

PIV Analysis of Forcing a Planar Jet Using a Loudspeaker

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Introduction

Fluid flow modeling and control is extensively researched due to its wide range of applications and its potential for drastic economic and environmental savings. In particular aerospace and combustion applications have great potential for increased efficiency.

Direct numerical simulation (DNS) of a flow is often too slow a process for practical engineering purposes. In place of this some researchers have taken the approach of using “lower order” models which use fewer state variables to describe a flow, and thus increasing the speed at which a given flow can be modeled. The tradeoff for this speed is that the approximations inherent in the reduction of the model’s order yield inaccuracies.

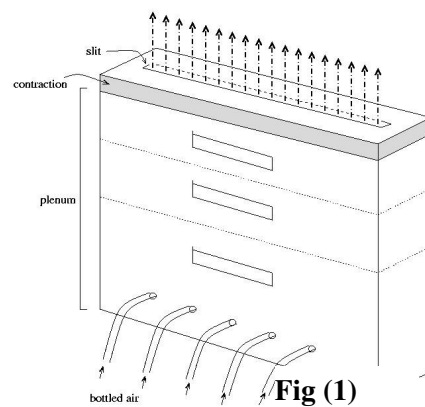
This research is part of a broader initiative attempting to compensate for the lower order model’s inaccuracy by correcting the model with actual observations of the flow. Specifically we are using knowledge of flow dynamics to selectively correct a point-vortex model. This paper will detail the process and results of the acquisition of Particle Image Velocimetry (PIV) lab data describing a low Reynolds number Planar Jet . The data will be used to test the data assimilation process.

PIV is the process of determining the velocity throughout fluid flows by tracking the displacement of seeded particles in the flow between laser pulses. We used the process of 2-frame cross correlation to track this motion.

Experiment Set-Up

The idealized planar jet is approximated by considering the cross section of a stream of air exiting a long slit. The set-up for this appears as in Figure (1). Air enters the base of a plenum, composed of 4 sections, through 10 hoses. The internal cross section of the plenum measured 400 mm by 15 mm. Between each of the four sections the air passed through a flow treatment screen using 24 mesh with .0075- in diameter wire for flow conditioning. For further flow conditioning $\frac{1}{4}$ in diameter BB's were placed between the two lowest sections. Once the air reached the top of the plenum, the air passed through a matched cubic contraction of area ratio 6:1, providing additional conditioning of the flow. Finally the flow exited through a 400mm by 2.5 ± 0.01 mm slit.

The plenum was placed on vibration control mounts, as well as semi-enclosed by a 1-m³ Plexiglas box in order to minimize the effects of mechanical vibrations and ambient



air flow. This experiment set-up was designed and constructed by Thomas Peacock, with the aid of Jean Hertzberg.

Because the apparatus was used in previous work, our first task was to disassemble it in order to understand its design, as well as to clean it. The jet apparatus is constructed such that each of its 4 sections is held in place by two columns on either side of the jet. By removing the screws connecting each section to the column (4 screws total), each section can be removed by sliding it vertically up, and out of the column. The combination of tight tolerances and silicone sealant require a significant amount of force to raise each section. This was achieved by using uni-strut to construct a column with a sturdy base and a short cantilever of adjustable height. The cantilever was then be used as a support to attach a C-Clamp to either side of each section, then the C-clamps can be tightened, producing the necessary force to move each section. Once each section was removed it was cleaned with alcohol and all excess silicone was removed using razor blades. The jet was reassembled, and silicone reapplied to the junction of each adjoining section.

We elected to examine the jet with a characteristic Reynolds number of 70 at the nozzle. This value was chosen because under these conditions it is possible to excite both the jet's symmetric, as well as its anti symmetric, modes of instability under external forcing. This paper will address only the anti-symmetric mode. The flow rate necessary to achieve $Re \approx 70$ was

determined according to Eq(1) where V_0 is the centerline stream-line velocity, d is the jet half width, and ν is the kinematic viscosity.

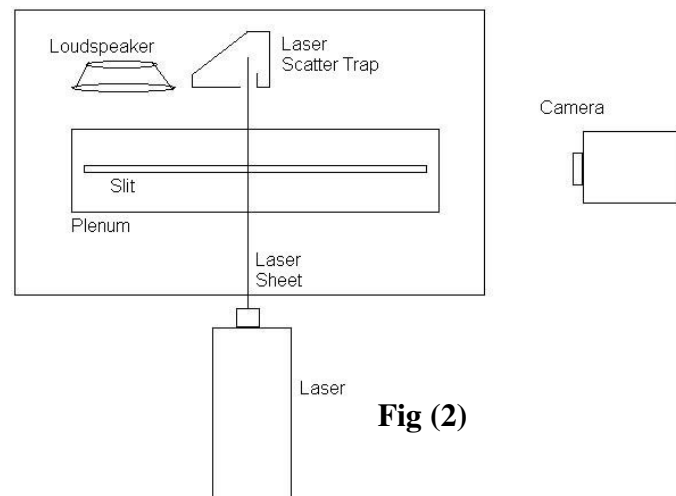
$$\text{Re} = \frac{V_0 d}{\nu} \quad \text{Eq(1)}$$

By using the approximation $V_0 = \frac{Q}{A}$ we determined that the approximate necessary flow rate into the plenum was 50.4 L/min. In order to insure that this flow was room temperature it passed through a copper coil that was placed in a water bath prior to entering the jet. After leaving the bath the air travels through a flow meter, and then reaches a junction with two branches. One branch flows into a 55 gallon drum which is seeded with theater fog in order to allow the PIV imaging. Air then flows from the drum to into the plenum. The second branch bypasses the fog system and flows straight into the plenum. Each of these branches is controlled by a variable valve which allows us to control the concentration of seeding in the air as it enters the plenum. The air in the drum was seeded with fog through the use of a theater fog generator. Air that exits the seeding system without any dilution is too densely seeded to use for PIV analysis. Through trial and error we determined that the proper level of dilution could be achieved by completely opening the branch to the seeding system, and closing the bypass branch. Then we set the external flow rate at 30 L/min. After this we opened the seeding system bypass valve until the flow rate reached the desired level of 50.4 L/min.

In order to minimize the effects of ambient air motion the jet was enclosed by a Plexiglas box. We used a vacuum system which removed air at the same rate it was entering through the jet. In order to optimize the seeding of the box for PIV analysis we allowed the box to fill as uniformly with fog particles as possible prior to taking PIV data.

The forcing of the jet was accomplished by placing a loudspeaker whose center was offset from the jet slit by approximately 25 cm and 15 cm from the plane that is being used to image the planar jet. This is shown in figure (2). The loudspeaker was powered by an amplifier that was connected to a function generator. The

function generator produced a sinusoidal wave at 16.83 hertz, which was determined in previous work to be the natural frequency of the jet. We used an oscilloscope in order to insure that the wave form and voltage remained constant through the experiments.



At the conclusion of the experiment we also tested designs for piezo-electric actuators. The setup with the actuators remained the same however the function generator was set to a sinusoidal wave of 2.4 kHz, with amplitude modulation occurring at 16.83 Hz. This setup was successful in forcing the jet in the anti-symmetric mode.

We imaged this forcing using a TSI Incorporated Particle Image Velocimetry System.

This system consists of a New Wave Research Solo Nd:Yag laser, a TSI PIV 13-8 camera, a TSI model 610034 laser synchronizer and a computer with a TSI Framergripper installed. The laser was mounted perpendicularly to the slit of the jet in order to illuminate a cross section that is representative of a planar jet.

The laser was focused into a vertical light sheet using a -15mm cylindrical lens and a 500mm spherical lens. The laser was positioned so that the light sheet was thinnest at the slit. The camera was oriented perpendicularly to, and focused on, the plane illuminated by the laser. Both the laser and the camera were mounted on tripods outside of the Plexiglas box. In order to maintain the desired light sheet the laser was shone through a section of the box where the Plexiglas had been replaced with a quartz window. In order to maintain optical clarity the camera took the pictures through a section of the box where the Plexiglas was removed in favor of a sheet of photography glass. Additionally a laser light scatter trap was placed behind the slit, and in line with the light sheet, in order to prevent any reflecting laser scatter from illuminating seeding particles outside the plane of light.

The frame grabber and the laser synchronizer worked together to coordinate the firing of the laser and the taking of pictures. Using the TSI Insight 3G software we were able change the timing, as well as other capture settings, of the laser and camera firing in order to optimize the

process for our flow. The capture settings we found that produced the best results can be seen in Table(1).

Due to the fact that the laser's maximum rate of fire, approximately 10 Hz, was less than the jets natural frequency we had to implement a system of phase locking. Through this process we took a sample of data from the same point in the cycle every sixth cycle. This process was

Table (1)	
Capture Type	PIV
PIV Frame Mode	Straddle
Capture Mode	Sequence
Exposure Mode	Synchronized
Save Mode	To Disk
Pulse Rep Rate	4
Q Switch Divide	1
	150
Delta T	235
	250
Laser Pulse Delay	
PIV Cam. Exposure Time	

repeated for 16 divisions of the jet cycle. We accomplished this by using the sync signal from the function generator to act as an external trigger to the laser synchronizer. We setup Insight to pause for a set amount of time between receiving the external trigger, and initiating the capture sequence. The pause lasted five cycles of the jet, plus the length of time into the jet's cycle that we wanted to image. Each phase of the cycle was imaged 500 times near the jet exit and 500 times downstream.

Once the data for each phase was collected it was processed using Insight. The processor settings we used can be seen in table(2). Once the data was processed we applied validation

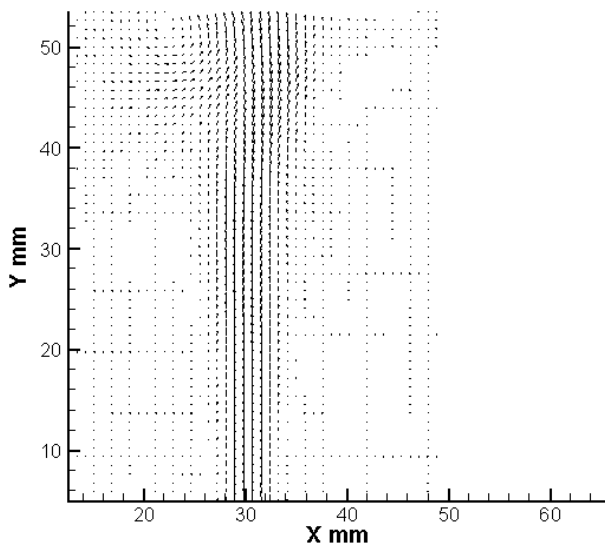
filters in order to eliminate any spurious vectors that arise due motion in and out of the plane, as well as to interpolate holes in the vector field where correlation failed. Following the validation of the vector fields, we used Insight's add-on to the program Tec Plot in order to create an average field for each phase. We also created an average field describing the jet when there was no forcing.

We then examined the RMS for the vectors in each phase in order to insure that the fields were converging. We did this by creating average fields composed of 30,60,120,240, and 480 sample fields for each phase. We then used a matlab script to look at the individual vectors which experienced the greatest amount of change in RMS between the final two doubling of sample sizes. We then examined the RMS for these vectors through all of the vector sample sizes to be sure that the data was converged.

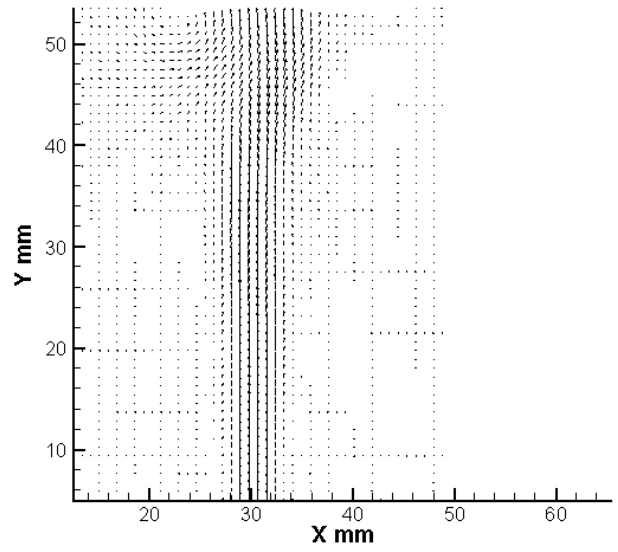
Table (2)	
Grid Engine	Nyquist Grid
Spot Mask Engine	Gaussian Mask
Correlation Engine	FFT Correlator
Peak Engine	Gaussian Peak
Starting Spot A Width	32 pixels
Starting Spot A Height	32 pixels
Starting Spot B Width	64 pixels
Starting Spot B Height	64 Pixels
Maximum Displacement	8 pixels

Results: Forced Upstream Data-

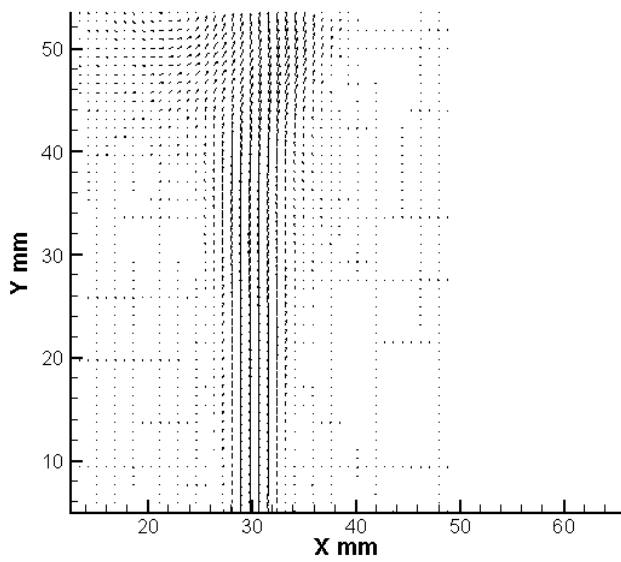
Phase 1 Upstream.vec



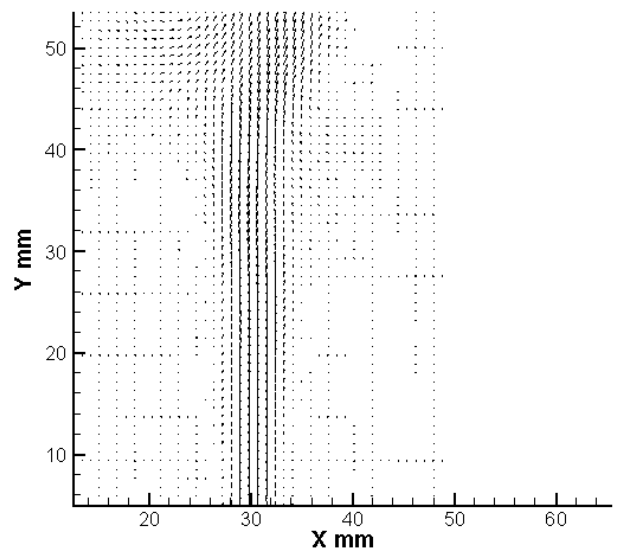
Phase 2 Upstream.vec



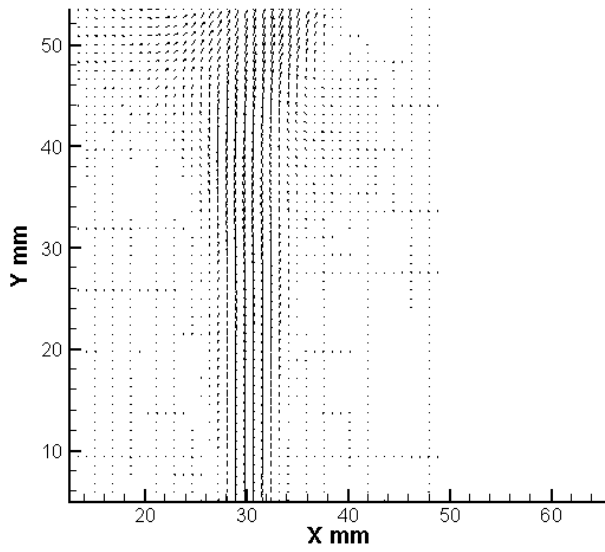
Phase 3 Upstream.T.D.P.H..vec



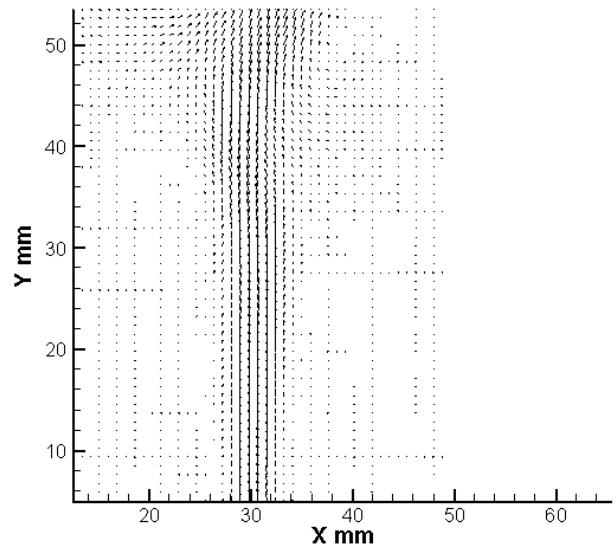
Phase 4 Upstream.vec



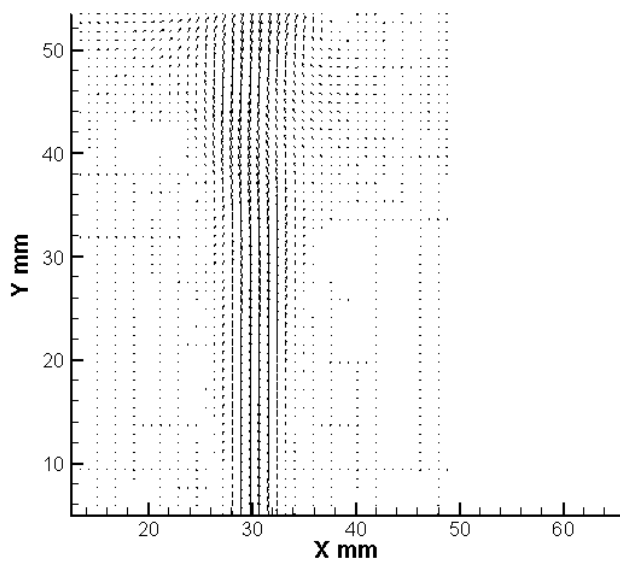
Phase5 Upstream.vec



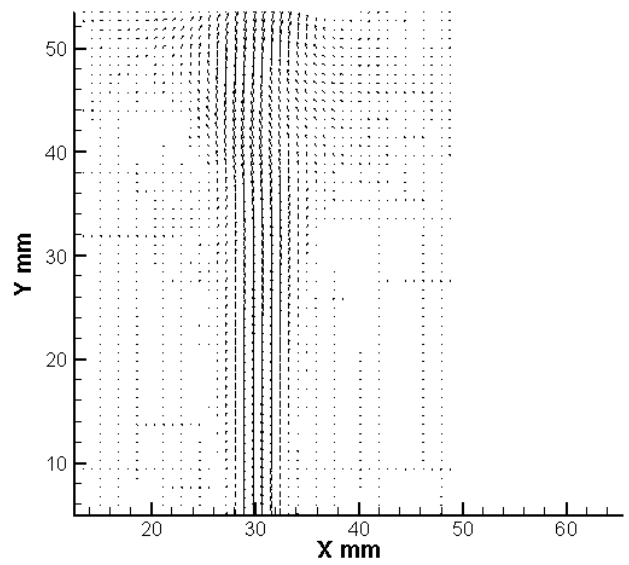
Phase6 Upstream.vec



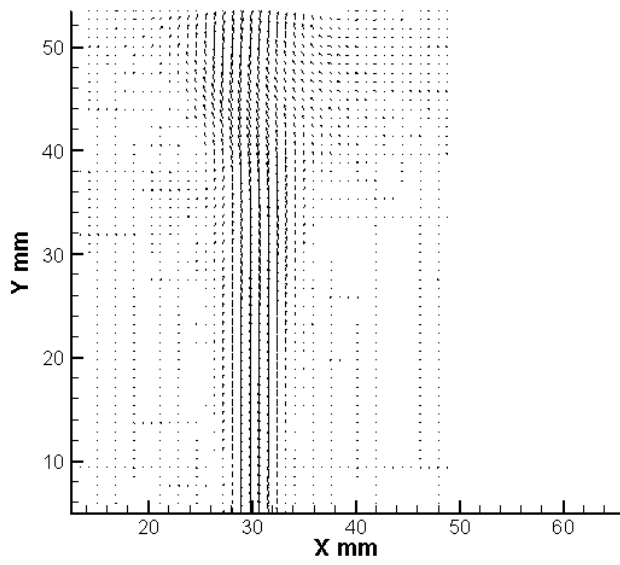
Phase7 Upstream.vec



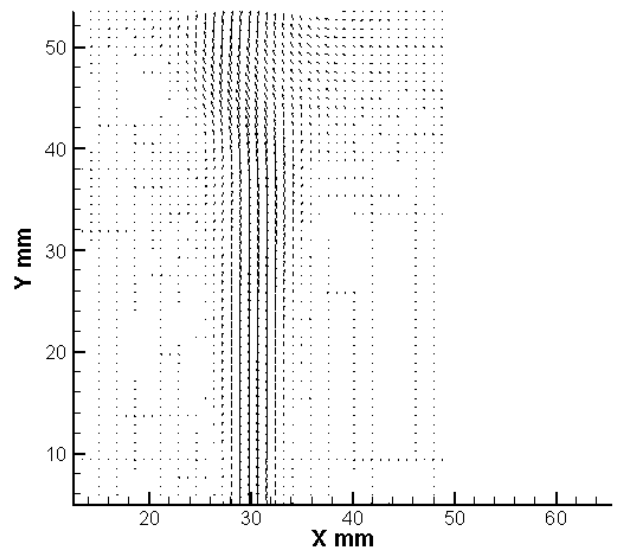
Phase8 Upstream.vec



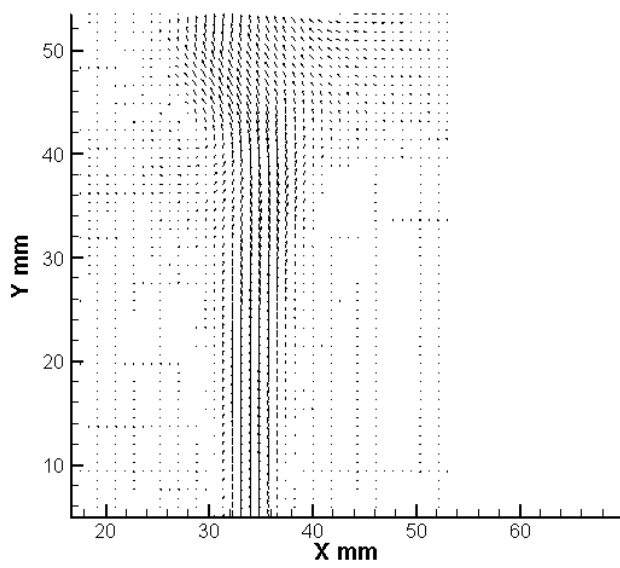
Phase9 Upstream.vec



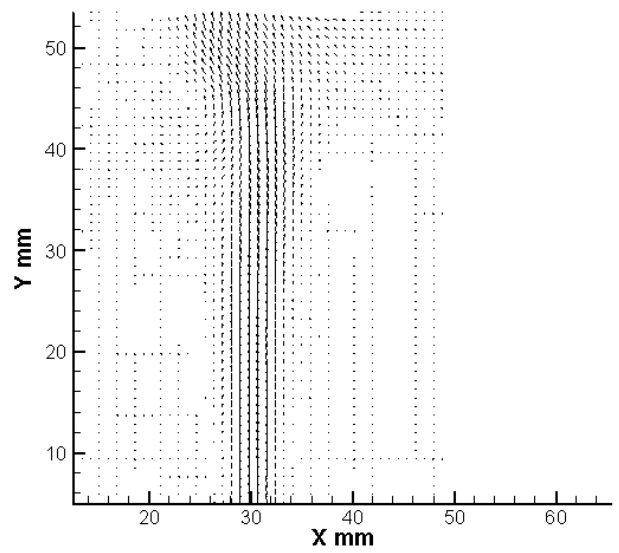
Phase 10 Upstream.vec



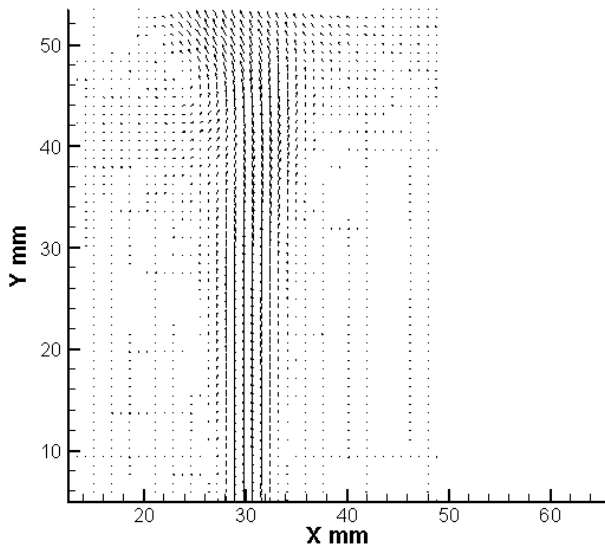
Phase 11- Downsteam.vec



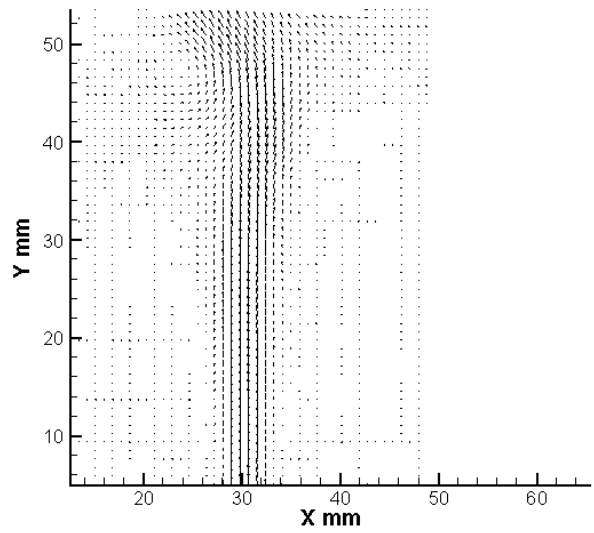
Phase 12 Upstream.vec



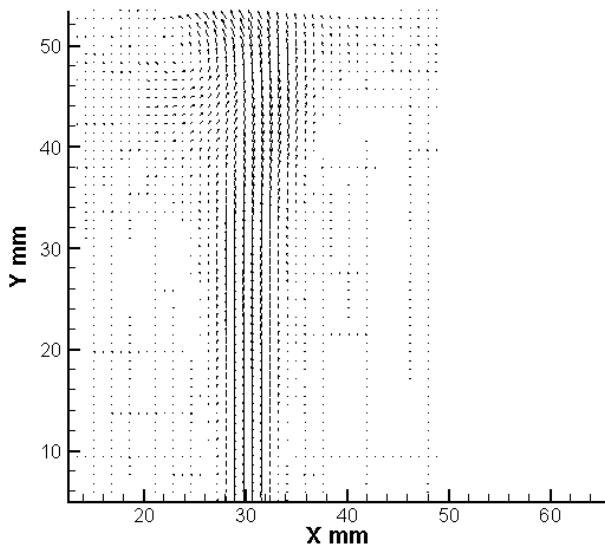
Phase 13 Upstream.vec



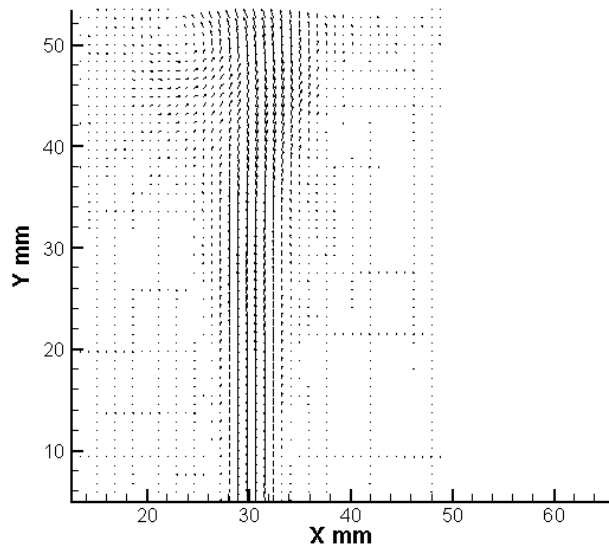
Phase 14 Upstream.vec

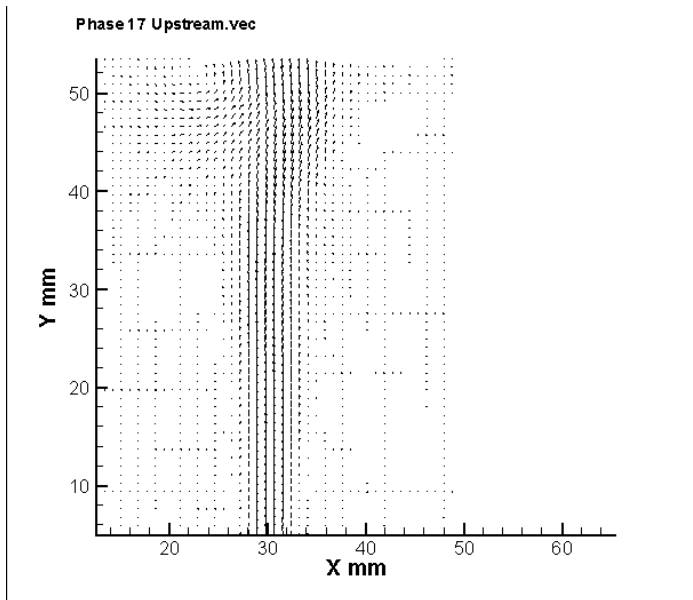


Phase 15 Upstream.vec



Phase 16 Upstream.vec

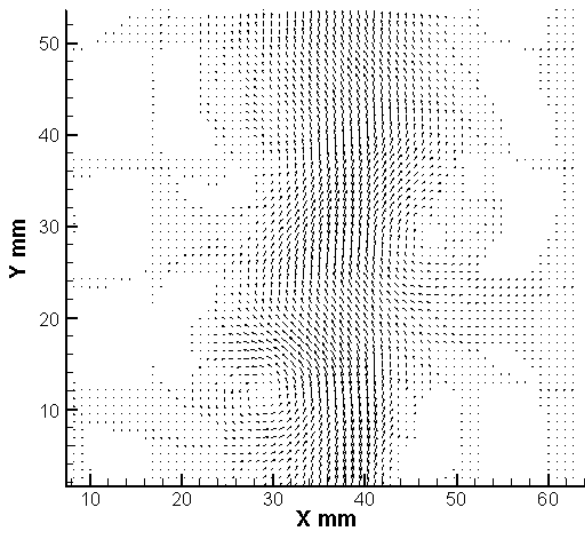




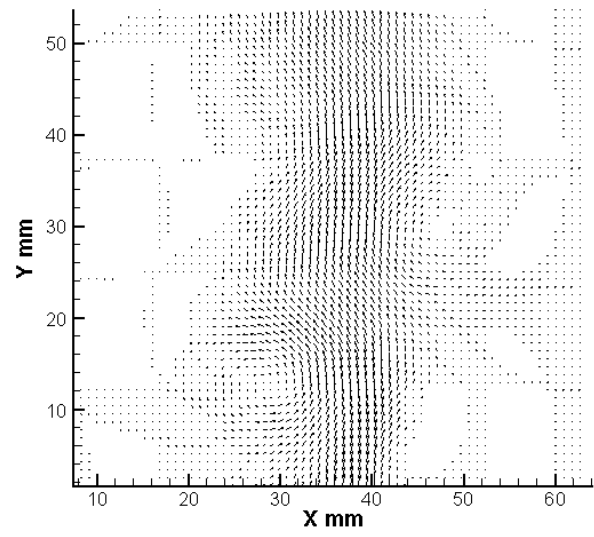
Forced Downstream Data:

These fields are Offset +6.1 mm in the x direction, and +37.2 mm in the y direction from the center of the jet in the upstream data.

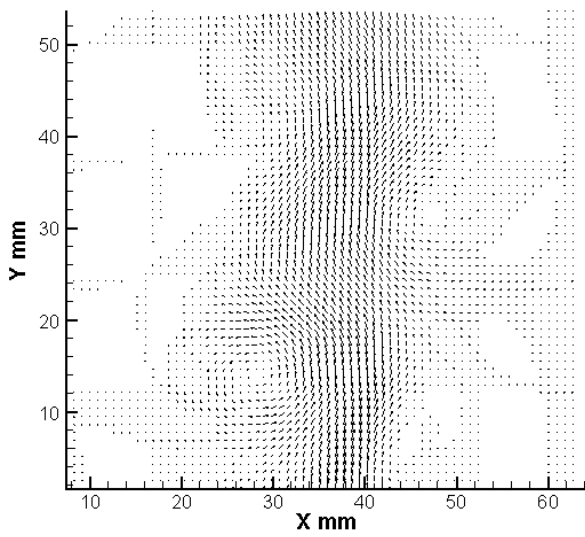
P-1-D.vec



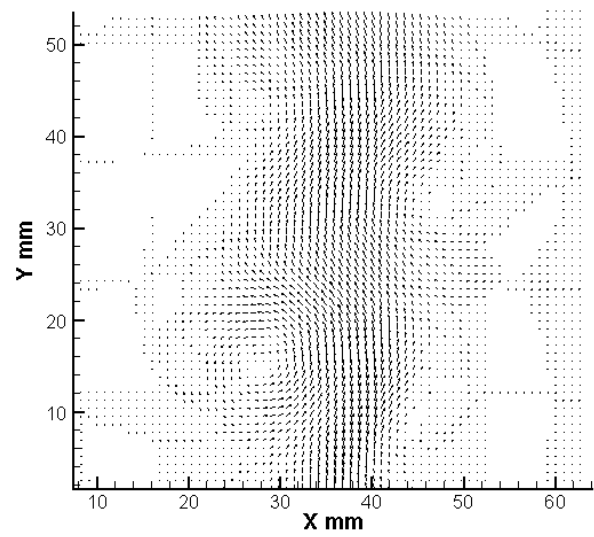
P-2-D.vec



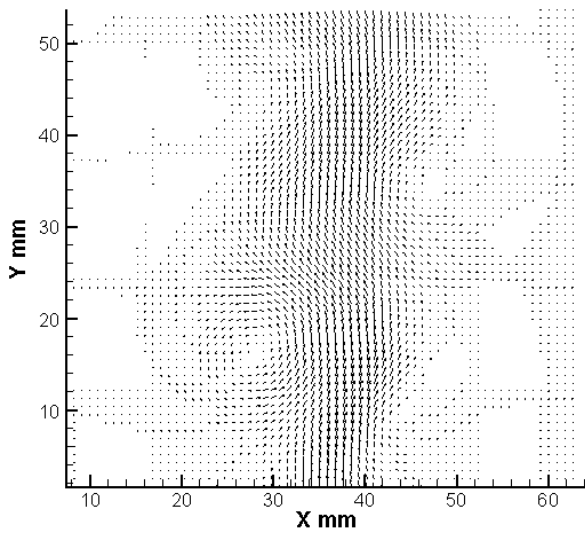
P-3-D.vec



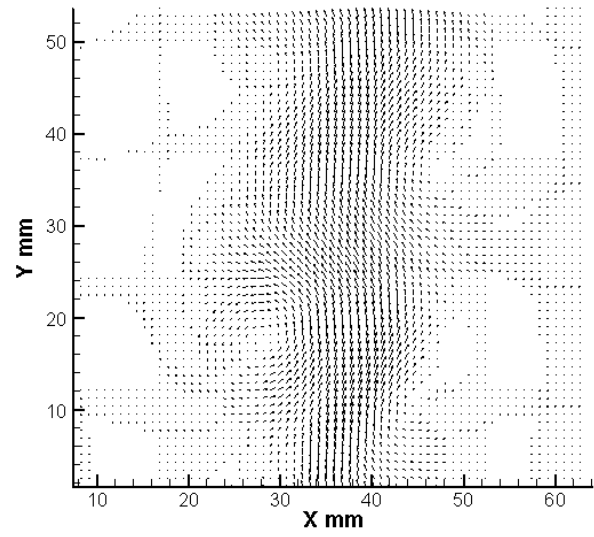
P-4-D.vec



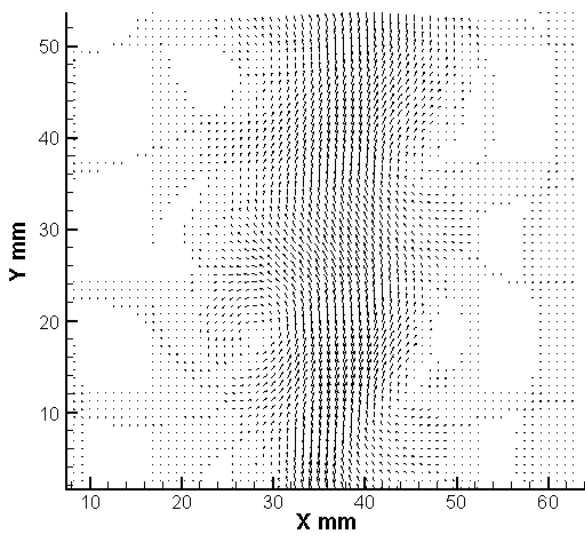
Phase 005 - DownstreamAvgL.vec



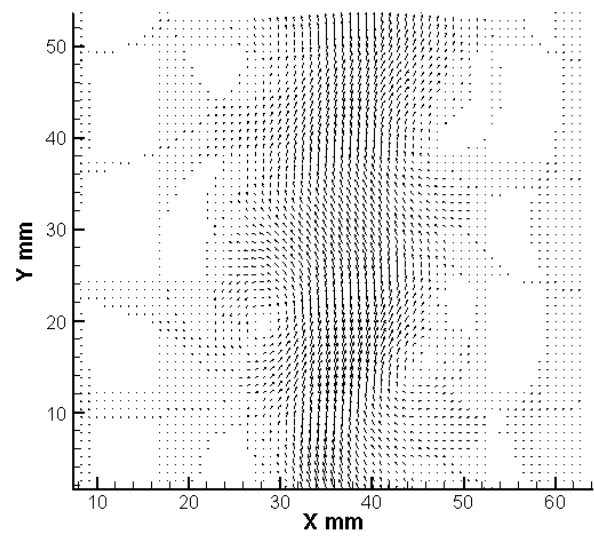
Phase 006 DownstreamAvgL.vec



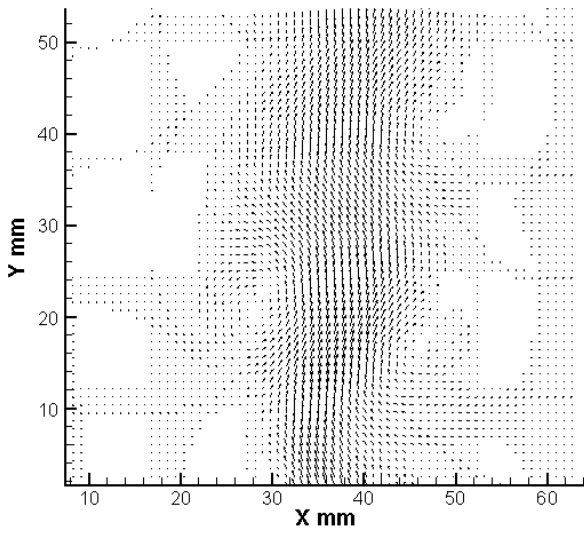
Phase 007 DownstreamAvgL.vec



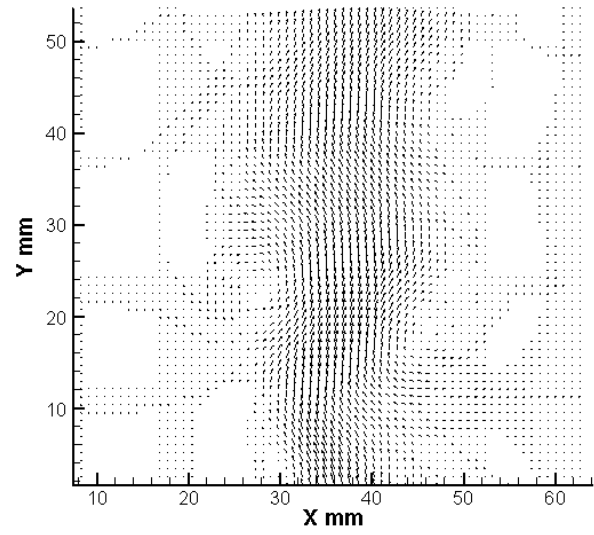
Phase 008 DownstreamAvgL.vec



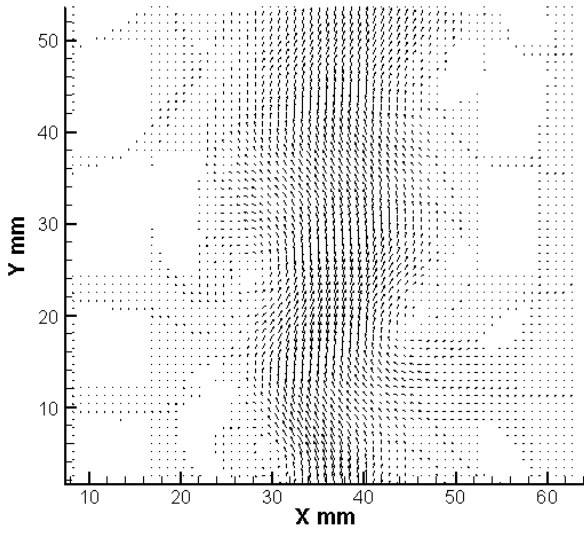
Phase009 DownstreamAvgL.vec



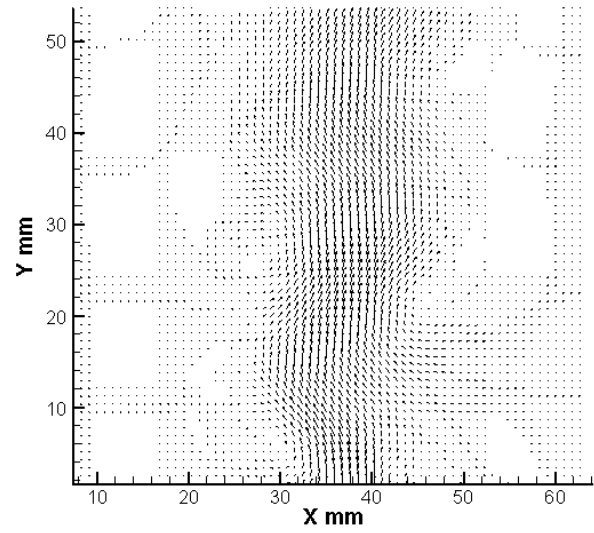
Phase010 DownstreamAvgL.vec

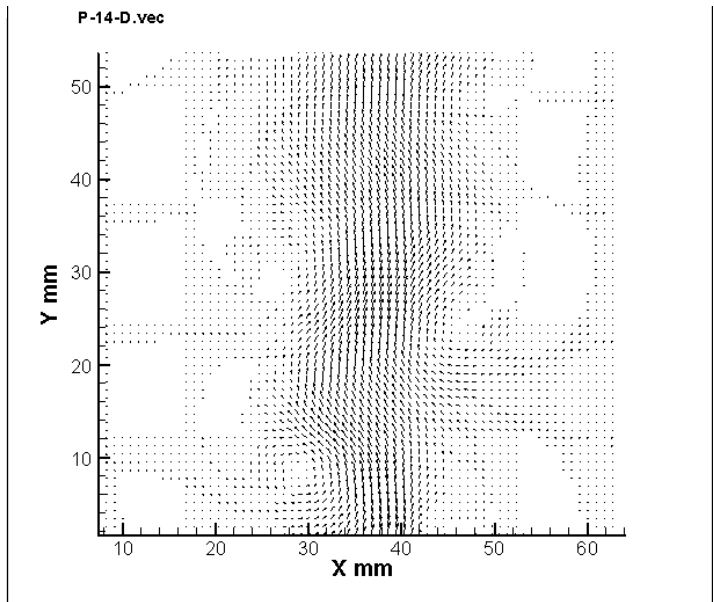
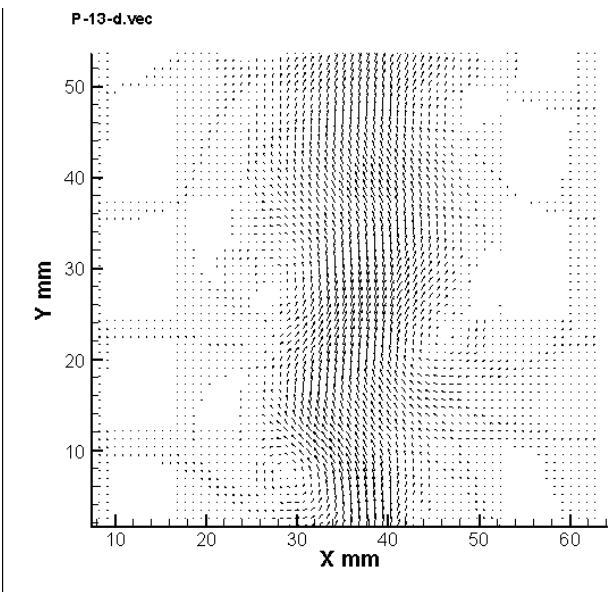


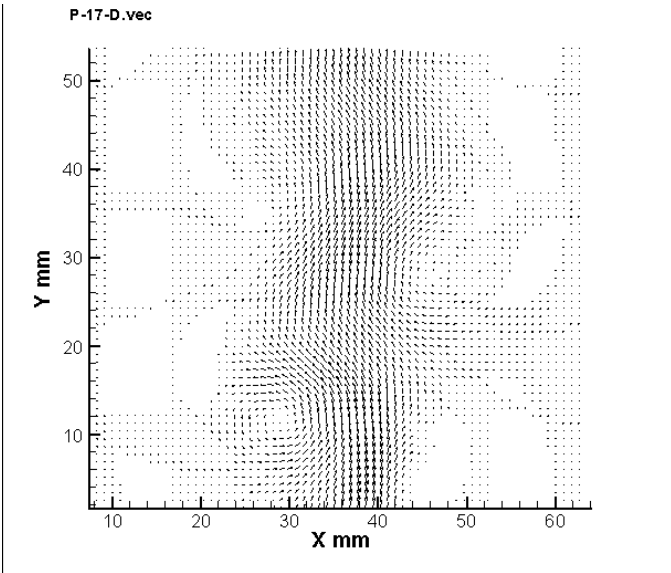
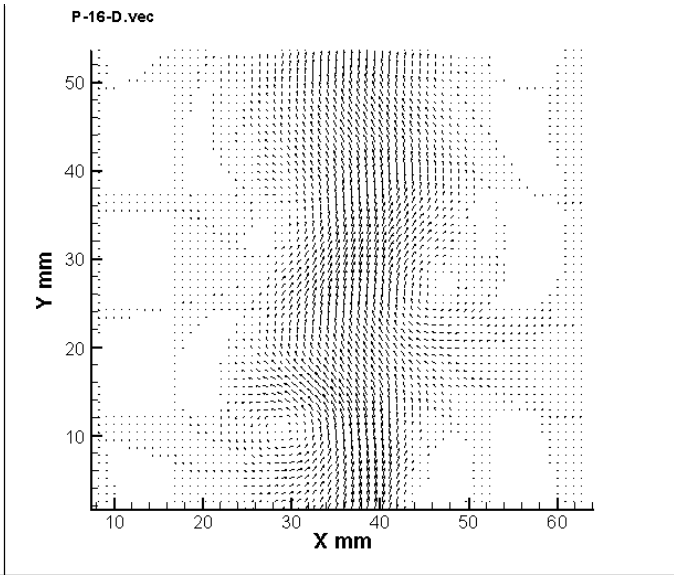
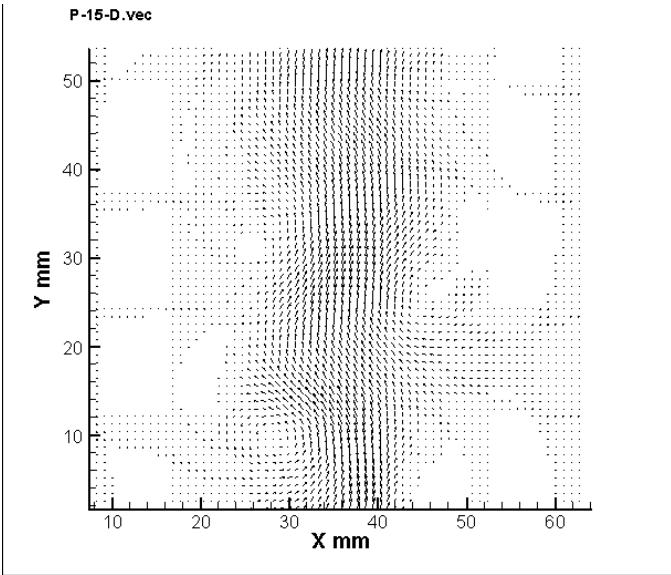
Phase011 DownstreamAvgL.vec



P-12-D.vec

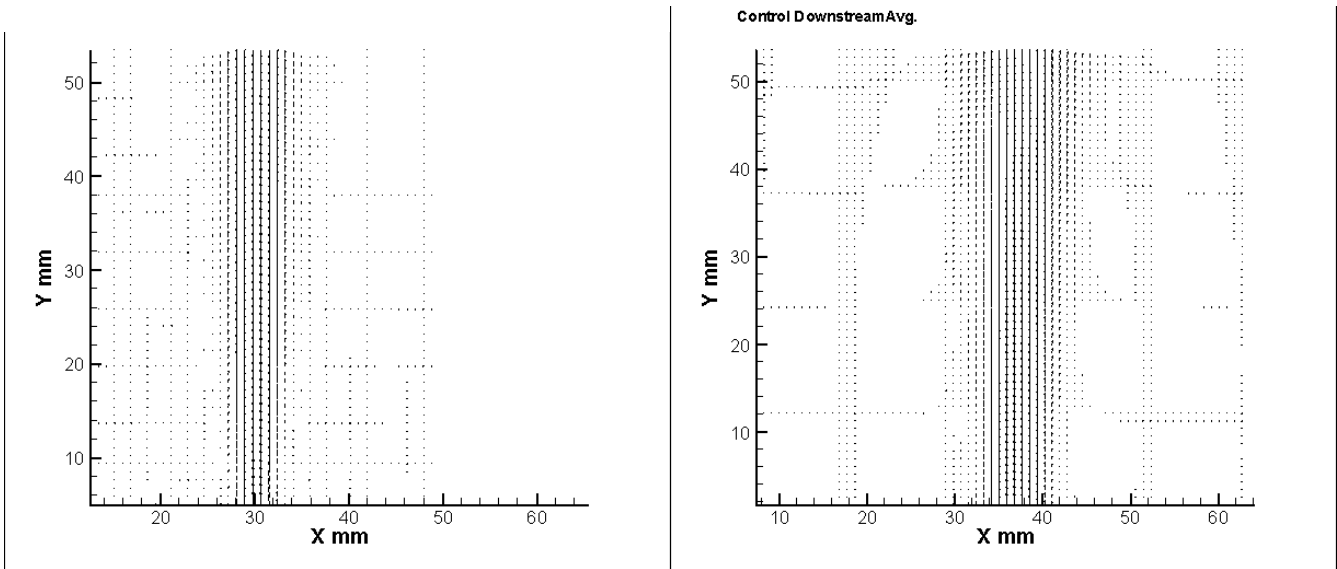






Unforced Flow:

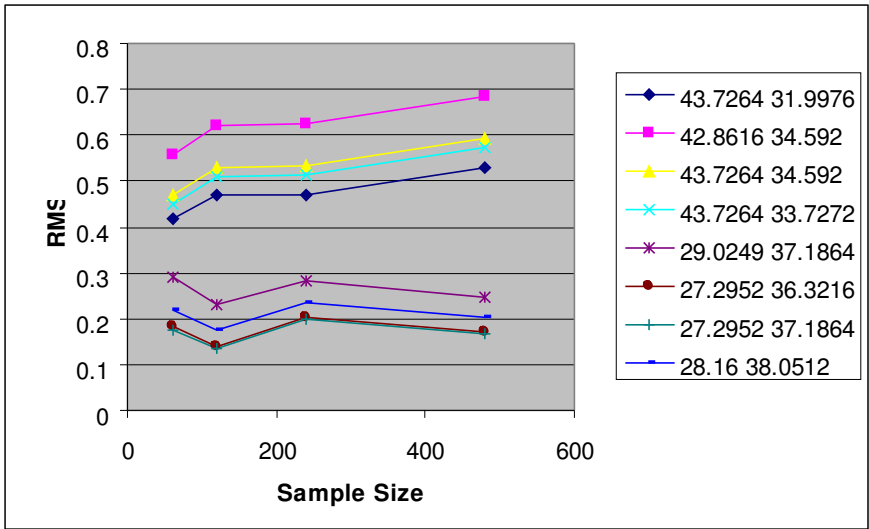
Upstream



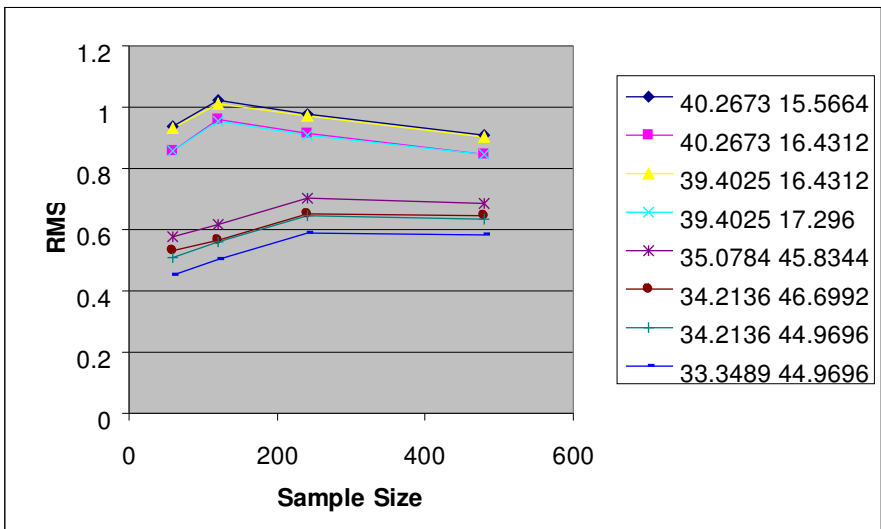
Accuracy of the Data:

In order to insure that the data had approximately converged in the number of samples we took we plotted the variation in RMS (Root Mean Square) of the velocity between increasing sample sizes for each phase. The points plotted are the eight points that experienced the greatest variation in RMS between the two greatest increases in sample sizes. For each of these points we plotted the RMS for sample sizes of 60, 120, 240, and 480 individual vector fields. We consider that the data is sufficiently converged for our purposes in all phases.

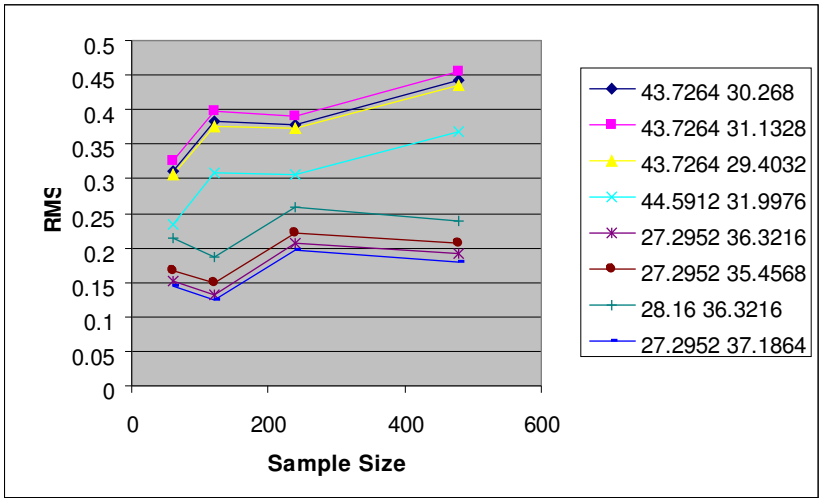
Phase 1:



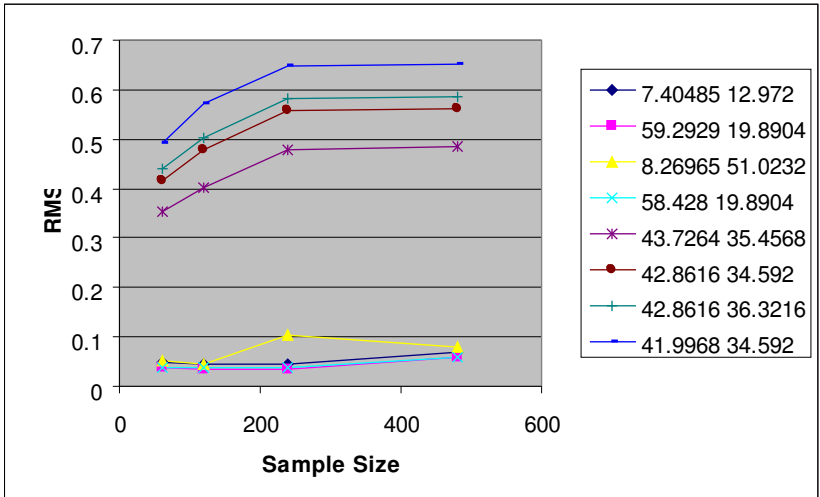
Phase 2:



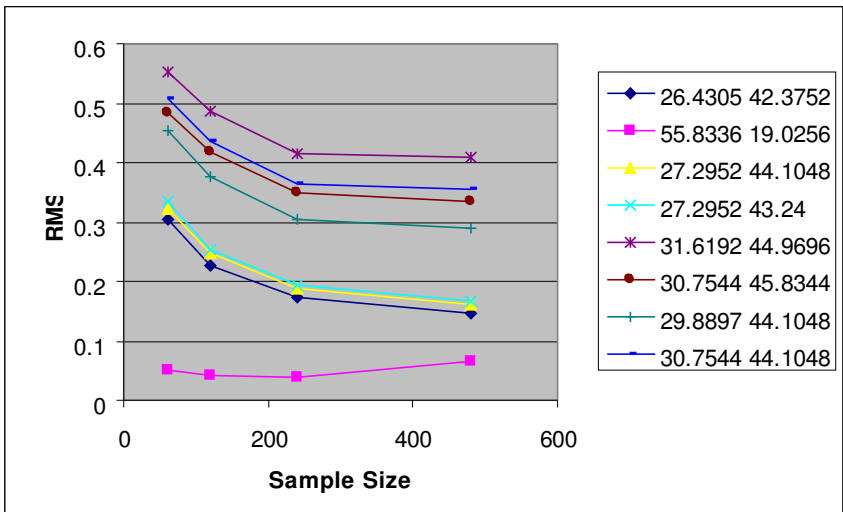
Phase 3:



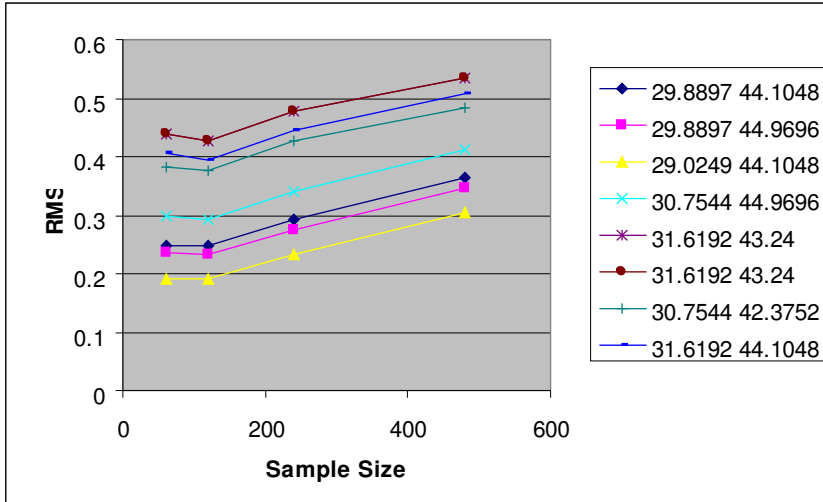
Phase 4:



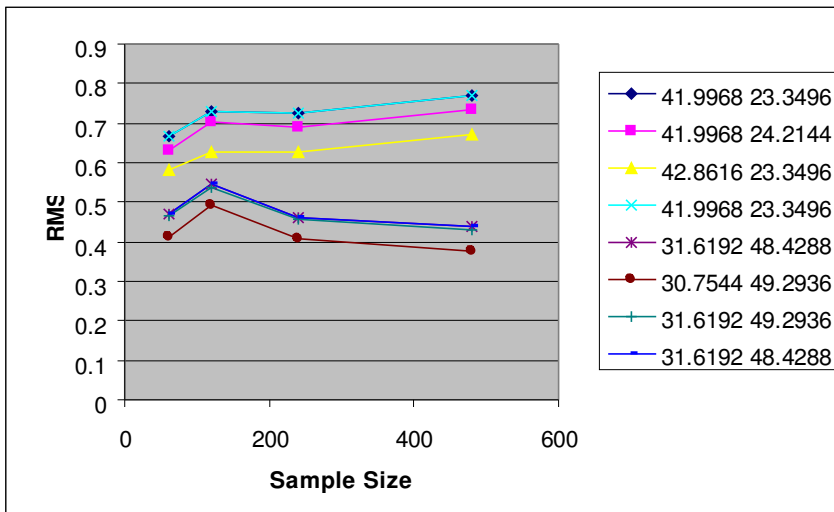
Phase 5:



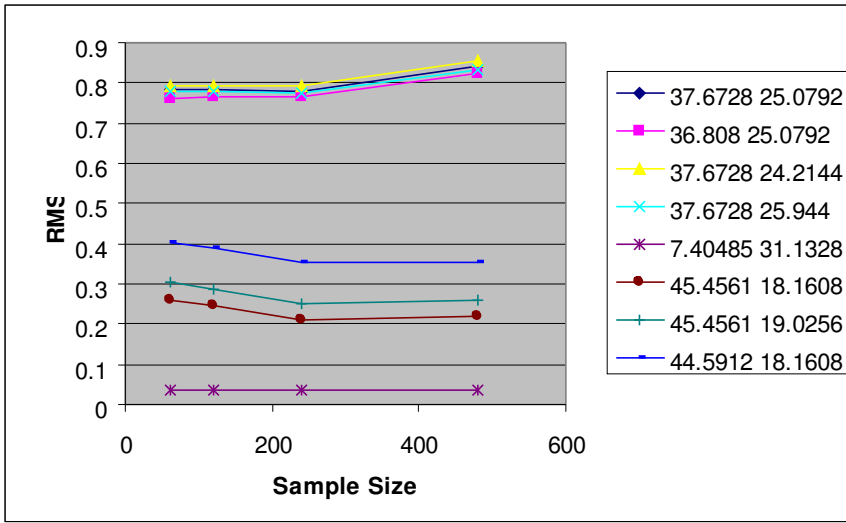
Phase 6:



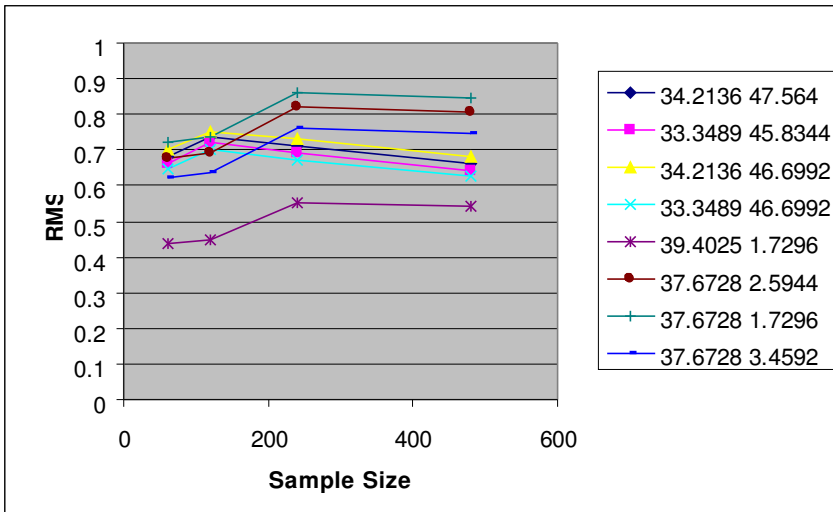
Phase 7:



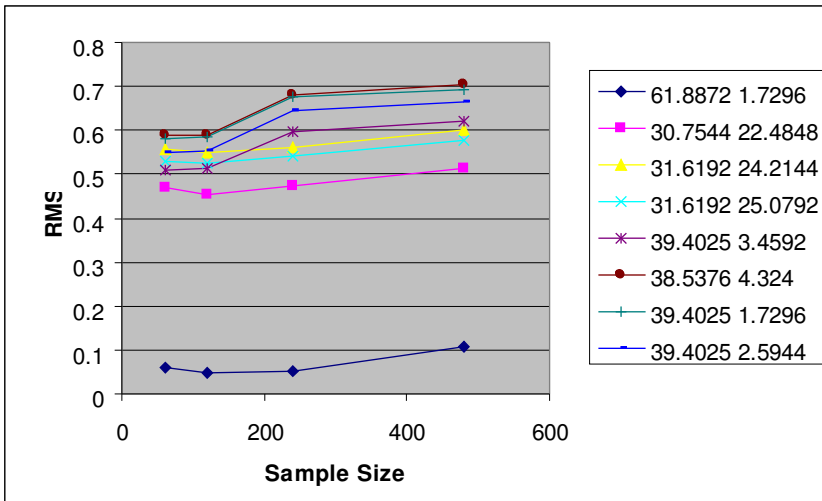
Phase 8:



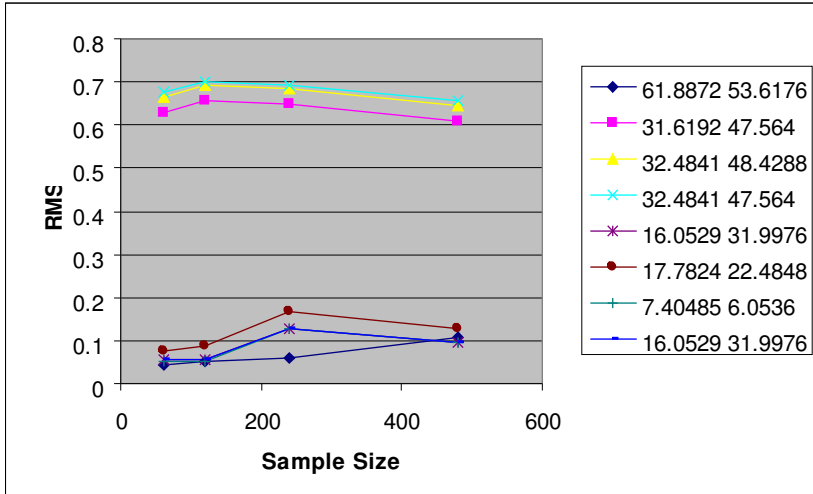
Phase 9:



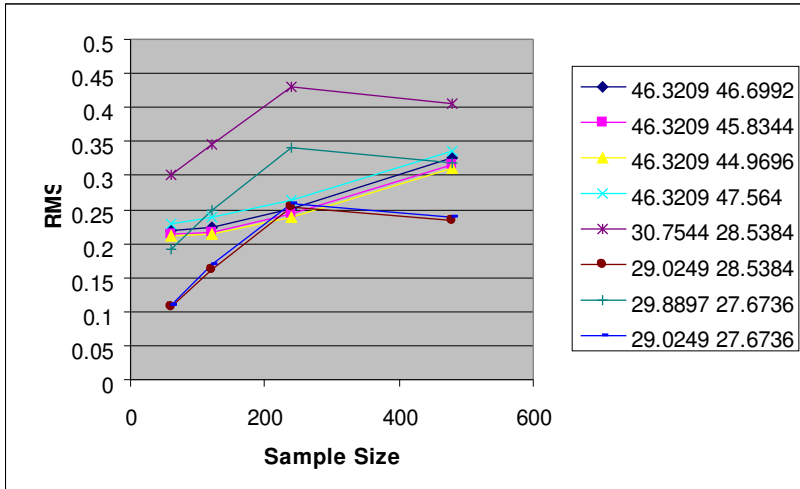
Phase 10:



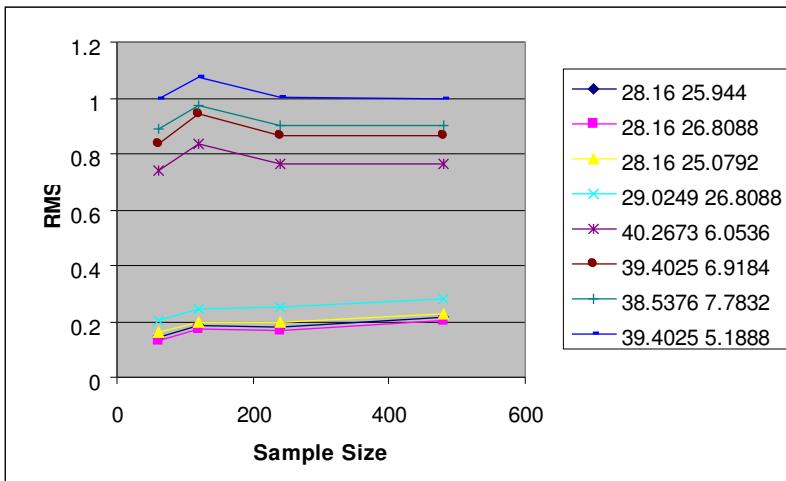
Phase 11:



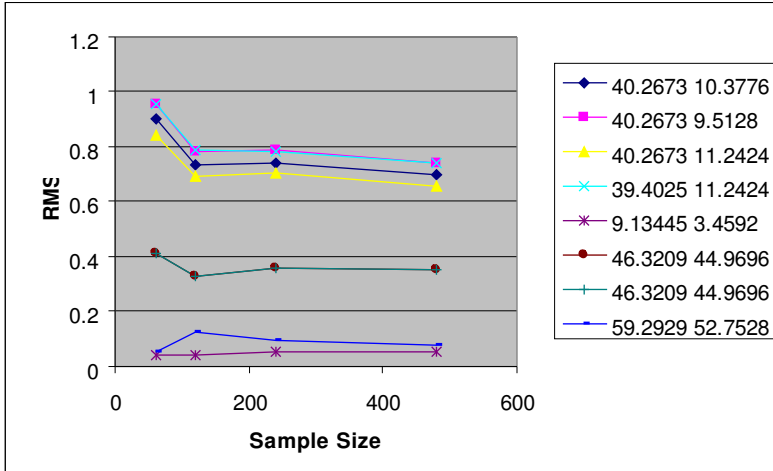
Phase 12:



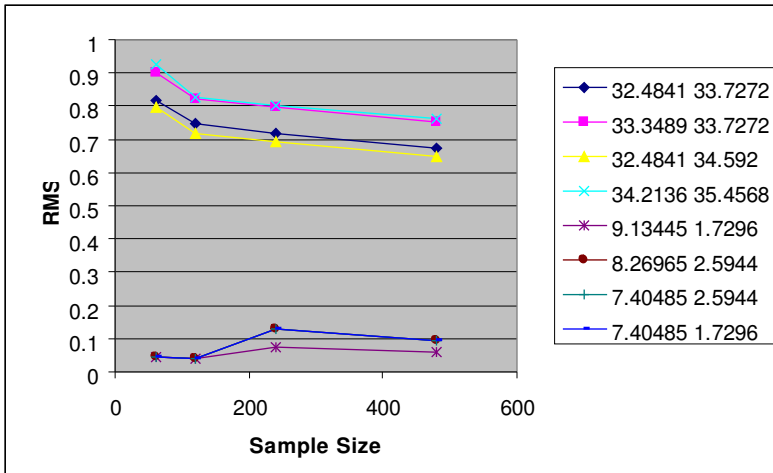
Phase 13:



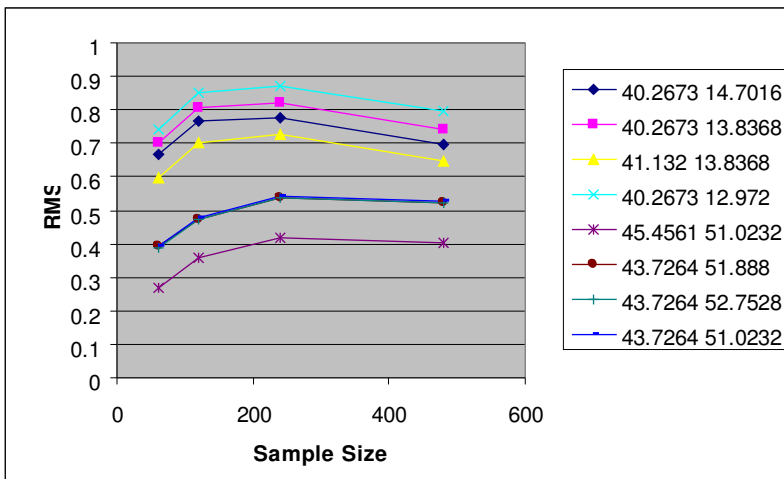
Phase 14:



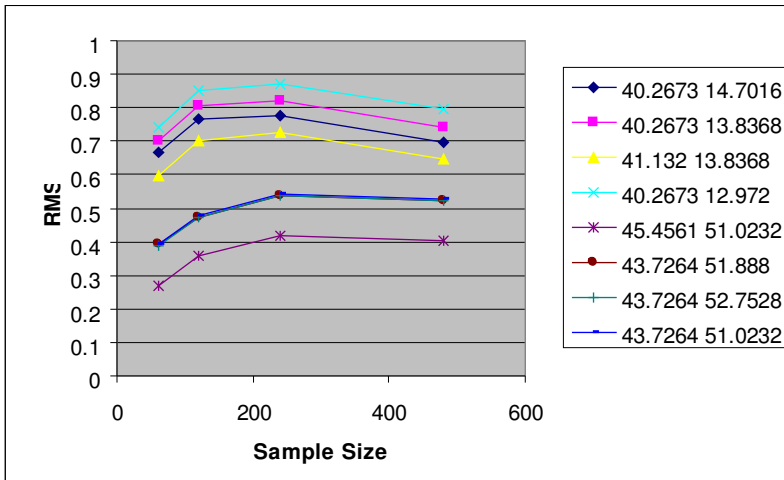
Phase 15:



Phase 16:



Phase 17:



Conclusions and Further Work

We were able to successfully excite an anti-symmetric mode in a planar jet using a loudspeaker. More importantly we were able to track structures that formed as a result of the excitations using PIV. This experiment was an important first step in that it provided a relatively simple foundation to gain experience with using PIV to analyze the planar jet, as well as producing an initial data set on which to begin testing the various processes involved in Dynamics Informed Data Assimilation.

This work will be continued by replacing the loud speaker with actuators capable of producing a relatively two- dimensional excitation. Actuators will be placed on both sides of the slit allowing for the excitation of both symmetric and anti-symmetric modes of instability in jet. We will use PIV to analyze the characteristics of both of these instabilities, and use that data to continue refining the use of Dynamics Informed Data Assimilation.