle logic, look in older versions to recover it.

```
! include *'vorticity.in"'
real delta
when we look for a corresponding corner, it will be in a particular direction +/- delta deg.
integer ULH, URH, LRH, LLH
pointers to the UpperLeftHand, UpperRH, LRH, and LLH
vertices of the polygon under construction

logical IncrP
integer NumPts, look
external NumPts, look, IncrP

n = NumPts( vel, 4)
delta = 30.0
look for point ∩ direction +/- delta deg.
p = 0
we have currently found zero polygons

Do 100 ULH=1, n

URH = look( ULH, vel, 4, RIGHT, delta, matches, ierr)
if( URH.ne.BAD.and.ierr.eq.0) then
found the URH corner
LRH = look( URH, vel, 4, DOWN, delta, matches, ierr)
if( LRH.ne.BAD.and.ierr.eq.0) then
LLH = look( LRH, vel, 4, LEFT, delta, matches, ierr)
if( LLH.ne.BAD.and.ierr.eq.0) then
we have an OK polygon
if( IncrP( p)) then
poly(p, 1) = ULH
poly(p, 2) = URH
poly(p, 3) = LRH
poly(p, 4) = LLH
else
  return
doesn't make sense to look for any more polygons if poly is full....
endif
endif
endif
if(ierr.ne.0) then
c  there was an error "lookinl"
  return
endif
c
in every other case, we couldn't find a satisfactory polygon.
Forget using this corner as the start of a polygon.
c
100  continue
return
end

logical function IncrP(p)
c  simple-minded routine to increment p or quit if there's a problem
c  returns: TRUE if p is <= the size of poly
#include "vorticity.a"
c
  p = p+1
  IncrP = (p.le.MaxPoly)
c
return
end
integer function look( p, points, dim, angle, delta, matchs, ierr)

Description: "look" uses the location of point 'p' among the given points. It examines all the other points for ones which are between 100 and 195 pixels away, lying between vectors at angles "angle + delta" and "angle - delta".

\[ \text{angle + delta} \quad \text{no good} \]
\[ \text{angle - delta} \]

Return value: "look" returns BAD if no point falls within the defined search region.

If only one point matches, "look" returns the pointer to that point.

If more than one point matches, "look" returns a pointer to the one which is closer to the preferred direction.

Author: Chuck Genorich

History:
August, 1987 v1.0

include "vorticity.h"

integer dim
real points( MaxPts, dim)
real angle, delta
integer NumPts
external NumPts

integer found
real AplusD, AminusD
\quad -- to store Angle + Delta and Angle - Delta
real x1, y1, x2, y2, dx, dy
real d, direction
\quad distance and direction from (x1,y1) to (x2,y2)
real MinD, MaxD
parameter( MinD = 40.0)
parameter( MaxD = 180.0)

c the closest and farthest that a point has to be
in order for it to be considered.

c real Distnc( MatchDim)
c difference between the desired and the actual angle

c integer best
a pointer to the best match (when there's more than one)
c
logical first, DoDraw
c character*1 char
save
data first/.TRUE./
c
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we'll simply 'continue' on to the next one.

if( i.eq.p) goto 100

x2 = points( i, X)
y2 = points( i, Y)
if( DoDraw) then
call circ( x2, y2, SMALLRAD)
endif
dx = x2-xl
dy = y2-yl
d = sqrt( dx*dx + dy*dy)

if( d.lt.MinD.or.d.gt.MaxD) goto 100

direction = tanl( dy, dx)

if( direction.gt.AplusD) direction = direction - 360.0
  NB -- tanl always returns 0 <= angle <= 360
  but if AminusD < 0 and the direction really is
  OK at its position in the fourth quadrant, it'll
  never match. Plus, we have to have A+D > A - D...
  Therefore, if direction > A+D, we'll give it a
  chance to match with angles in the 4th quad.

if( direction.le.AplusD.and.direction.ge.AminusD) then
  found = found + 1
  if( found.gt.MatchDim) then
    ierr = 12
    return
  endif
  if( DoDraw) then
    call circ( x2, y2, BIGRAD)
    call color( RED)
    call move2( xl, yl)
    call draw2( x2, y2)
    call color( WHITE)
  endif
  Distnc( found) = dist( xl, yl, x2, y2)
  matches( found) = i
endif

100 continue

So now we've looked at every point

if( found.eq.0) then
  look = BAD
else if( found.eq.1) then
  look = matches(1),
else
  look for the match which deviates the least from the
desired angle
  best = 1
  do 200 i=2, found
  if( Distnc(i).lt.Distnc(best)) then
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    best = i
    endif
    continue
    look = matches( best)
    endif
    return
    end
subroutine fluids( vel, poly, UnDim, ierr)

Description: calculates the fluid mechanical properties of the flow. The object is to produce plot(s) of
(1) du/dy
(2) du/dx
(3) dv/dy
(4) dv/dx
(5) uv
(6) Wz (vorticity)

Output: all output will be written to stdout. If you want it in a file, put a tee on the process when you run it.
e.g.: freyja> vorticity | tee output_file

Procedure: First the conversion factor for pixel <-> mm is obtained, along with the time between each frame and the absolute Y offset for both frames.

Author: Chuck Genarich

history:
August, 1987 vl.0 -- lots of linear interpolation. ugh.
15 aug 87 <cpg> vl.1 -- removed triangle logic. see older versions to recover it.
16 aug 87 <cpg> vl.2 -- added the non-dim title stuff
22 jan 88 <cpg> vl.3 -- graphics to draw the polygons
7 apr 88 <cpg> vl.4 -- defines a colormap based on Wz[min-max]

#include "vorticity.h"

real ad, d, avg, dist
integer NumPts, NumPoly
external NumPts, NumPoly, d, avg, dist

integer a, b
  a and b point to the vertices of the side along which the velocity is to be integrated next

real suba, subi
real area, integral, GAMMA
  area of the polygon which is integrated
  integral of V * ds around the polygon
  GAMMA is the total circulation throughout the frame

logical UnDim
  from convert... TRUE if results are being UnDim'd

character*2 num
character*5 Xunits, result
character*7 Runits
  for titling the output: depending on whether the results are being non-dimensionalized or not...
real Parray( 2, 4)
c array - points array. XY locations of polygon vertices
array - intensity array. vorticity at the corners.

real Wz( MaxPoly), WZmax, WZmin
Stores the values of Wz, their max. and min.

integer Csplit, shade
parameter( Csplit= 56)
the total number of colors which we can draw

1000 format( ' X',a5,' Y',a5,3x,a5,a7)

p = NumPoly( poly)
n = NumPts( vel, 4)
if( UnDim) then
    XYunits = ' (noD)' 
else
    XYunits = ' (mm)'
endif

vorticity

if( GoOn()) then
    title = 'vorticity'
endif
result = ' Wz '
call CutHere( title)
if( UnDim) then
    Runsits = ' (noD)'
else
    Runsits = ' (1/sec)'
endif
write( *, 1000) XYunits, XYunits, result, Runsits

GAMMA = 0.0
call color( WHITE)
call clear()
WZmin=+999999.
WZmax=-999999.
do 100 i=1, p
    call color( RED)
    area = 0.0
    integral = 0.0
    do 50 j=1,3
        a = poly( i, j)
b = poly( i, j+1)
c and b are the endpoints of the side along which
V * ds is to be integrated.
call integral( a, b, vel, suba, subi)
x1 = vel( a, X)
x2 = vel( b, X) 
y1 = vel( a, Y)
y2 = vel( b, Y)

call move2( xl, y1)
call draw2( x2, y2)
area = area + suba
intgr1 = intgr1 + subi

50 continue

c now for the last side (4 --> 1)
a = poly(i,4)
b = poly(i,1)
call integrt( a, b, vel, suba, subi)
x1 = vel( a, X)
x2 = vel( b, X)
y1 = vel( a, Y)
y2 = vel( b, Y)

call move2( xl, y1)
call draw2( x2, y2)

area = area + suba
intgr1 = intgr1 + subi
Wz = intgr1 / area
Wzs(i) = Wz
if( Wz.lt.WZmin) WZmin=Wz
if( Wz.gt.WZmax) WZmax=Wz

c call centroid( poly, vel, i, xO, yO, ierr)
if( ierr.ne.0) goto 100

intgrl = intgrl * 50.0 * 0.29520809 * 0.29520809 / 1.0
GAMMA = GAMMA + intgrl

ifdef DEBUG
print*, 'Area=',area,' intgrl=',intgrl,' GAMMA now=',GAMMA
endif

call convert( xO, yO, Wz, 0.0, UnDim)
call color( CYAN)
call cmov2( xO, yO)
write( num,'(i2)') i
call charst( num, 2)

100 continue
GAMMA = GAMMA

circ = (pix**2 / frame) * (frame/sec) * (mm/pix)**2
print*, 'Total circulation is ',GAMMA,' (mm^2/sec)'
if( GoOn() ) then
do 150 i=1,p

draw shaded polygons
shade = (Wzs(i) - WZmin) / (WZmax-WZmin)* (Csplit)+0
ifdef DEBUG
print*, 'Vorticity ',i,' is ',Wzs(i),'. Shade is ',shade
endif
call color( shade)
do 125 j=1,4
Parray( X, J, j) = vel( poly(i,j), X)
Parray( Y, j) = vel( poly(i,j), Y)

continue
call polf2( 4, Parray)

continue
endif
if( GoOn()) then
  continue
endif
c

c = du/dy
c
title = 'du/dy'
result = 'du/dy'
call CutHere( title)
write( *, 1000) XYunits, XYunits, result, Runits
c
do 200 i=1, n
da = u( Vx, udy, i, vel, ierr,
ignore cd and ierr -- either something was found and
printed or it wasn't... dd produces its own output...
c
do 400 i=1, n
da = d( Vy, ddy, i, vel, ierr)
c= dv/dy
c
title = 'dv/dy'
result = 'dv/dy'
call CutHere( title)
write( *, 1000) XYunits, XYunits, result, Runits
c= dv/dx
c
title = 'dv/dx'
result = 'dv/dx'
call CutHere( title)
write( *, 1000) XYunits, XYunits, result, Runits
c
Reynold's stress

```fortran
title = 'instantaneous Reynolds stress'
if( UnDim) then
    result = ' uv '
else
    result = 'uv (m'
    Runits = 'm/s)^2 '
endif
```
call CutHere( title)
write( *, 1000) XYunits, XYunits, result, Runits
do 600 i=1,n
    call convert( vel(i,X), vel(i,Y), 0, vel(i,Vx)*vel(i,Vy),
                 UnDim)
600    continue
creturn
dend
```
subroutine getline( line)

Prompting needs to be done before calling getline.

Input:
- line initially contains the default value

Return value:
- line contains the output

character*80 line, inline, blank
character*1 comment

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data blank/ ' '/',data comment/ '\'/

format( '/ Default: ',a80)

format( a80)

write( *, 1000) line

continue

return here if the line is a comment
read( *, 1010, end=200) inline

ifdef DEBUG
write( *, 1020) inline

endif

format( ' getline: ',a80)

if( inline(1:1).eq.comment) goto 100
if( inline.ne.blank) then
    line=inline
else
    don't change the line....default was accepted.
endif

return

continue

EOF was detected

line = blank
return

end

real function getreal( prompt)

character*80 prompt
real value

call getline( prompt)
read( prompt, '(f10.3)') value

getreal = value
return

end
logical function Again(ierr)

Description: Print out a diagnostic and figure out whether the user wishes to stop the program or rerun the section which just generated the error.

Author: Chuck Gendrich

History:
August, 1987, v1.0

character*1 YorN

include "vorticity.e"

1000 format(a80/' Do you wish to repeat the section where ', + 'the error occurred? [y]'
1010 format(' al)
1020 format(' Please input either 'y' or 'n'.')

continue
write( *, 1000) err ierr)
read( *, 1010,end=20) YorN
if( YorN.ne.'y'.and.YorN.ne.'Y'.and.YorN.eq.'n'.and.YorN.ne.'N' ) then
  the user goofed, can't type or something :-/
  write( *, 1020)
  goto 10
else
  Again = ( YorN.eq.'y'.or.YorN.eq.'Y'.or.YorN.eq.'n'.or.YorN.eq.'N')
  return
endif

20 continue

EOF encountered
Again = .FALSE.
return
end
subroutine CutHere(title)
  c
  c include "vorticity.n"
  c
  write(*,1000) title
  c
  1000 format(/ \
               '/
               '/ =------------ cut here for: ',a40/
               '/
  c
  return
  end
real function d( VxVy, dd, p, vel, ierr)

Description: Take the derivative of U or V with respect to x or y (as indicated by dd). The derivative is to be taken at point p in velocity descriptor array vel.

du/dy Procedure: Look down. If a "down" point exists, see what angle it's at, interpolate to find u at a point directly below the original point. This makes dx == 0.

Then calculate du/dy = (u1-u2) / (y1-y2) at the point (x0, avg(y))

du/dx Procedure: Similar to du/dy, but swap X's and Y's

dv/dy Procedure: Identical to du/dy, but use vel(Y) instead.

This should be taken care of by the routine being called with VxVy set to either Vx or Vy (as appropriate).

Author: Chuck Genrich

History:

August, 1987 v1.0

...
\begin{verbatim}
 ierr = 0 if (dd.eq.ddy) then
   j = look( p.vel.4, DOWN, delta, matches, ierr)
   ifdef DEBUG
     write( *, 1010) 'down', p, j
   endif
 else
   j = look( p vel.4, RIGHT, delta, matches, ierr)
   ifdef DEBUG
     write( *, 1010) 'right', p, j
   endif
 endif
1010 format( 'look'd ',a5,' from ',i2,' and found ',i2,'')
c* + /' Here's the match array:'20(i1x,i2))
c c error check point j
 if( j.eq.BAD.or.2.err.ne.0; zhen
 d = BAD
   if( ierr .ne. 0, then
     return
   else
     ierr = 21
     return
   endif
 endif
c x0 = vel( p,X)
x2 = vel( j,X)
x = x2 - x0
c y0 = vel( p,Y)
y2 = vel( j,Y)
y = y2 - y0
c angle = tan1 dy, ax)
 if( d eq.ady) then
   if( angle .gt. DOWN) then
     k = look( j vel.4,LEFT, delta, matches, ierr)
   else
     k = look( j vel.4,RIGHT, delta, matches, ierr)
   endif
 else
   if( angle .gt. delta ) then
     it's in the 4th quadrant.
     k = look( j vel.4,UP, delta, matches, ierr)
   else
     k = look( j vel.4,DOWN, delta, matches, ierr)
   endif
 endif
 interpolate if we found a point to interpolate with...
 if( k .ne. BAD .and. ierr .eq. 0) then
\end{verbatim}
there is a point to interpolate to

ifdef DEBUG
write( *, 1020) j,k
1020 format(' \ams' Going to interpolate between points ',i2, ' and ',i2, '.')
endif
if( dd.eq.ddy) then
u = interp( x2, vel(j,VxVy), vel(k,X), vel(k,VxVy), x0,ierr)
else
u = interp( y2, vel(j,VxVy), vel(k,Y), vel(k,VxVy), y0,ierr)
endif
else
use the lower/right velocity and ignore dx/dy... eek!
u = vel( j,VxVy)
endif

ifdef STRICT
if( k.eq.BAD.or.ierr.ne.0) then
return
endif
endif

du = u - vel( p,VxVy)
if( dd.eq.ddy) then
d = du/dy
call convert( x0, avg( y0,y2), du/dy, 0, UnDim)
else
d = du/dx
call convert( avg( x0,x2), y0, du/dx, 0, UnDim)
endif
return
1040 format( 3(2x,8.3))
end
subroutine convert(xpix, ypix, ddpix, uvpix, UnDim)

Description: print out the conversion to "real units"
of the above values. Only print out the ones whicharen't zero (generally either ddpix or uvpix)...

Output: all output will be written to stdout. If you want it ina file, put a tee on the process when you run it.
e.g.: lori 38> vorticity | tee output_file

Procedure: First get conversion factors and the time betweeneach frame. Since this subroutine is "saved", these valuesonly have to be obtained once, then they're applied to everysubsequent value as appropriate...

Caveats: No values are printed out the first time through.

Author: Chuck Gencrich

History:
August, 1987 v1.0

cccccclccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

logical UnDim

true if values should be non-dimensionalized

real xpix, ypix, ddpix, uvpix
xpix and ypix are (X, Y) in pixel values
ddpix is a spatial derivative of some velocity(e.g., uu/dx)

uvpix is the product of two velocities(e.g., Vx*Vy)

real xmin, ymin, ddmn, uvmm

x, y, dd, and uv converted to "real units" or non-
dimensionalized (local copies of the numbers so thatwe don't accidentally try to set some constant equal
to something else....)

real Xmpixel, ut, mdt, mdzt, xorf, yoff

real Uw, nu, t, xytact, ddtact, uvfact
Uw -- wall velocity
nu -- kinematic viscosity
t -- total elapsed time

xytact -- non-dimensionalizing factor for x's and y's

ddtact -- non-dimensionalizing factor for dd's

uvfact -- non-dimensionalizing factor for uv's

real etreal
external etreal

cchararter*60 line
save

data mmPixel, dt/ 2*0.0/

1000 format( 'Please enter the multiplication factor to convert'/
+ ' pixels to mm. (pixel_value * factor) = (mm_value)' )
1020 format( 'Please enter the time between frames (dt).' )
1030 format( 'Please enter the Y offset for frame 1.'/
+ ' (Y(frame1) - Yoffset) = Y (abs dist to the wall)' )
1040 format( 'Would you like the values to be non-dimensionalized?',
+ '[n]' )
1050 format(a80)
1060 format( 'Please enter the wall velocity, Uw.' )
1070 format( 'Please enter the kinematic viscosity, nu.' )
1080 format( 'Please enter the total elapsed time, t.' )
1090 format( '/ convert: mmPixel: ',f10.9,' , dt: ',f10.9,' , Yoff: ',
+ f10.7 )
1100 format( '/ convert: non-dimensionalizing. xyfact: ',e9.4,
+ ' gafact: ',e9.4,' uvfact: ',e9.4/ )
1110 format( '/ convert: printing values with real units./ )
1120 format( '/ convert: Pixel values -- (',f8.2,',',f8.2,')/ /
+ spat. deriv: ',f12.3,' and uv value: ',f12.3/ )
1130 format(4(2x,f11.3) )

cccc-ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

set the conversion to mm's and the time between frames if necessary

if(mmPixel.ne.0 .and. dt.ne.0) goto 100
neither of these values is permitted to be zero...

10 continue

write( *, 1000 )
line = '0.029520809 mm/pixel'
0.0277 mm/pixel when .50" = 458.13 pixels
mmPixel = getreal( line )

write( *, 1020 )
line = '0.020000000 sec'
dt = getreal( line )

Umat = mmPixel/dt
Umdt2 = Umat * .6mdt

write( *, 1030 )
line = '560.0 Pixels'
Yoff = getreal( line )

Yoff = 0.0

10 continue

set non-dimensionalizing constants (or set them to 1.0)

write( *, 1040 )
read( *, 1050) line
if( line(1:1).eq.'Y'.or.line(1:1).eq.'y') then
   UnDim = .TRUE.
else if( line(1:1).eq.'N'.or.line(1:1).eq.'n'.or. +
   line(1:1).eq.'n') then
   UnDim = .FALSE.
else goto 20
endif

if( UnDim) then
   write( *, 1060)
      line = '5.0 in./sec'
      Uw = getreal( line)
   write( *, 1070)
      line = '0.00310460 in^-2/sec.'
      nu = getreal( line)
write( *, 1080)
      line = '5.25 sec.'
      t = getreal( line)
      xyfact = 1.0/( 2.0 * 25.4 * sqrt( nu * t))
      ddfact = 4.0 * sqrt( nu * t) / Uw
      uvfact = 1.0
      don't know how to non-dimensionalize this one
else
      xyfact = 1.0
      ddfact = 1.0
      uvfact = 1.0
endif

C ifDEBUG
write( *, 1090) XmPixel, ut, Yoff
if( UnDim) then
   write( *, 1100) xyfact, udfact, uvfact
else
   write( *, 1110)
endif
endif

if((mPixel.eq.0.or. ut.eq.0) goto 10
      return
      don't print anything out the first time through
100 continue

C ifdef DEBUG
write( *, 1120) xpix, ypix, adpix, uvpix
endif

uxm = (xpix - Xoff) * XmPixel * xyfact
uym = (ypix - Yoff; * XmPixel * xyfact
zomm = ddpix / ut * ddfact
uvmm = uvpix * Mmdt2 * uvfact

! if(ddmm.ne.0.and.uvmm.ne.0) then
  write(*,1130) xmm, ymm, ddmm, uvmm
! else if(ddmm.ne.0.and.uvmm.eq.0) then
  write(*,1130) xmm, ymm, ddmm
! else if(ddmm.eq.0.and.uvmm.ne.0) then
  write(*,1130) xmm, ymm, uvmm
! else
  write(*,1130) xmm, ymm
endif

! return
end
subroutine integrt( pl, p2, vel, area, intgrl)
C
Description: Integrating from point pl to point p2 (whose X- and Y-coordinates are described in vel), return the area under the curve and the value of V * ds. Simple trigonometric and calculus identities are used; e.g., the area between a line and the x-axis is 1/2 (y1 + y2) (x2 - x1) and
V*ds = |V|*|s|*cos( the angle between the two vectors)

Temporary variables are used to store intermediate results so that the steps are clear.

Author: Chuck Gendrich
History:
August, 1987 v1.0

C define DEBUG
C include "vorticity.h"
C
integer pl, p2
real area, intgrl
real avg, dist, tanl
external avg, dist, tanl
real Ubar, Vbar, V, s, thetaV, thetaS
Ubar is the average Vx for a side
Vbar is the average Vy for a side
V is the magnitude of the velocity vector
s is the length of a side
thetaV is the angle V makes with the -x axis
thetaS is the angle S makes with the -x axis
real pil80
parameter( pil80 = 0.017453293)
pi/180 for converting degrees to radians
if( pl.eq.0.or.p2.eq.0) then
we're integrating to or from a non-existent point
area = 0.0
intgrl = 0.0
return
endif
xl = vel( pl, X)
yl = vel( pl, Y)
x2 = vel( p2, X)
y2 = vel( p2, Y)
cx = x2 - xl
ay = y2 - yl
Ubar = vel(pl, Vx)
Vbar = vel(pl, Vy)
Ubar = avg( vel(pl, Vx), vel(p2, Vx))
Vbar = avg( vel(pl, Vy), vel(p2, Vy))
V = sqrt( Ubar*Ubar - Vbar*Vbar)
s = sqrt( cx*dx + dy*dy)
thetaV = tanl( Vbar, Ubar)
thetaS = tanl( dy, dx)
intgrl = V * s * cos( (thetaV - thetaS) * pi/180)
area = 0.5 * (y1 + y2) * dx

ifdef DEBUG
write( *, 1000) pl, p2, dx, dy, Ubar, Vbar, V, s, thetaV, thetaS
1000 format('/' intgrl: from ',i2,' to ',i2,'. ax: ',f8.3,' ay: ',f8.3,' Vbar: ',f8.3,' V: ',f8.3,' s: ',f8.3,' thetaV: ',f9.3,' and thetaS: ',f9.3)
write(*, 1010) intgrl, area
1010 format(' line intgrl: ',f12.3,' area: ',e14.3)
endif
return
end
subroutine vector(dy, dx, scale)

  Description: Draw a 2D vector with arrow head from the current
  point through the final point. The length of the vector will be
  equal to its original length times 'scale'.

  The arrow head will always be the same size (more or less).

  Current values for linewidth, color, etc. are used.

  Author: Chuck Gendrich <cpg>
  ("You mean I can't just find this in some library?!OL")

  History:
  12 dec 87 -- original inception and coding

  real uy, dx, scale

  real SideLen, dAng
  parameter( SideLen = 8.0)
  parameter( dAng = 20.0)

  real xl, yl, x2, y2, x3, y3, a2, a3
  destination points for the far end of the vector and the
  two ends of the arrow head...

  real angle
  the angle that the vector makes with the X-axis

  real tanl
  external tanl
  real pi
  parameter( pi = 3.141592653589)

  Figure the angles that the lines will be at WRT the X-axis

  angle = tanl( uy, dx)
  a2  = (angle - dAng) * pi / 180.0
  a3  = (angle + dAng) * pi / 180.0

  Figure the relative moves

  xl = scale * dx
  yl = scale * dy
  x2 = -SideLen * cos( a2)
  y2 = -SideLen * sin( a2)
  x3 = -SideLen * cos( a3)
  y3 = -SideLen * sin( a3)

  Draw it

  call rarl(xl, yl)
call rdr2( x2, y2)
call rmv2(-x2, -y2)
call rdr2( x3, y3)

C

Put the cursor back where we started

C

call rmv2(-x3,-y3)
call rmv2(-x1,-y1)

C

return
end
logical function GoOn()

character*1 char
logical first, slow
save

data first/.TRUE./

if( first) then
  first = .FALSE.
  print*, 'Slow mode? [y]'
  read( *, '(A1)') char
  if( char.eq. 'n' .or. char.eq. 'N') then
    slow = .FALSE.
  else
    slow = .TRUE.
  endif
endif

if( SLOW) then
  print*, '<RETURN> to continue...
  read( *, '(A1)') char
endif

GoOn = .TRUE.
return
end
makefile for the vorticity determination program (vorticity) 
and other miscellaneous test and error-analysis programs 

LIBS= 
DESTDIR=/usr/thor/gendrich/bin/iris/ 

OBJS1= getline.o getframe.o errors.o sort.o match_points.o count_points.o 
velocities.o make_poly.o geometry.o look.o main.o fluids.o 
cut_here.o ddx.o convert.o integrate.o vector.o GoOn.o 

OBJS2= TestLook.o getline.o getframe.o count_points.o geometry.o sort.o 
convert.o GoOn.o 

OBJS3= TestMatch.o getline.o getframe.o errors.o look.o count_points.o 
geometry.o sort.o convert.o vector.o GoOn.o 

OBJS4= TestDdx.o getline.o getframe.o errors.o sort.o match_points.o 
count_points.o velocities.o geometry.o look.o ddx.o convert.o 
vector.o GoOn.o 

OBJS5= getline.o getframe.o errors.o sort.o match_points.o count_points.o 
velocities.o one_poly.o geometry.o look.o TestPoly.o fluids.o 
cut_here.o ddx.o convert.o integrate.o vector.o GoOn.o 

OBJS6= Errors.o stats.o vector.o sort.o count_points.o match_points.o 
getframe.o getline.o geometry.o look.o errors.o convert.o 

OBJS= $(OBJS1) $(OBJS2) $(OBJS3) $(OBJS4) $(OBJS5) $(OBJS6) 

SRCS1= main.f getframe.f count_points.f sort.f match_points.f velocities.f 
geometry.f make_poly.f look.f fluids.f getline.f errors.f cut_here.f 
ddx.f convert.f integrate.f vector.f GoOn.f 

SRCS2= TestLook.f getline.f getframe.f count_points.f geometry.f sort.f 

SRCS3= TestMatch.f look.f getframe.f errors.f getline.f count_points.f 

SRCS4= TestDdx.f ddx.f getframe.f count_points.f sort.f match_points.f 
velocities.f geometry.f look.f convert.f getline.f errors.f 

SRCS6= Errors.f stats.f 

ALL= vorticity TestLook TestMatch TestDdx TestPoly Errors 

0= 
\ can't optimize FORTRAN code. bummer. 
DBG= 
DBG= -g -DDEBUG 

COPTS= -2f -Zg 

CFLAGS= -O $(COPTS) $(CCONFIG) $(DBG) 

CC= f77 

INSTALL=nv -f 

CHMOD= chmod 

OBJMODE=755 

.o: 

$(CC) $(CFLAGS) -c -o $*.o $*.f 

vorticity: $(OBJS1) 

$(CC) $(COPTS) -o vorticity $(OBJS1) $(LIBS) 
$(CHMOD) $(OBJMODE) vorticity 

TestLook: $(OBJS2) 

$(CC) $(COPTS) -o TestLook $(OBJS2) $(LIBS)
$(CHMOD) $(OBJMODE) TestLook

TestMatch:  $(OBJS3)
            $(CC) $(COPTS) -o TestMatch $(OBJS3) $(LIBS)
            $(CHMOD) $(OBJMODE) TestMatch

TestDdx:  $(OBJS4)
            $(CC) $(COPTS) -o TestDdx $(OBJS4) $(LIBS)
            $(CHMOD) $(OBJMODE) TestDdx

TestPoly:  $(OBJS5)
            $(CC) $(COPTS) -o TestPoly $(OBJS5) $(LIBS)
            $(CHMOD) $(OBJMODE) TestPoly

Errors:  $(OBJS6)
            $(CC) $(COPTS) -o Errors $(OBJS6) $(LIBS)
            $(CHMOD) $(OBJMODE) Errors

install: vorticity TestPoly Errors
            $(INSTALL) vorticity $(DESTDIR)
            $(INSTALL) TestPoly $(DESTDIR)
            $(INSTALL) Errors $(DESTDIR)

all: $(ALL)

print:
            pr $(SRCS1) Makefile | rsh freyja lp

clean:
            rm -f core junk $(ALL) $(OBJS)
            mv vor.* Results

TestLook.o: TestLook.f vorticity.h graphics.h
TestMatch.o: TestMatch.i vorticity.h graphics.n
TestDdx.o: TestDdx.f vorticity.h graphics.h
TestPoly.o: TestPoly.f vorticity.h graphics.h Makefile
main.o: main.f vorticity.h graphics.h Makefile
Errors.o: Errors.f stats.h
stats.o: stats.i stats.n
convert.o: convert.f Makefile
count_points.o: count_points.f vorticity.n
cut_here.o: cut_here.f vorticity.h
ddx.o: ddx.f vorticity.h Makefile
errors.o: errors.f vorticity.e
fluids.o: fluids.f vorticity.h
geometry.o: geometry.f vorticity.h Makefile
getline.o: getline.f Makefile
getframe.o: getframe.f vorticity.h
integrate.o: integrate.f vorticity.h Makefile
look.o: look.f vorticity.n
make_poly.o: make_poly.f vorticity.h
one_poly.o: one_poly.f vorticity.n
match_points.o: match_points.f vorticity.h
sort.o: sort.f vorticity.h
velocities.o: velocities.f vorticity.h
Measurement of two-dimensional fluid dynamic quantities using a photochromic grid tracing technique

R. E. Falco, C. C. Chu
Turbulence Structure Laboratory, Department of Mechanical Engineering
Michigan State University
MEASUREMENT OF TWO-DIMENSIONAL FLUID DYNAMIC QUANTITIES USING A PHOTOCHROMIC GRID TRACING TECHNIQUE

R. E. Falco and C. C. Chu

Turbulence Structure Laboratory, Department of Mechanical Engineering, Michigan State University

ABSTRACT

A non-intrusive photochemical phenomena called photochromism is used to obtain important fluid quantities such as velocity, and vorticity over a two-dimensional domain of a fluid flow. Using a uv laser, and a novel beam splitting and steering technique, a grid of lines is impressed in the prepared fluid. Two successive pictures are needed to calculate the fluid dynamic quantities. Measurements in a Stokes' layer are compared against exact solutions, with measurement of the circulation of a vortex ring is presented. The technique will be useful in turbulent and unsteady flows.

1. INTRODUCTION

There is an increasing need to obtain flow field information over a region of flow simultaneously. Examples include the study of mixing in internal combustion engines, and the understanding of the importance of coherent motions in many turbulent and unsteady flows. Furthermore, there is a need to obtain more detailed information about these and many simpler flows, including vorticity and strain-rate measurements. Existing probe techniques are at best able to provide single point estimates of these quantities in flows with steady mean velocities.

Hummel and his co-workers first exploited the phenomena of photochromism. Using a single line of uv radiation for excitation, he and his co-workers were able to measure one component of velocity in flows with predominately one direction of motion. With the advent of high power uv lasers and new chemicals it is increasingly possible to apply the technique to more complicated flows. We have generalized the technique to to uniquely tag specific points in the flow on a specified grid. As a result we have a non-intrusive photophysical technique which can be used to obtain two velocity components and the spatial gradients of these components, at a large number of points in a flow field.

2. USE OF PHOTOCHROMISM TO MEASURE FLUID DYNAMIC QUANTITIES

The phenomena of photochromism has been defined by Brown as a reversible change of a single chemical species between two states having distinguishably different absorption spectra, such change being induced in at least one direction by the action of electromagnetic radiation. The chemical used in this study was 1,3-Trimethyl-8-nitrospiro[2-H-l-benzopyran-2,2'-indoline]. We excited it at 351nm using pulses of 20ns produced by a Tachisto Excimer laser running on XeF (approximately 100mj output). Dissolved in the working fluid, which was kerosene, we found that the chemical, thus excited, reflected blue light for the order of tens of seconds. Thus, the fluid was tagged long enough for it to move appreciably. In practice, for the velocities of our experiments, we needed to follow the lines only a fraction of a second to obtain the information required.

2.1 Use of a grid to tag fluid particles

To enable us to measure two components of the velocity in a flow using the visualization, we must tag and follow specific fluid particles. The simplest way to do this is have two lines intersect. That intersection defines a point in the flow which, because it is colored, we can follow. To measure a spatial gradient, we must simultaneously mark two points in the flow.

To enable us to measure a spatial gradient in a prescribed direction, we need several points and must use interpolation. Thus, creation of a grid of intersecting marked fluid lines would enable both velocities and gradients to be measured.

2.2 The beam divider

We sought a method of dividing a beam of laser light into 'n' beams where 'n' would be 5-25, using a static device. In doing so, we sought to use as little light as possible. Thus, we designed a divider that appears as an oversized blazed reflection grating; the steps size 'a' is approximately 2mm. The incident laser energy was directed at a shallow angle to the plane of the grating. Because the facets are so much larger than a wavelength of light, we expected to see specular reflection. The separation of the specularly reflected portions of the beam were determined by the difference of the angle of incidence and the blaze angle, and the grating step width and spacing as shown in Fig. 1. A photo of the actual beam divider is shown in Fig. 2. It was manufactured by individually fixing Aluminum coated mirrors (with the coating optimized for shallow incidence angles) to a machined base. Apart from diffraction effects, no incidence laser energy would be lost.

![Fig. 1. The specular reflection from the beam divider.](image)

As expected, however, diffraction effects were exhibited. A photo of the output of the beam divider using a Helium Neon laser is shown in Fig. 3. We see the specularly reflected beams, and the superimposed diffraction pattern. The diffraction bands are spaced as expected from the grating equation. The appearance of the first and higher order bands are a source of 'noise' in the present grid making scheme. When experiments were performed with the Excimer laser at...
351 nm, the diffraction pattern was, for reasons we do not understand, not observed. If it was present, results showed that it was too weak to excite the photochromic chemical (see Fig. 5a and 5b).

Fig. 2. The beam divider

![Image of beam divider](image)

Fig. 3. A photo of the output of the beam divider.

Fig. 4 shows a sketch of the optical set-up for making the grid shown in Fig. 5a. Note that the lines in Fig. 5a remain uniform and show little divergence. The mesh size is the order of 1mm. The two photos in Fig. 5 are 0.4 seconds apart, taken by a still camera with a motor drive. From the distortion of the grid in Fig. 5b with respect to that in Fig. 5a, (one laser pulse, two photos at apart) we can calculate all the kinematic quantities of the flow in the plane of the film. (Note, that in practice we would not use a second image which has distorted as much as Fig. 5b, but we present it to illustrate the ideas involved.)

![Image of optical setup](image)

Fig. 4. The optical setup used to produce a grid of laser lines.

Fig. 5. An example of the grid. a) shortly after the laser pulse, b) 4sec later.

2.3 Algorithms to obtain fluid dynamic quantities

For convenience, we pick up one 'grid box' in Fig. 5a which, if the mesh size is small enough, can be thought of as a text book fluid 'particle' in flow at time \( t = 0 \). This fluid particle is shown using solid lines in Fig. 6a. As this particle moves with the flow, it may undergo several motions such as translation, rotation and deformation. The dashed lines in Fig. 6b show the same fluid particle after a short time interval, \( \Delta t \). Because we know the history of this specific fluid particle, we can compute the velocity of each corner by taking the time derivative of displacement \( ds \) associated with each point, that is, \( ds/\Delta t \). The deduction procedures are shown in Fig. 6b.
Note that \( V \) is designated as the velocity at point 1 which is then positioned at the midpoint between point 1' and point 1''. Fig. 7 shows the velocity vectors deduced from Fig. 6. Actually, a fluid particle moving in a general three-dimensional flow field may have motions about all three coordinate axes, however, we limit the discussion to the projection of this motion onto the plane of the photos which is parallel to the initial plane of the grid.

To obtain velocity gradients, vorticity, and strain rates from the velocities, we must difference across the distance of a grid box. Thus, for a given flow the grid must be small enough to resolve the smallest scales of motion.

An alternative method can be used if we are only interested in the vorticity. Using the definition of the circulation \( \Gamma \),

\[
\Gamma = \oint V \cdot ds
\]

and Gauss' theorem to relate the surface integral to an area integral,

\[
\Gamma = \int \omega \cdot ndA
\]

we can obtain the vorticity component normal to the film plane, \( \omega_z \), from a grid box of arbitrary shape, with circumference \( C \) and area \( A \).

The velocity component \( V \cdot ds \) in Eq. (1) is estimated by forming the average of the corner velocity components (see Fig. 7). Dividing \( \Gamma \) by the area of the fluid particle results in the average vorticity at the centroid of this fluid particle. This technique has the advantages of avoiding a second differencing of the experimental data.

Thus, by following the distortions of a single grid box we can obtain the velocities, circulation, vorticity and even the Reynolds stresses and strain rates if desired, over that small area. By doing this for the other grid mesh points, we can obtain the important fluid dynamic quantities at many locations over a two-dimensional field in a fluid flow simultaneously.

2.4 Error analysis

Consider the grid box in Fig. 6. We will assume that the grid mesh is spaced \( \epsilon \) and that a worse case line movement between images is \( 1/2 \) the mesh width. After time \( \Delta t \) standard analysis shows that the error in estimating the vorticity \( \omega_z \) is

\[
\delta \omega_z = \frac{1}{1} \left( \frac{\delta \epsilon}{\epsilon} \right)
\]

to first order in \( \epsilon \).

As an example of the designed accuracy of our experiments, if we produce 100μm lines on a grid mesh of 1mm, and our error in reading the center of the lines is 10%, we obtain \( \delta \epsilon/\epsilon = 0.1 \). For \( \Delta t = 0.01 \)sec, the error in the measurement of vorticity is 1/sec. This is better than has been possible with hot-wire probes, and is comparable with the most sophisticated single point laser doppler measurements.

3. EXPERIMENTAL RESULTS

Two experiments were performed to demonstrate the technique. Both used deodorized kerosene with 10 ppm of the photochromic chemical dissolved in it. The data were recorded on Kodak Tmax 400 ASA film through a Photo-Sonics 35mm high speed movie camera, framing between 150 and 200 frames per second. The films were analyzed on a NEC film analyzer which is accurate to .05mm.

Fig. 6. Procedure for conversion of the displacement of a grid box to velocities.

Fig. 7. Decomposition of the velocities used to calculate the circulation around a grid box.
3.1 Stokes' layer flow

We can test the accuracy of the technique in a flow for which an exact solution of the Navier-Stokes equations is obtainable. The flow is that of an impulsively started infinite plate in an initially still infinite ambient. The problem involves the two-dimensional diffusion of vorticity generated at the plate into the ambient. The thickness of the boundary layer, $\delta$, is a function of the kinematic viscosity, $\nu$, and the time after the start of the plate's motion. We have approximated this motion using a belt in a tank which can be rapidly started. Fig. 8 shows the experimental setup. The width of the belt is 17.8 cm, and the distance between the rollers is 152.4 cm, with the test position 90 cm downstream of the lead roller. All experimental data was obtained before the leading edge effects reached the test position. Furthermore, the aspect ratio is sufficient to prevent the disturbances generated in the corners from reaching the center of the belt at the test section in the test time interval. Therefore, the wall layer flow measured was two-dimensional. The speed of the belt was adjustable from 2.5 to 22.9 cm/sec. It reaches a constant speed within a second. This short acceleration reasonably approximates an impulsive start. A grid mesh size of .156 was used, with the laser lines intersecting as in Fig. 8.

Fig. 8. Setup used to create and measure the Stokes' layer flow.

Results of the velocity gradient obtained from double differentiation in the Stokes layer are shown in Fig. 9, where they are compared with the exact solution. Everything is non-dimensionalized by the similarity variables of the exact solution. Because the flow is two-dimensional, incompressible, and doesn't change with the streamwise coordinate, $x$, the continuity equation reduces to $\partial \nu / \partial y = 0$, and a check on this is also shown in Fig. 9 ($v$ is the velocity component normal to the wall, and $y$ is the coordinate normal to the wall). We see that both the error in the estimates of the continuity equation, and in the velocity gradient distribution are of similar magnitude. The absolute value of the error is $\pm 2/\nu$, consistent with the design error analysis. The deviation of the experimental profile in the near wall region is a consequence of the grid mesh being too large to adequately resolve the large value of the gradient $\partial \nu / \partial y$. On the whole the results are very encouraging.

3.2 Vortex ring flow

The real value of the technique is its ability to measure flows that are not measurable, analytically solvable or numerically calculable. The vortex ring is a common place example. It represents a class of flow fields that are of particular importance in turbulent and unsteady flows.

The experimental setup used to generate the vortex ring is shown in Fig. 10. A small amount of fluid from a constant head reservoir was emitted from a 1.9 cm orifice to create the rings. A solenoid valve whose opening time could be adjusted controlled the outflow. The kerosene in the reservoir was dyed with chlorophyll to partially mark the ring. The convection velocity of the rings was measured to be 3.8 cm/sec at the test section which is located 7.6 cm downstream of the orifice. The Reynolds number of the ring is approximately 700, based on the ring's core diameter and its convection velocity. The flow is axisymmetric, so that we only needed to align our grid through an axis of symmetry and measure the flow in half of the ring to measure its circulation.

Fig. 10. Setup used to create and measure the circulation of a vortex ring.

The instantaneous circulation distribution of the ring is shown in Fig. 11. Although no solution exists for the experimentally created ring, we show a comparison with Hill's exact solution for a ring in which the vorticity occupies a sphere. The core of our ring is smaller than that of the hypothetical Hill's ring, the overall shape is an oblate spheroid, and it is unlikely that the vorticity distribution is similar, but, as the data shows, the circulation of the ring (Reynolds number = 700) is not very different.
A new technique for obtaining velocity and velocity gradient data over a two-dimensional domain of a fluid flow is presented. Calibration depends only upon a time and a length scale. Comparison of measurements with the exact solution in a Stokes' flow indicates that its accuracy can be predicted by classical analysis, and is comparable or better than that achievable with the best single point probe techniques. The circulation of a vortex ring has been measured.

5. CONCLUSIONS

6. ACKNOWLEDGMENTS

7. REFERENCES

THE CIRCULATION OF AN AIRFOIL STARTING VORTEX OBTAINED FROM
INSTANTANEOUS VORTICITY MEASUREMENTS OVER AN AREA

R. E. Falco, C. C. Chu, M. H. Hetherington and C. P. Gendrich
Turbulence Structure Laboratory
Department of Mechanical Engineering
Michigan State University

ABSTRACT

By dissolving a photochromic chemical in an organic liquid and exciting it with ultraviolet light, a colored line can be created anywhere in the liquid. A device has been constructed which divides a laser beam into \('n\)' lines which are made to intersect to form a grid. Introducing two sets of these lines into the flowing fluid produces a grid of 100\(\mu\)m colored fluid lines with mesh spacing \(g\) of approximately 1mm. The color change persists long enough so that the grid lines are distorted by the flow before disappearing. The process is completely non-intrusive. The lines are analyzed by an image processing algorithm to allow the grid intersection points to be located quickly and with high precision. The movement of the intersection points in a unit of time results in temporal gradients of position, which in conjunction with estimates of the circulation around each grid box can be used to obtain the vorticity. Additionally, differencing again across a grid box results in spatial gradients of velocity. Experiments in a Stokes' flow indicate that the vorticity can be measured to 1/\(\text{sec}\). Application to the measurement of the formation of lift on an impulsively started airfoil has been made and compared with known results. It appears that the separating streamline is fixed to the trailing edge significantly before the Kutta condition is established, resulting in a starting vortex with less circulation than expected.

1. INTRODUCTION

The generation of lift has important technological consequences for both military and civilian aircraft. Whenever a change in velocity, attitude, or wing conformation is made, lift changes. For helicopters, each blade on the rotor continually experiences velocity changes. Batchelor\(2\) states: "It is a remarkable fact that a) in a vortex form and is shed from the body. When this happens, the rear stagnation streamline moves to the trailing edge. Shortly after, a smooth flow is established, and we have the Kutta condition, which states that for the conditions of this problem, the separation streamline leaves from the trailing edge, and there is no net shear across this streamline. Figure 1 summarizes this classical view. The shed vortex is the so called 'starting vortex', which many authors suggest contains the full circulation. Calculations of the roll up of a semi-infinite vortex sheet such as those of Pullin\(4\) support this point of view.

![Figure 1](image)

Figure 1. a) Evolution of the starting vortex from the irrotational solution. b) The starting vortex after the Kutta condition has been satisfied.

Many authors have not been entirely comfortable with this view. Lamb\(3\), states "It is still not altogether easy, in spite of the attempts that have been made, to trace out deductively the stages by which the result is established when the relative flow is started." Goldstein\(5\), after presenting it, states: "In this way the establishment of such a circulation may be held to be at least partly explained". Prandtl\(12\) states that "when the motion begins, a surface of discontinuity forms at the rear edge of the airfoil, and the fluid originally flows past it as... irrotational flow around the airfoil plus the initial
rolled up sheet of discontinuity. This avoids the difficulty of infinite velocities, but he does not describe how the sheet of discontinuity forms. The Russian authors Kochin, Kibel and Roze do not allude to the details indicated above, but only say that "the process of shedding of vortices with prevalence of vortices of one sign will continue until the circulation \( \Gamma \) reaches the value for which the velocity at the trailing edge of the airfoil will be finite." These differing descriptions are consistent with the lack of direct experimental evidence about the origin of lift. Up to now, it has been impossible to measure the instantaneous vorticity over the starting vortex, and at other relevant places. To our knowledge, only one set of measurements of the circulation in the fluid downstream of an impulsively started airfoil have been made. Walker used a dense concentration of particles to determine the growth of the total circulation in the fluid aft of an airfoil that was started from rest. He found that more than six chord lengths were required before the circulation reached 90% of the steady flow value.

2. EXPERIMENTAL TECHNIQUES

2.1. Review of the measurement technique

The technique of Laser Induced Photochemical Anemometry (LIFA) is reviewed. The first use of excited photochromic chemicals to measure fluid properties was made by Popvich and Hummel. They used the reaction to produce time lines, from which they obtained velocity fields for some quasi one-dimensional flows. The extension described by Falco and Chu -- which is reviewed below -- enables time resolved measurement of planar velocity vectors, instantaneous Reynolds stress components, the in-plane strain-rate components and the component of vorticity perpendicular to the plane of interest in fluctuating three-dimensional velocity fields.

2.1.1. The photochromic dye

Use is made of the phenomena of 'photochromism' to measure both velocity and vorticity in the starting airfoil problem. Brown has defined it as "a reversible change of a single chemical species between two states having distinguishably different absorption spectra, such change being induced in at least one direction by the action of electromagnetic radiation." The chemical used in this study was Kodak 1,3-Trimethyl-8-nitrospiro[2-H-l-benzopyran.2,2'-indoline]. We excited it at 351nm using pulses of 20ns produced by a Tachisto Excimer laser running on XeF (approximately 100mJ output). The chemical, which was dissolved in kerosene, reflected blue light for the order of tens of seconds. Thus, the fluid was tagged long enough for it to move appreciably. In practice, for the velocities of our experiments, we needed to follow the lines only a fraction of a second to obtain the information required.

2.1.2. Use of a grid to tag fluid particles

To enable us to measure two components of the velocity in a flow using the visual technique, we must tag and follow specific fluid particles. The simplest way to do this is to have two lines intersect. That intersection defines a point in the flow which, because it is colored, we can follow. To measure a spatial gradient, we must simultaneously mark two points in the flow. To enable us to measure a spatial gradient in a prescribed direction, we need several points and must use interpolation. Thus, the creation of a grid of intersecting marked fluid lines enables both velocities and their gradients to be measured.

We required a method of dividing a beam of laser light into 'n' beams where 'n' would be 5-25. In doing so, we sought to lose as little light as possible. Thus, we designed a divider that appears as an oversized blazed reflection grating with step size approximately 2mm (see Figure 2). The incident laser energy was directed at a shallow angle to the plane of the grating. Because the facets are so much larger than a wavelength of light, we expected to see primarily specular reflection. The separation of the specularly reflected portions of the beam were determined by the difference of the angle of incidence and the blaze angle, and the grating step width and spacing. It was fabricated by individually fixing aluminum coated mirrors (with the coating optimized for shallow incidence angles) to a machined base. Apart from diffraction effects, no incident laser energy would be lost.

As expected, however, diffraction effects were exhibited. We determined that as long as the grid was formed closer than approximately 1 m from the divider, we were in the Fraunhofer regime, and we obtained no noticeable diffraction effects.

2.1.3. Algorithms to obtain fluid dynamic quantities

For convenience, we pick up one 'grid box' which, if the mesh size is small enough, can be thought of as a textbook fluid 'particle' in the flow at time \( t=0 \). As this particle moves with the flow, it may undergo translation, rotation and deformation. Because we know the history of this specific fluid particle, we can compute the velocity of each corner by taking the time derivative of displacement \( ds \) associated with each point, that is, \( ds/dt \). The deduction procedures are described in Falco and Chu. In a three-dimensional flow field a fluid particle may have motions about all three coordinate axes; however, we will obtain the projections of this motion onto the plane of the photos which is parallel to the initial plane of the grid.

To obtain velocity gradients, vorticity, and strain rates from the velocities, we must difference across the distance of a grid box. Thus, for a given flow the grid must be small enough to resolve the smallest scales of motion.

An alternative method can be used if we are only interested in the vorticity. Using the definition of the circulation \( \Gamma \).

\[
\Gamma = \int_C \mathbf{v} \cdot ds \tag{1}
\]
and Gauss' theorem to relate the surface integral to an area integral,

$$
\Gamma = \int_{A} \omega \cdot dA
$$

we can obtain the vorticity component normal to the film plane, $\omega_n$, from a grid box of arbitrary shape, with circumference $C$ and area $A$.

The velocity component $v$ at any side of a grid box is obtained by forming the average of the velocity components obtained at two of the corners of the box. Dividing $\Gamma$ by the area of the box results in the average vorticity at the centroid of this area. This technique has the advantage of avoiding a second differencing of the experimental data.

Thus, by following the distortions of a single grid box, we can obtain the velocities, circulation, vorticity and even the instantaneous Reynolds stresses and strain rates if desired, over that small area. By doing this for the other mesh elements, we can obtain the important fluid dynamic quantities at many locations over a two-dimensional field in a fluid flow simultaneously.

The intersection information was processed into fluid kinetic quantities on an IRIS 3120. The IRIS provided not only a fast CPU but also a graphics environment in which the individual steps of the algorithm could be checked for consistency.

2.1.4. Error analysis

Consider a single grid box. We will assume that the grid mesh is spaced $\varepsilon$ and that a worse case line movement between images is 1/2 the mesh width. After time $\Delta t$ standard analysis (see Taylor 1982) shows that the error in estimating the vorticity $\omega$ is

$$
\delta \omega = \frac{1}{\Delta t} \frac{\delta \varepsilon}{\varepsilon}
$$

3

to first order in $\varepsilon$.

As an example of the designed accuracy of our experiments, if we produce 100 $\mu$m lines on a grid mesh of 1mm, and our error in reading the center of the lines is 10%, we obtain $\delta \varepsilon/\varepsilon = .01$. For $\Delta t = .01$sec, the error in the measurement of vorticity is 1/sec. This is better than has been possible with hot-wire probes, and is comparable with the most sophisticated single point laser doppler measurements (see Lang 19).

2.2. Experiments performed

Two experiments are described. The first may be considered as a calibration of the LIPA technique. Its objective was to measure the boundary layer that develops on an impulsively started moving wall. Since this has an exact solution of the Navier-Stokes equations, we can use it to determine the accuracy of our vorticity measurements. The second experiment concerned measurement of the lift formation process on an impulsively started airfoil.

![Figure 2. The optical setup used to produce a grid of laser lines.](image)

For both experiments the same laser, chemicals and similar optical arrangements were used. A Tachisto excimer laser outputting 100$mJ$ and 35$nm$ was used to excite the chemical. Figure 2 shows a sketch of the optical setup used to produce a grid of laser lines. Figure 3 shows an example of the grid produced after it has been distorted by the fluid motion. For the Stokes' layer problem the grid extended across the entire layer. For the airfoil problem Figure 4 shows the size of the measurement volume relative to the starting vortex diameter as indicated by the roll up of photochromic dye generated on the airfoil for the case when the airfoil had traveled 1.3 chords. This is the largest it grew to during our measurements. Thus we anticipate capturing essentially all of the vorticity in the starting vortex. Figure 5 shows the setup used to create the impulsively started flows. The mylar belt was chain driven by a 1/4 HP Dayton DC motor regulated by a Dayton SRC controller. In the starting airfoil experiment this combination accelerated the belt to a final velocity of 61$mm/s$ in .06 sec (.057 of a chord length). The airfoil, which approximated a NACA 0012, had a chord length of 63.5$mm$. The chord Reynolds number was 1550, and it was fixed at a 4.7 degree angle of attack.

A 35$mm$ high speed Photosonics 35ML camera with a quartz regulated motor was used to record data. A lens arrangement providing approximately 1:1 magnification was used. For the Stokes' flow experiments, we framed at 150 frames/second, while for the airfoil experiment 50 frames/second were used. For the airfoil problem the following timing sequence was used. The camera was started approximately 1 second before the belt to bring it up to speed, then the belt motor was started along with the delay timer. The delay timer triggered the laser at preselected delay times corresponding to 3.8 and 1.3 chord lengths of travel of the airfoil. Only the first two frames after the laser fired were used, in each case, for the calculation of the vorticity.
3. RESULTS

3.1. Stokes' layer flow

We can test the accuracy of the technique in a flow for which an exact solution of the Navier-Stokes equations is obtainable. The flow is that of an impulsively started infinite plate in an initially still infinite ambient. The problem involves the two-dimensional diffusion of vorticity generated at the plate into the ambient. The thickness of the boundary layer, $\delta$, is a function of the kinematic viscosity, $\nu$, and the time after the start of the plate's motion. We have approximated this motion in a tank using a belt which can be rapidly started (see Figure 5). The width of the belt is 17.8 cm, and the distance between the rollers is 152.4 cm, with the test position 90 cm downstream of the lead roller. All experimental data was obtained before the leading edge effects reached the test position. Furthermore, the aspect ratio is sufficient to prevent the disturbances generated in the upstream corners from reaching the center of the belt at the test section in the test time interval. Therefore, the wall layer flow measured was two-dimensional. The speed of the belt was adjustable from 2.5 to 22.9 cm/sec. It reaches a constant speed within .06 second. This short acceleration reasonably approximates an impulsive start. A grid mesh size of .156 was used, with the laser lines intersecting as in Figure 5.

Results of the velocity gradient obtained from double differentiation in the Stokes' layer are shown in Figure 6, where they are compared with the exact solution. Both data reduction by hand and using the image processing equipment are shown. All quantities are non-dimensionalized by the similarity variables of the exact solution. Because the flow is two-dimensional, incompressible, and doesn't change with the streamwise coordinate, $x$, the continuity equation reduces to $\frac{\partial v}{\partial y} = 0$, and a check on this is also shown in Figure 6 ($v$ is the velocity component normal to the wall). We see that both the error in the estimates of the continuity equation, and in the velocity gradient distribution are of similar magnitude.

Figure 3. A photo of the grid after it has been distorted by fluid motion. The wing is moving left to right.

Figure 4. The size of the measurement region with respect to that of the starting vortex at .3, .8 and 1.3 chords behind the airfoil. The wing is moving left to right.

Figure 5. Setup used to create and measure the Stokes' flow. This same device was modified to support an airfoil (see inset).

Figure 6. Comparison of experimental measurements of the velocity gradient in a Stokes' layer compared with the theoretical solution. (+) the algorithm, (o) manually. (-) the exact solution. A check of the continuity equation $\frac{\partial v}{\partial y} = 0$ is also shown. (x) the algorithm, (*) manually.
We can make use of all of the samples in the continuity equation to get a statistical estimate of the error in measurement of velocity gradients. The rms error equals 9/sec, consistent with the design error analysis. The deviation of the experimental profile in the near wall region is a consequence of the grid mesh being too large to adequately resolve the large value of the gradient $3u/3y$. On the whole the results indicate that we should be able to measure vorticity over an area more accurately than instruments using multiple hot-wires or multiple LDA beams can at a point. Furthermore, the resolution of each vorticity measurement can potentially be higher, since we are essentially constrained only by the minimum thickness of an ultraviolet laser beam.

3.2. Impulsively started airfoil

Using the photochromic dye, we could observe the direction of motion of fluid particles, and measure the time required for a point in the fluid to move along the upper surface to the trailing edge. We could observe motion in increments of $Ut/c = .02$. The motion of marked fluid was always observed to be downstream with respect to the airfoil. By positioning the airfoil under the laser generated grid, and firing it at a repetition rate high enough, we could successively mark selected “fluid particles” on the airfoil’s surface and follow their movements. Doing this, we obtained a definite indication that the separating streamline was fixed to the trailing edge by $Ut/c = .06$. We could resolve movement of .006 chord. During this time a vortex formed on the LOWER surface of the airfoil, very close to the trailing edge, but beneath the fixed separation point. It should be noted that although the trailing edge was sharp when viewed with respect to the airfoil as a whole, it had a radius of curvature of approximately .42mm.

Having established that the process of movement of the separation point was completed at $Ut/c = .06$, we examined the starting vortex. Using the grid technique described above, we measured the vorticity and circulation in the starting vortex after it had convected .3, .8, and 1.3 chord lengths downstream. $\Gamma/\rho_0$ was .392, .378 and .387. Thus, the magnitude of the circulation has not changed within our experimental error. The steady state circulation for our NACA 0012 airfoil was estimated to be 1024mm$^-2$ sec. The estimate at the .3 chord included all of the circulation aft of the airfoil. We see that the estimates indicate the starting vortex has developed to full strength by .3 chord. Thus, the circulation in the starting vortex is approximately 1/3 of the total circulation around the airfoil in steady motion.

The fact that $\Gamma$ of the starting vortex had not reached the theoretical value of $\pi \rho_0 u_a$ since by this position downstream was expected from results of Walker$^{17}$, and theoretical results of Wagner$^{16}$, and numerical calculations of Basu and Hancock$^1$ and Chow and Huang$^4$, among others. Explanations have alluded to the fact that when the starting vortex was at these chord positions, the separation streamline had not yet reached the trailing edge, so that additional vorticity was being shed – which might rearrange itself into additional vortices. However, we find that the separating streamline has moved to the trailing edge and remains fixed there by .06 chords, so the classical mechanism for the supply of vorticity is no longer operative.

Figure 7 compares our results with those of experiments of Walker$^{17}$ and theoretical estimates of Wagner$^{16}$. It is interesting to note that the value of the circulation we measured at .3 chord is (within experimental error) the same as that measured by Walker and calculated by Wagner. They are at all times considering the total circulation of the fluid downstream of the airfoils. At .3 chord we are also measuring the total circulation of our airfoil. This correspondence is expected, and adds weight to the accuracy of our measurements. The discrepancy found at .8 and 1.3 chords thus highlights the fact that processes other than the classical physical picture are taking place. It is interesting to point out that for impulsively started airfoils, only a single vortex is expected if similarity is assumed (Pullin$^{14}$). Thus, it appears that the process of roll up of the vorticity shed from the back of the airfoil does not conform to this hypothesis, since the starting vortex contains only a third of the vorticity responsible for the lift of the airfoil.

Further experiments were performed to determine whether additional vorticity was being shed off the airfoil after the circulation in the starting vortex.

![Figure 7: The increase in circulation with distance from the airfoil, compared with experimental and theoretical data.](image-url)
had reached its constant value. A single photochromic line was created .07 chord lengths behind the airfoil after it had traveled ,5, .75, 1 and 2 chord lengths. We examined the movement of this line, both above and below the airfoil to determine whether a shear existed across the wake. Indeed a shear existed in all the measurements. Figure 8 shows the distortion of a single photochromic line created approximately .06 chord lengths behind the airfoil, and photographed after approximately .22 chord lengths of travel, for the case where the airfoil has traveled 1/2 chord, i.e. after the starting vortex has attained its final value (see Figure 7). The sign of this vortex was the same as that in the starting vortex. This magnitude decreased as the airfoil had traveled further, but measurable shear existed in the experiment even after two chords of travel. Thus, there was continued generation of vorticity long after the separation streamline was fixed to the trailing edge, and the Kutta condition was therefore not satisfied after at least 2 chords of travel in our measurements.

![Image](image_url)

Figure 8. The shear that exists across the wake when the starting vortex is 0.5 chord downstream. The wing is moving right to left.

4. DISCUSSION

The demonstrated accuracy of the technique is sufficiently adequate to enable us to examine many unsteady fluid dynamic problems. Since, in principle, the calibration depends only on a time and a length scale, there is further room for improvement. In practice, determining the intersection points of the grid lines is limited by the grain size of the film used (or the resolution of a photo optical detector), the distortion of the developing process and the accuracy of either hand or automated measurements in defining the lines. Improvements in the grain limitation can be made by using a larger format camera or larger aperture lens/fine grain film combination.

For these preliminary low Reynolds number experiments, the average magnitude of the vorticity in each of our grid boxes was ,3 sec . Since the accuracy of our technique is ± .9 sec , we could only expect 66% accuracy per individual estimate. However, estimates of the circulation for each case involved integrating over an average of 23 circulation cells, thus significantly reducing the error in estimating . Furthermore, in a direct test of the reproducibility of our estimates, at .8 chords two independent runs were analyzed. These results indicated that the circulation varied by 4%. Another possible source of error was the possibility of not including all of the vorticity in the starting vortex for the case at 1.3 chords. However, as Figure 4 indicates, the dye suggests that most of the vorticity has been measured.

4.1. The generation of lift

If the circulation is no longer determined by the fact that the separating streamline has moved to the trailing edge, then what determines the magnitude of the circulation responsible for steady lift? Where is the additional circulation coming from? In the theoretical and numerical accounts, vorticity is continuously coming off in a sheet that rolls up into the starting vortex at some position downstream of the airfoil: the vorticity generation comes to an end when the Kutta condition is established. Graham critiques analysis which suggest that a sheet is shed approximately parallel to the bisector of the trailing edge and then rolls up. He notes that all evidence suggests that the surface of discontinuity rolls up immediately as it forms and comes off the airfoil. Using this hypothesis he arrives at a picture of the initial lift being very high, decreasing and then increasing as the Wagner function after Ut/c = .1. All of this work suggests that as the circulation is increasing the rear stagnation point is moving towards the trailing edge. However, it takes several chord lengths to have all of the vorticity shed.

The fact that we measured only 2/3 of the circulation expected in the starting vortex after 1.3 chords, and that there does not appear to be any change in the strength over the previous chord of motion, suggests that additional vorticity is continuing to be shed after the vortex rolls up. A contradiction arises. The classical theory suggests that the upper stagnation point will have moved to the trailing edge when the starting vortex has been shed, and thus there is no longer a mechanism for the generation of additional circulation. The unique irrotational solution for the circulation is established. However, in the irrotational solution the separating streamline is a stagnation streamline; in the real fluid it is not.

In our experiments the separation point has moved to the trailing edge after .06 of a chord of travel. Thus, it appears that the movement of the separation point to the trailing edge does not in itself establish the Kutta condition. It must be cautioned that we are not able to resolve the velocity field with sufficient resolution to determine the stagnation point, but our determination is being made by measuring the movement of lines of marked fluid that are created at large angles to the surface, and selected marked fluid particles (intersections of the marked fluid lines). We see that initially the lines and marked points move downstream with respect to the airfoil, and that after .06...
chord of airfoil travel they are fixed to the trailing edge. Thus, it is not at all certain that the initial position of the stagnation point is on the upper wing surface (we have no evidence for or against this possibility). After movement to the trailing edge (if this happens at all), one still has the presence of a strong shear layer. Accordingly, we feel that the shear layer still exists for more than 6 chords, i.e. the circulation is changing over airfoil travel of more than 50 times as long as indicated by the classical theory.

Finally, we note that this is a very low Reynolds number experiment. It could be argued that the lift on this airfoil will not be the same as that for a NACA 0012 at higher Reynolds numbers. However, it is interesting to note that the value for the total circulation which both Walker and we have measured after 3 chords is remarkably close. It is certainly possible to perform experiments of this type at considerably higher Reynolds numbers. The limitation is not the LIPA technique, but instead the mechanical mechanisms for rapid acceleration of the airfoil.

5. CONCLUSIONS

The generation of lift on an airfoil is re-examined. Using a new quantitative optical measuring technique, we determined that the separation streamline moves to the trailing edge of an airfoil long before the Kutta condition (unsheared flow from the trailing edge) is established, i.e. long before the change in circulation necessary to reach the steady flow lift has occurred. Preliminary results show that the vorticity in the starting vortex which has convected approximately 1.24 chords after the airfoil separation streamline has moved to the trailing edge, is much less than that predicted.

This suggests that the classical hypothesis relating the formation of lift and the establishment of the Kutta condition needs to be re-examined.

6. ACKNOWLEDGMENTS

We gratefully acknowledge support of the Air Force Office of Scientific Research under Grant No. AFOSR-87-0047. The contract monitor was Dr. Jim McMichael. We are also pleased to acknowledge the assistance of Mr. Sean Hilbert, especially for his role in the fabrication of the beam divider.

7. REFERENCES

Appendix D contains the original list of equipment requested under AFOSR-86-0242. It also contains the list of equipment which was ultimately purchased, as well as a copy of the letter explaining our reasons for requesting equipment substitutions.
<table>
<thead>
<tr>
<th>COMPANY/ITEM</th>
<th>MSU EQPT. COST-SHARING</th>
<th>MSU OTHER COST-SHARING</th>
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<td>CAM Corp. (P.O. 36154)</td>
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<td>Seiko color copier with video multiplexer; maintenance</td>
<td>$ 9,741.00</td>
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<td>Helix Ltd. (P.O. 37409)</td>
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Overhead (42% MTDC thru 6/30/88; 44% 7/1 thru 7/31/88)  

TOTALS  

$ 177,372.27  $ 28,211.70  $ 31,858.15

9,444.29
## ORIGINAL EQUIPMENT LIST

### EQUIPMENT

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<td>105 mm Nikon macro lens</td>
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### DEC MICRO VAX II HOST

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February 2, 1987

Dr. Jim McMichael
AFOSR/NA
Bolling AFB
Washington, D. C. 20332-6448

Dear Jim:

Request for Equipment Substitutions in DOD Equipment Grant
AFOSR-86-0242 DEF

I have made a thorough re-evaluation of the image processing equipment in
the grant, and have determined that a better system can be put together for
the same costs. This system will enable us to more accurately measure the
vorticity and strain rates, and to better understand the data. It will also
enable us to interface with the Direct Numerical Simulations that will be
coming from NASA Ames and other places.

The major new components of the system are:

a. Westinghouse 2" video camera that gives 2048 x 2500 pixels;
b. Megavision 1024M processor that will process 2048 x 2048 images and
can be upgraded to 4096 x 4096 images which will be necessitated by
later higher speed experiments;
c. Silicon Graphics IRIS processor, which will allow us to view the
data from any angle and to reconstruct the three-dimensional fields
from the two-dimensional slices of vorticity data we are obtaining,
and compare them with numerical computations.
d. Sun 3/260 with optical disk, to be the host computer for the
network of digitizer, image processor and graphics processor, mass
storage, and communications.
e. A hard copy device that will enable permanent records at the
resolution of the screen images.

A detailed list of the new equipment is attached. In each case I have
bargained for some special deal with the vendors. The net result is that I
have achieved this significant enhancement of system capabilities at no
additional cost.
Permission is requested to make these substitutions.

Sincerely,

Robert Falco
Professor and Director
Turbulence Structure Laboratory

Approved:

John R. Lloyd, Chairperson
Mechanical Engineering Dept.

Howard G. Gilder, Director
Contract & Grant Administration

William C. Taylor, Acting Assoc. Dean
Graduate Studies and Research

RF: kk
enc.
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<th>PROPOSED REVISED EQUIPMENT COST BREAKDOWN</th>
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Cost by source:
- AFOSR: 177439
- MSU: 60057