Hands-on session on Turbulence in Quasi-Two-Dimensional Electrolytic Layers

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1 Purpose

This experiment provides an opportunity to test recent theoretical advances in turbulence, one of today's great unsolved problems in physics. Specifically, the Hands-On School experiments examine quasi-2D flows for evidence of unstable periodic solutions, which recent theories suggest may be used to characterize turbulent flows. The experiments are original research and may lead to publishable results that help advance the understanding of turbulence.

The main elements covered in this document are:

- Theoretical Background
- Experimental Setup
- Flow Visualization and Image Acquisition
- Image Data Analysis

This document gives a very brief overview of these elements; further information and background will be found both in weblinks referred herein and files that accompany this document.

2 Introduction

Turbulence has long been associated with the idea of fluid flow that is irregular in space and unpredictable in time. However, decades of experimental observations demonstrate that characteristic patterns arise repeatedly. Numerous empirical methods have been devised to characterize these patterns, known as "coherent structure"; however, recent theory suggests that coherent structures observed in experiments are closely related to certain unstable solutions in the fluid equations (the Navier-Stokes equations). Firm experimental evidence supporting the connection between these unstable solutions and coherent structures has not yet been found.

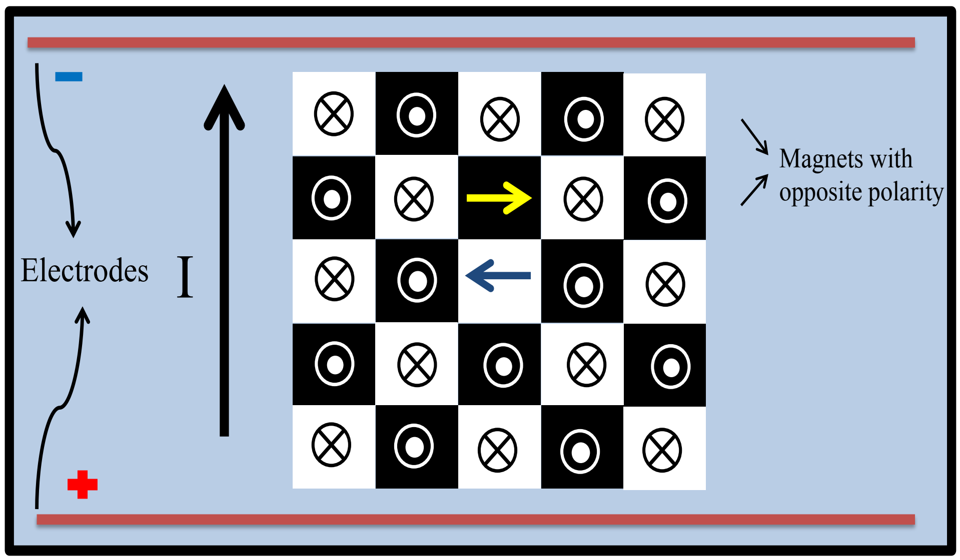


Figure 1: View from above of the experimental setup for chessboard-like flow. Current (black arrows) is passed through an electrolyte; in the region above several permanent magnets, Lorentz forces drive shear flow. As the current is increased, the system transitions into turbulence.

The theory to date has focused on flows in 3D (pipe flow, plane Couette flow); clear experimental evidence requires measurement of 3D time-dependent velocity fields, which is at the limit of today's experimental capabilities. By contrast, measurement of 2D velocity fields in fluid flows is relatively easy.

A general overview of research on unstable solutions in plane Couette flow can be found at: http://chaosbook.org/tutorials. The folder theory_background contains scientific journal articles that describe recent work (mostly theory) on unstable solutions and turbulence.

3 Experiment

The experiment uses electromagnetic forces to drive flow in a shallow layer of electrolyte. Permanent magnets with high field strength are placed in/under a plastic box; the box is then filled with a thin layer of electrolyte (saltwater). A current is passed through the electrolyte (black arrow), causing Lorentz forces to drive the flow. For small currents, the flow reflects symmetries (if any) of the magnets spatial arrangement; however, for sufficiently large currents, the flow breaks these symmetries and appears turbulent. Previous work has suggested the flow is quasi- 2D (i.e., the in-plane velocity fields are different at different vertical positions; however, these in-plane fields are weakly coupled to one another due to the smallness of the vertical velocities in the layer.) A number of earlier experiments in this system have explored the statistics of 2D turbulence (e.g., energy and enstrophy cascades) and, more recently, the problem of turbulent mixing in 2D. However, no previous experiments have explored the role of unstable solutions in 2D turbulence.

A note about power supplies to run the experiment: Any readily available power supply with a range of approximately 5V and 0.3 A should be sufficient for the type of experiment apparatus similar to the one you are working with in this lab. Ideally, the supply should be operated in current control mode; this fixes the electromagnetic forcing (which is proportional to the applied current). Here, we use an inexpensive current-controlled supply built from a cell-phone charger and a few electronic parts. For a detailed discussion on how to construct a suitable current-controlled power supply, see power_supply.pdf, which accompanies this document. The folder exp_background contains selected scientific journal articles including review articles that describe earlier table-top experiments on 2D turbulence, including experiments on electromagnetically-driven electrolytes.

4 3. Flow Visualization and Image Acquisition

The flow can be observed by sprinkling glass microspheres (mean diameter40 micrometers) on the electrolyte layer. The glass microspheres float at the layer surface; thus, when the fluid layer is in motion, the glass microspheres "track" the flow at the top of the fluid layer. (The microspheres must be sufficiently small to respond rapidly.)

A web camera that connects to the computer is used to image the visualized flow. We use the Fire-I web camera, whose software drivers (freely downloadable from the web) permit setting both the frame rate and shutter speed. Any web camera can be used to obtain suitable images; for general web cameras, we suggest using the freeware application, VirtualDub, for image acquisition. The VirtualDub executable and documentation are easily found by a keyword search ("VirtualDub") online. Regardless of the hardware/software used for the acquisition, the images need to be stored in .tif format in preparation for processing to find fluid velocities.

5 Data Analysis

After a time series of suitably named images (e.g., Frame_0001.tif) has been collected, the image data can be processed. The following is the sequence of Matlab scripts to execute to process a time series of images.

Matlab Scripts (Listed in Execution Order)	Purpose
image_process('startnum', 'stopnum', h_cm, fps);	Calls OSIV software to perform PIV
taverage;	Time averages data to reduce noise
vfield_cgs;	Converts velocities and lengths to cgs units
vortex_cgs;	Calculates vorticity contour in cgs units
remove_vortex_noise	Removes noisy parts of vorticity to make data look smoother
make_video(jump, video_fps);	Generates an AVI video of the flow
recurrence;	Generates a recurrence plot of the velocity field time-series

The arguments for image_process are (e.g. image_process('002', '900', 4.8, 7.5))

- 'startnum' a string containing the number portion of the first input image to be processed, with leading zeros (if applicable)
- stopnum a string containing the number portion of the last input image to be processed, with leading zeros (if applicable)
- h_cm the height of the image in centimeters; can be obtained by imaging a ruler
- fps the rate at which the data was collected (in frames per second)

The arguments for make_video are (e.g. make_video(8, 15))

- jump the number of time steps to jump over between consecutive frames of the video; a larger number makes the video speed up (8 is suggested)
- video_fps the speed at which to encode the movie in frames/second (15 is suggested)

5.1 Details

There are several steps to image analysis that are performed by the numerous scripts included in the "image_analysis" folder. The first and most important step is particle image velocimetry (PIV). PIV is a process in which a time-series

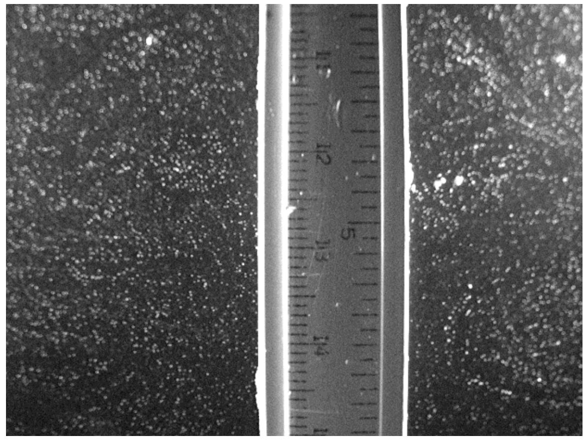


Figure 2: A ruler image is captured to convert the pixel displacement into displacements in physical units

of a velocity field can be extracted from images of a fluid flow taken in rapid succession. To perform the PIV analysis, we use the open source package OSIV. This package can be installed under Windows, Mac OS X, or Linux and run as a toolbox from within the MATLAB environment. (The package can also be installed and run directly from the command line in these operating systems.) Once OSIV is installed, our scripts can be executed.

For simplicity, one only needs to call the function image_process to perform PIV. To execute image_process, while in the directory containing a time-series of images, type:

image_process('startnum', 'stopnum', h_cm, fps)

where "startnum" and "stopnum" are the indices corresponding to the first and last image to be processed, h_cm is the height of the image in centimeters, and fps is the rate at which the data was collected (in frames per second). The h_cm input is used to scale pixel units to centimeters, and we usually obtain h_cm by taking a picture of a carefully positioned ruler (see Figure 2). Note that the first two input arguments are strings, so if the first file is Frame_002.tif, the last file is Frame_900.tif, a picture of a ruler shows that the height of our image is 4.8 cm, and the data was collected at 7.5 frames per second, then one would type:

image_process('002', '900', 4.8, 7.5)

where the zeros are necessary to include. The program will warn you if a frame is missing, as will occasionally happen when the camera skips a frame. For a more thorough discussion of the methods and output of our scripts, continue reading below. Explanation of the scripts are available in the files, themselves, which are well commented.

5.2 Particle Image Velocimetry (PIV)

This technique is a widely-used method of measuring velocity fields. To determine a single velocity field "snapshot" requires two images of the tracer particles in the flow; the images are recorded at slightly different times, such that the tracer particles have moved a little bit (but not too much) in the time interval between the two images. Each image is then divided into a collection of interrogation windows. A spatial cross-correlation is performed between the pair of corresponding windows; the shift that produces the maximum in the cross-correlation corresponds to the most likely displacement vector associated with the windows; by knowing the time interval between the images, we can find an estimate of the average velocity vector (displacement vector / time interval) associated with the pair of windows. Repeating this process for all interrogation windows yields a set of velocity vectors distributed on a uniform grid, i.e., the velocity field snapshot for the two images. By performing this same analysis between each pair of adjacent (in time) images from a time series of the visualized flow, we can determine the corresponding flow velocity field time series. Our function pivCorrelate_fi(first,last) is what sets the PIV specifications and calls the OSIV software.

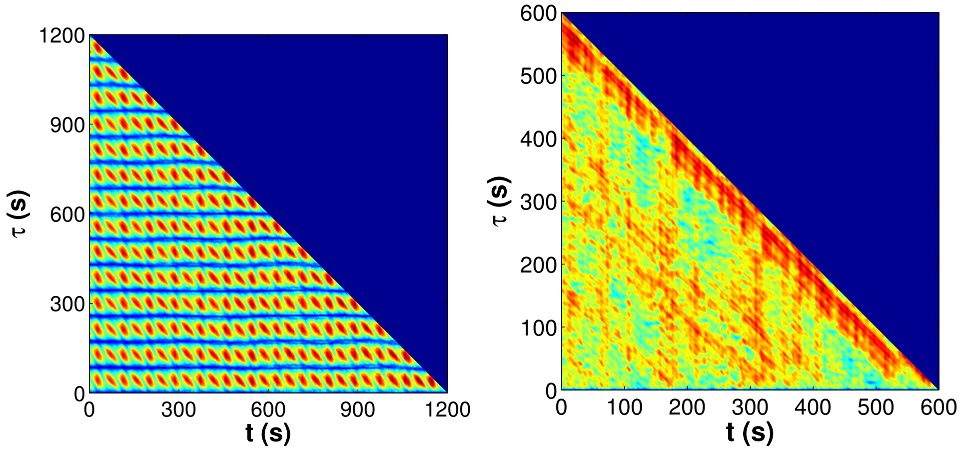
AVI Video: A video file of the flow, sped up to several times real time, is a convenient and useful way to visualize data. OSIV provides a large number of ways to tune and to optimize the analysis; for full details and downloads, see http://osiv.sourceforge.net/

5.3 Recurrence Plots

In our fluid flow measurements, we are particularly interested in searching for occurrences where the flow field repeats a similar pattern that the flow exhibited earlier; these recurrences are evidence for the possible existence of unstable periodic orbits in the flow. To search for recurrences in a quantitative way, we compute a "distance" (more precisely, an energy norm) between the velocity fields at time t and at time t + τ, which, in discrete form suited for our computed velocity fields is given by:

$$\mathrm{rec(i\ ,\ j)} = \sqrt{||\mathbf{V_{t+\tau}} - \mathbf{V_t}||} \tag{1}$$

This energy norm can be represented on a single time delay plot (or recurrence plot) where a color scale can be used to represent the size of the energy norm. Regions of the recurrence plot where the energy norm is small are of particular interest since this suggests that the two flow fields are nearby; the corresponding time difference τ *may* be related to an unstable periodic orbit in the flow dynamics. Convincing evidence of the presence of such unstable periodic orbits in an experiment on turbulent flow would represent an important advance in our understanding of turbulence.



(a) (b)

Figure 3: (a) Recurrence plot for a stable periodic orbit. As one could see, the system repeats its state every **T** seconds (b) Recurrence plot for a flow that is temporally chaotic.

6 Acknowledgements

We would like to thank Daniel Borrero (Georgia Tech), who helped in organizing the 2010 Hands-On School in Cameroon, for writing the first version of this document. We would also like to thank Jon Paprocki (Georgia Tech), who wrote the initial version of the Matlab scripts.

Guide to Constant Current Power Supplies

Written by Daniel Borrero (Georgia Tech)

In the experiment conducted during the Hands-On session on turbulence, we used a constant current power supply. This is different from your usual DC power supply (e.g., cell phone or laptop AC adapters). Regular power supplies operate in such a way that they will supply whatever current is needed to maintain the voltage across the load at a fixed value. On the other hand, constant current supplies adjust their output voltage so that the output current is fixed independent of the load.

Our particular choice of constant current supply is based on the LM317 Adjustable Regulator from National Semiconductor Corporation. The LM317 has 3 terminals which are called the input terminal (Vin), the output voltage terminal (Vout) and the adjustment terminal (ADJ). On the TO-220 package (many other common electronics packages are also available) these are arranged as shown in **Figure 1**.

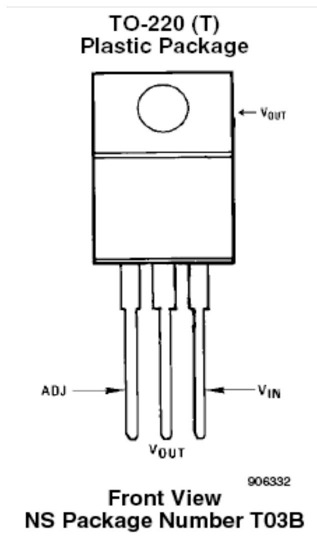


Figure 1. Pinout for LM317

While the inner workings of the LM317 are fairly complicated, its basic operation is as follows: The chip is powered by a voltage applied to the input terminal (in our case, we used a 15V power supply from an old laptop). The chip then does whatever it takes to establish a voltage difference of 1.25 volts between the output terminal and the adjustment terminal. The adjustment terminal has high impedance so that very little current is allowed to flow into it, as long as there is an easier way for it to get to ground.

We can use this to our advantage as shown in **Figure 2**. By placing a resistor between the output and adjustment terminals, we will drive a current through the resistor given by I = 1.25V/R, where R is the resistance of the resistor. If we now create a path for the current to flow to ground that has lower impedance than the adjustment terminal, the current will take this path. Notice that this current is independent of the load (at least as long as the impedance of the load is much smaller than the impedance of the adjustment terminal). If we now replace the resistor with a variable resistor or potentiometer (in our case we used a 200 Ohm variable resistor), we will have constructed a power supply where we can control the output current directly independent of the load.

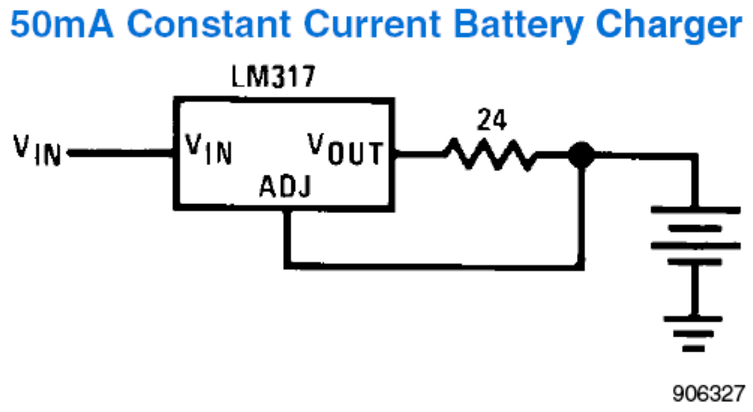


Figure 2. Constant Current Power Supply Schematic. In our session, we replaced the fixed resistor with an adjustable resistor and have replaced the battery with a generic load (e.g., our electrolyte or our LED arrays).

Using a constant current supply was convenient in our experiment because the forcing of the system is proportional to the current making this the natural choice of control parameter. If, on the other hand, we had used a constant voltage supply, the amount of current driven into the electrolyte would depend on the fine details of the electrolyte solution (e.g., salt concentration or temperature). The constant current supply lets us adjust the current independent of the details of our electrolyte.

Constant current supplies are useful for many other purposes. In our session, we also used them to power arrays of LEDs that we used for illumination. Powering the LEDs this way is useful for a couple of reasons. First, it makes it very simple to adjust the intensity of the light. Larger current, brighter lighting. Smaller current, dimmer lighting. Second, because they are being driven by DC, the LEDs will not flicker, a fact that is convenient when we are taking many images per second. If we had powered the LEDs with AC, the camera would detect variations in illumination as the current varied.

For more information on the LM317 and other application ideas, see the LM317 datasheet.