4th International PIV Challenge
Test case E: Vortex Ring Time Resolved, Stereo-PIV

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1. Introduction

Vortex rings are commonly analyzed in fluid dynamics experiments due to the physical insights that they can provide and due to the wide range of related engineering applications. Generally, vortex rings are produced by impulsively driving a slug of fluid through a circular aperture for a short duration. The circular geometry creates an approximately two-dimensional flow, however due to hydrodynamic instabilities three-dimensional behavior commonly arises even for laminar vortex ring flows.

2. Technical Information

The vortex ring experiment was conducted in the AEThER laboratory at Virginia Tech. The data set contains single-pulsed images from five cameras imaging the illuminated particle field. Polystyrene fluorescent particles with a mean diameter of 27 μm were used as flow tracers (Duke Scientific Corporation catalog number 36-5B). Both heads of a 10 mJ per pulse 527 nm Nd:YLF laser were simultaneously pulsed at 1000 Hz to illuminate the flow field. The vortex ring used in the data set had a Reynolds number of approximately Re = 2300. The camera array consisted of three Photron FASTCAM APX-RS cameras aligned vertically and two Photron FASTCAM SA4 cameras placed on either side of the three APX-RS cameras, as is shown in Figure 1. Cameras 2 and 4 used Scheimpflug adapters to account for the angle between the cameras and the laser sheet. Cameras 3 and 5 did not have Scheimpflug adapters, so the lens aperture was stopped down to ensure that the particles remained in focus. The optical axis of camera 1 was normal to the laser sheet, thus all the particles were in focus with the lens aperture fully open.

A total of 1800 frames were recorded, however the participants will receive only 100 frames from only one pair of cameras. The participants will calculate the velocity field, the vorticity field, and the circulation of each core at 50 time steps.

Calibration grid images will be provided in addition to the particle field images. The calibration grid was translated to seven (7) different Z-axis positions with a spacing of ΔZ = 1 mm. The grid consists of two levels spaced 3 mm apart with a rectilinear grid of 3.2 mm diameter dots. The dots on the grid are spaced 15 mm apart both horizontally and vertically.

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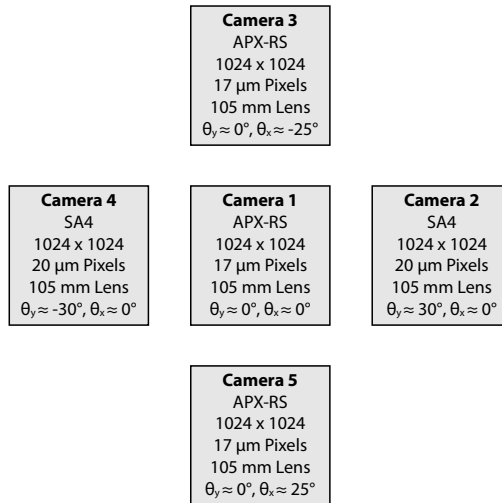
Figure 1: Arrangement of the five high-speed cameras used to record the PIV data for the stereo vortex ring experiment. The cameras in this diagram are arranged such that they are imaging a volume that is into the page.

Table 1: A summary of the technical parameters during the PIV data acquisition.

Laser:	New Wave Pegasus 527 nm 20 W Dual Cavity Nd:YLF
Particles:	Polystyrene 27 µm Fluorescent Spheres
Frame Rate:	1000 Hz
Image Number:	1800 Images
Cameras:	Photron FASTCAM APX-RS and Photron FASTCAM SA4
Image Size:	1024 x 1024 Pixels
Calibration Grid:	LaVision Type #21 with seven (7) Z Positions

The technical challenges involved in accurately measuring this data include: out-of-plane motion, rotational flow, a difference in the magnification between the cameras, the lack of a Scheimpflug adapter on the off-axis camera resulting in distorted particles, and a large dynamic range in the velocity field.

3. Data Format, Vector grid, Desired Quantities and Name Convention

Data will be provided to the participants from camera 1 and camera 3. The data will be in the form of single-frame images in uncompressed 16-bit TIFF file format with a resolution of 1024 x 1024 pixels. The particle image data will be named using the following format

E_camera_i_frame_j.tif

where "i" gives the camera number (1 or 3) and "j" gives the frame number (00001 to 00100). This image sequence has a time step of Δt = 0.001 s. The corresponding times of the individual frames is given by

"E_camera_1_frame_00001.tif"	"E_camera_3_frame_00001.tif"	t=0.000 s
"E_camera_1_frame_00002.tif"	"E_camera_3_frame_00002.tif"	t=0.001 s
"E_camera_1_frame_00003.tif"	"E_camera_3_frame_00003.tif"	t=0.002 s
:	:	:
"E_camera_1_frame_00100.tif"	"E_camera_3_frame_00100.tif"	t=0.099 s

The calibration grid data will be given using the format

E_camera_i_z_k.tif

where "k" gives the Z-axis position (1 to 7) of the calibration grid. The approximate location of the calibration grid with respect to the center of the laser sheet is given in the table below.

Z-axis Image Name	Approximate Z Position
…z_1.tif	- 3 mm
…z_2.tif	- 2 mm
…z_3.tif	- 1 mm
…z_4.tif	0 mm
…z_5.tif	+ 1 mm
…z_6.tif	+ 2 mm
…z_7.tif	+ 3 mm

For the calibration data, the grid dot located 30 mm to the right and 7.5 mm above the square marker is taken as the X = 0 and Y = 0 point in the world coordinates. This dot is shown as the origin of the coordinate system specified in Figure 2.
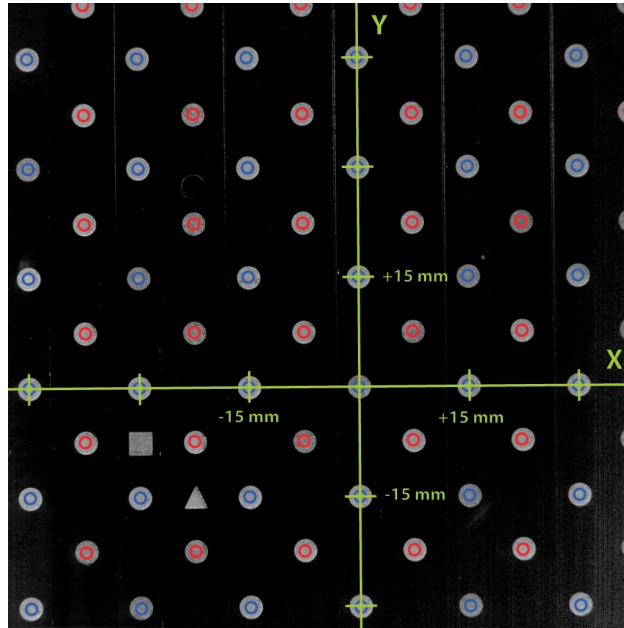
Figure 2: A calibration grid image from camera 1. The green axes denote the location of the defined origin on the two level calibration grid. The blue circles denote the front-level dots while the red circles denote the back-level dots. The spacing between the front and back levels is 3 mm. The spacing between the dots on each level is 15 mm both horizontally and vertically.

3.1 Data format and vector grid

The evaluated data must be provided by the participants in the following data format. If the submitted format deviates from this format (e.g. different number of vectors or additional variables) the file will not be included in the challenge. Data sets with the wrong data format will not be considered!

The data files must be provided in ASCII-Tecplot format. The following example shows the data structure for a displacement vector field:

```
TITLE = "[FileName]"
VARIABLES = "x", "y", "z", "Vx", "Vy", "Vz", "Flag"
ZONE, I=121, J=121, K=1, F=POINT
-34.00  -27.00   0.00   5.45732  6.78354 0.23615   1
-33.55  -27.00   0.00   5.14894  5.97568 1.09732   1
  :        :       :        :        :        :     :
20.00   -27.00   0.00   4.51546  6.57674 2.92864   1
-34.00  -26.55   0.00   6.56494  6.63287 3.93875   1
-33.55  -26.55   0.00   5.47537  5.75648 0.01948   1
  :        :       :        :        :        :     :
20.00   -26.55   0.00   6.52546  7.57974 4.32892   1
  :        :       :        :        :        :     :
-34.00   27.00   0.00   3.51546  6.47674 8.29232   1
  :        :       :        :        :        :     :
```

```
    20.00   27.00   0.00   5.51846   4.27974   2.38994   1
```

The separation of the numbers should be done with a white space. The number after "I=" is the number of vectors in the X-direction, the number after "J=" is the number of vectors in the Y-direction, and the number after "K=" is the number of vectors in the Z-direction (which should be one). These numbers are fixed, see above.

The convention for "Flag" is as follows:
  "0" Not valid
  "1" Valid
  "2" Interpolated

The participants must provide the results on the following grid:

  Vector grid: The locations of the vector grid points are:
                 X = -34.00 mm to 20.00 mm   use grid distance of ΔX = 0.45 mm $\rightarrow$ 121 nodes
                 Y = -27.00 mm to 27.00 mm   use grid distance of ΔY = 0.45 mm $\rightarrow$ 121 nodes

  Origin: The origin of the grid is shown in Fig. 2.

The X and Y grid points in the data file must have units of "mm" while the measured velocity field must have units of "m/s". When Particle Tracking Velocimetry (PTV) is used for data evaluation, the velocity information must be interpolated on the grid specified above. The participants are free to choose the interpolation scheme.

3.2 Desired Quantities and Name Convention

3.2.1 Velocity fields, evaluation 1 [eval1]

The participants will be given 100 sequential images and are required to calculate the velocity field at 50 time steps. The velocity field must be calculated on the grid specified in section 3.1, but any evaluation method may be used. The 50 velocity fields that the participants will calculate should correspond to the following time steps:

Time Step 25
t=0.024 s to t=0.025 s $\rightarrow$ "E_eval1_[TeamName]_00025.dat"

Time Step 26
t=0.025 s to t=0.026 s $\rightarrow$ "E_eval1_[TeamName]_00026.dat"

  :   :

Time Step N

t=0.001*(N-1) s to t=0.001*N s →   "E_eval1_[TeamName]_[%05N].dat"

:   :   :

Time Step 74
t=0.073 s to t=0.074 s   →   "E_eval1_[TeamName]_00074.dat"

This results in a total of 50 DAT files. The ASCII files should contain the following information:

```
TITLE = "E_ eval1_[TeamName]_[%05N].dat"
VARIABLES = "x", "y", "z", "Vx", "Vy", "Vz", "Flag"
ZONE, I=61, J=61, K=1, F=POINT
[data, 7 columns]
```

The participants must provide a file "Documentation_E_eval1_[TeamName].txt" or ".doc" which outlines the parameters and methods that were used for the evaluation.

3.2.2 Vorticity and Circulation measurement, evaluation 2 [eval2]

For this evaluation, the participants must calculate the Z-vorticity component across the measurement plane and the circulation of both vortex ring cores at the 50 time steps specified in section 3.2.1. The participants are free to choose any method to estimate the vorticity and the circulation. The participants will then provide ASCII formatted DAT files containing (1) the vorticity plane and (2) measured circulation at all time steps.

The provided data must be in the following format

Vorticity

Time Step 25
t=0.024 s to t=0.025 s   →   "E_eval2_[TeamName]_00025.dat"

:   :

Time Step N
t=0.001*(N-1) s to t=0.001*N s →   "E_eval2_[TeamName]_[%05N].dat"

:   :   :

Time Step 74
t=0.073 s to t=0.074 s   →   "E_eval2_[TeamName]_00074.dat"

The ASCII DAT file for the vorticity should contain the following information

```
TITLE = "E_eval21_[TeamName]_[%05N].dat"
VARIABLES = "x", "y", "Vort_z", "Flag"
ZONE, I=61, J=61, K=1, F=POINT
[data, 4 columns]
```

where the variable "x" and "y" are the same coordinates specified in section 3.1 and "Vort_z" corresponds to Z-vorticity. The "Flag" column uses the same convention specified in section 3.1 and states whether the vorticity measurement is "Not Valid," "Valid," or "Interpolated." The participants must provide a file named "Documentation_E_eval2_[TeamName].txt" or ".doc" that outlines the parameters and methods that were used for the evaluation.

Circulation

The participants must provide the circulation measurements at the same time steps as the velocity and vorticity measurements. The file name of the circulation data must be given in the form

"E_eval3_[TeamName]_00025_to_00074.dat"

The ASCII DAT file should contain the following information

```
TITLE = " E_eval3_[TeamName]_00025_to_00074.dat"
VARIABLES = "t", "Ca", "Cb"
ZONE, I=50, F=POINT
[data, 3 columns]
```

where the variable "t" corresponds to the time step which should range from t=0.024 to t=0.073 (and has units of seconds). Additionally the variable "Ca" corresponds to the circulation of the top vortex core and "Cb" corresponds to the circulation of the bottom vortex core. The units of the circulation must be in "m^2/s". The participants must provide a file "Documentation_E_eval3_[TeamName].txt" or ".doc" that outlines the parameters and methods that were used for the evaluation.