E0271- Graphics & Visualization
Project Report

Submitted by
Sankar , Masavir Khliq, Phani Madhusudhan

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Visualization of Vortex Shedding in 3D Flow Around a Confined Square Cylinder using Tracking Graphs

Faculty Advisor: Prof. Vijay Natarajan
CSA, Indian Institute of Science (IISc), Bangalore

1. Problem Statement

Exploring and analyzing the spatio-temporal evolution of features in largescale time-varying datasets is a common problem in many areas of science and engineering. One such area pertaining to this problem is the Fluid Mechanics and Combustion Dynamics where the flow of Newtonian fluids particularly gases have the propensity to demonstrate chaotic unsteady turbulent behavior. Advanced Simulations can predict the behavior of the fluids in situations that are prone to be difficult when conducted as experiments and measuring different data using sensors. A simple fluid flow animation requires solving complex PDE of Navier-Stokes Equation. Advanced solvers with parallel computing systems are even able to solve the DNS of Navier-Stokes equation subjected to certain boundary conditions and assumptions. But the main outcome of doing this lies not only in just solving these equations but understanding the resulting data of Velocity and Pressure. The problem with that is simulations generate mountains of data which makes it difficult and even impossible for the human mind to process them. Hence better visualization strategies are needed to understand the data and the spatio-temporal feature attributes. Hence we aim to develop a strategy that helps in a streamlined understanding of large dataset and able to track certain physical phenomenon of interest like the Vortex Shedding behavior in the Fluid flow around a Bluff body.

1.1. Problem with large Scientific Datasets

- Scientific simulations produce large datasets
- Challenges when using large datasets
- Analyzing features
- Understanding temporal evolution
- Combustion or Fluid flow simulations - TB size data sets, Several hundred timesteps. For Example: Burning of premixed hydrogen - 100 timesteps 400GB in size
- Can we Identify track the important regions in time from the large dataset?

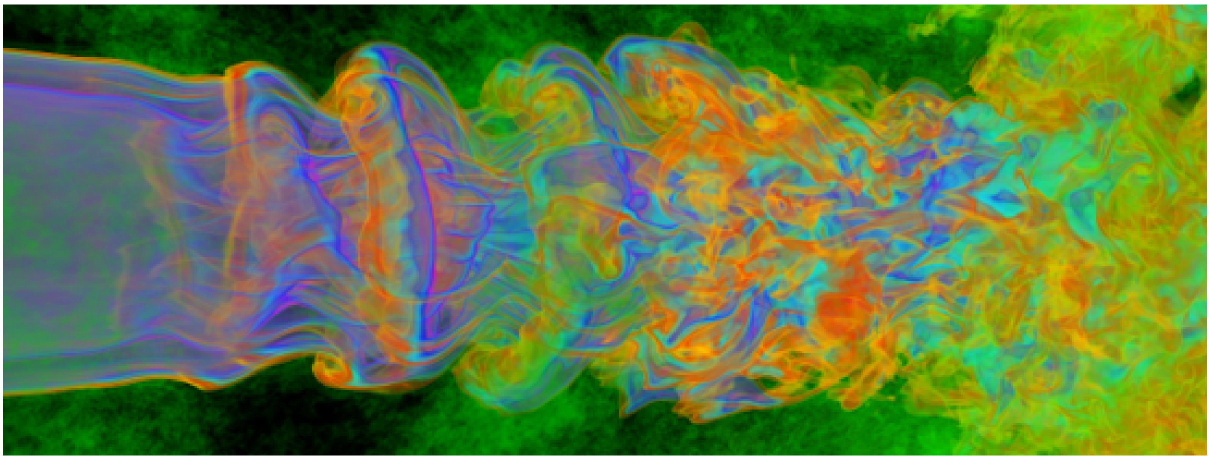

Fig. Large Combustion Simulation

1.2. Difficulties and Challenges in Existing Problem

- Exploring and analyzing the spatio-temporal evolution of features in largescale time-varying datasets is a common problem in many areas of science and engineering
- For practical data sets creating the corresponding optimal graph layouts that minimize the number of intersections can take hours to compute with existing techniques.
- Defining, extracting and analyzing features in the increasingly large and complex datasets produced by state of the art simulations still poses a significant challenge.
- Furthermore, the resulting graphs are often unmanageably large and complex even with an ideal layout.
- Finally, due to the cost of the layout, changing the feature definition, e.g. by changing an iso-value, or analyzing properly adjusted sub-graphs is infeasible.

- Coupling the corresponding analysis across time steps to understand the temporal evolution of such features increases the difficulty exponentially

- First, a temporal analysis multiplies the amount of data that must be considered simultaneously, often exceeding available memory and other resources.

- Second, the resulting data potentially contain information about thousands of features across hundreds of time steps making it challenging to present them in a comprehensible manner.

- Finally, for all but the smallest datasets, even assuming an optimal layout, graphs quickly become too large and convoluted for users to understand.

- Consequently, most existing techniques to visualize and explore time-varying datasets have primarily focused on high dimensional projections, illustration, and change detection

2. Objective

- To Develop Visualizations that demonstrates the Spatial-Time Evolving Features in 3D Flow around a Confined Cylinder dataset using the concept of Tracking Graph

- To able to track the transition from Laminar to Turbulent flow regime in the different timesteps

- To figure out the important subset region of interest out of the entire set of 4D volume of data 192x64x48x102

- To understand the behaviour of Vortex Shedding Phenomenon (Von Kármán Vortex Street) by tracking each and every vortex separately

- To understand how different Visualization techniques perform under the increasing unsteadiness of the fluid flow

- To demonstrate the Streamlines, Streaklines and Pathlines in a 3D Visualization

3. Introduction to background

3.1. Overview about the Dataset

- This is a 3D time-dependent flow field resampled onto a uniform structured grid of 192 x 64 x 48 for 102 timesteps.

- It is an incompressible solution with a Reynolds number of 200 and the square cylinder has been positioned symmetrically between two parallel walls.

- The flow has periodic boundary conditions in spanwise Z-direction. It exhibits periodic vortex shedding leading to the well known von Kármán vortex street.

- In contrast to most flow data sets, this simulation is initiated from an impulsive start-up and the periodic vortex shedding develops with time.

- In order to show the alternating behavior of the vortex shedding, two smoke surfaces were seeded such that the red one passes above the cylinder and the blue one passes below.

- Each time step is written as a single file in AmiraMesh format.

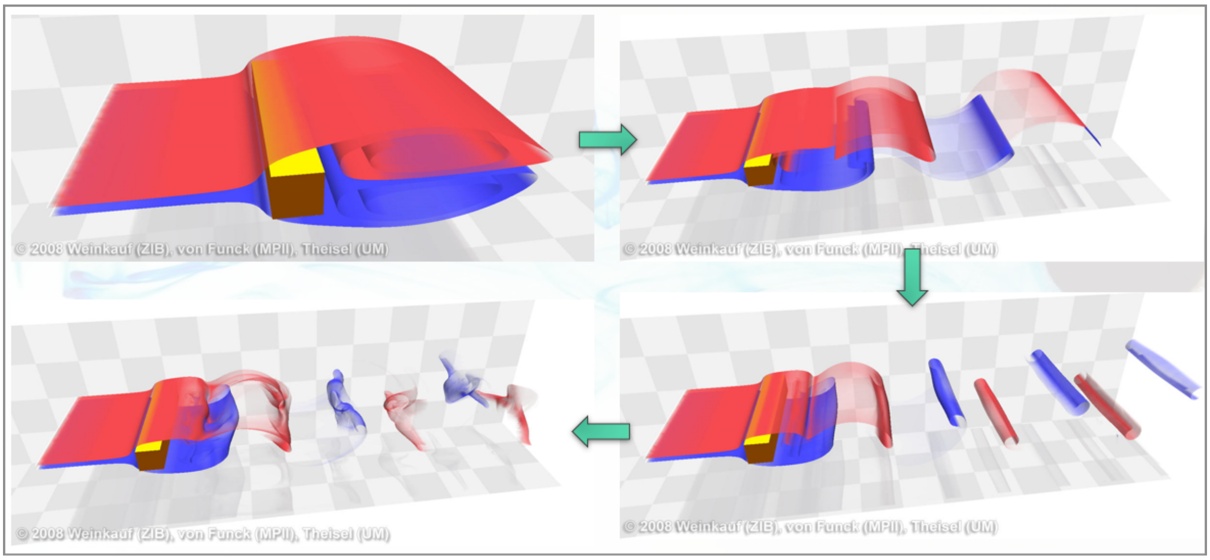

Fig. Visualization Result of the Dataset

3.2. Vortex and Vorticity

- In fluid dynamics, a vortex (plural vortices/vortexes) is a region in a fluid in which the flow revolves around an axis line, which may be straight or curved.

- A key concept in the dynamics of vortices is the vorticity, a vector that describes the local rotary motion at a point in the fluid, as would be perceived by an observer that moves along with it.

- Vortices form in stirred fluids, and may be observed in smoke rings, whirlpools in the wake of a boat, and the winds surrounding a tropical cyclone, tornado or dust devil.

- Vortices are a major component of turbulent flow.

- The distribution of velocity, vorticity (the curl of the flow velocity), concept of circulation are used to characterize vortices.

- In most vortices, the fluid flow velocity is greatest next to its axis and decreases in inverse proportion to the distance from the axis.

- Once formed, vortices can move, stretch, twist, and interact in complex ways.

- A moving vortex carries some angular and linear momentum, energy, and mass, with it.

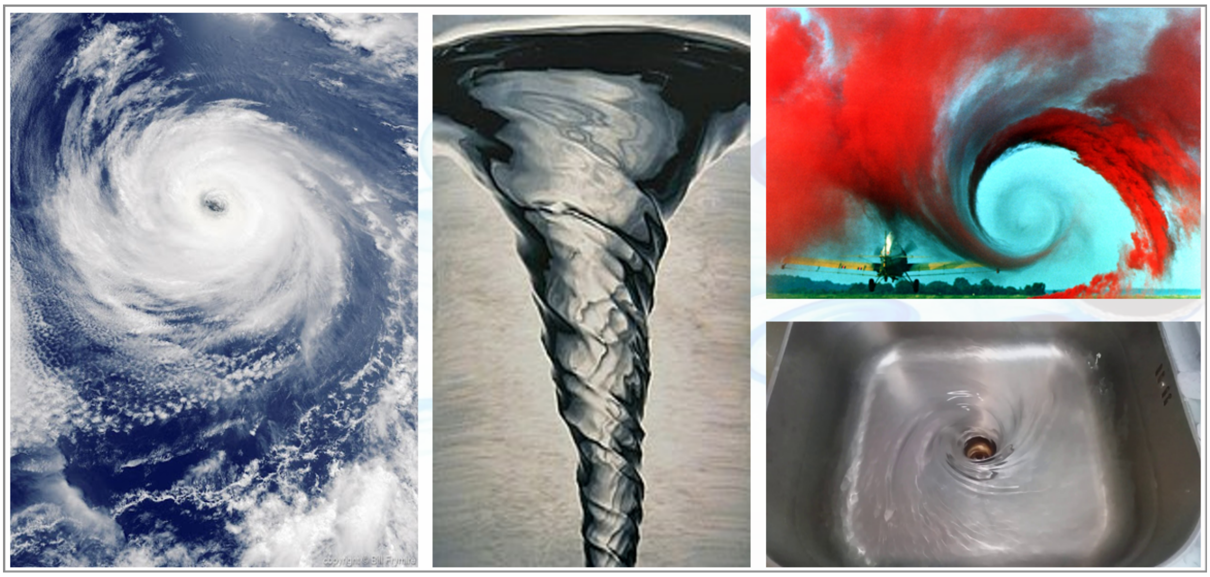

Fig. Vortex Examples

3.3. Vortex Shedding

- In fluid dynamics, vortex shedding is an oscillating flow that takes place when a fluid such as air or water flows past a bluff (as opposed to streamlined) body (body that, as a result of its shape, has separated flow over a substantial part of its surface) at certain velocities, depending on the size and shape of the body.

- In this flow, vortices are created at the back of the body and detach periodically from either side of the body forming a Von Kármán vortex street.

- The fluid flow past the object creates alternating low-pressure vortices on the downstream side of the object.

- Vortex Shedding is Characterized by Strouchal Number given by $S_t = \frac{f.D}{V}$

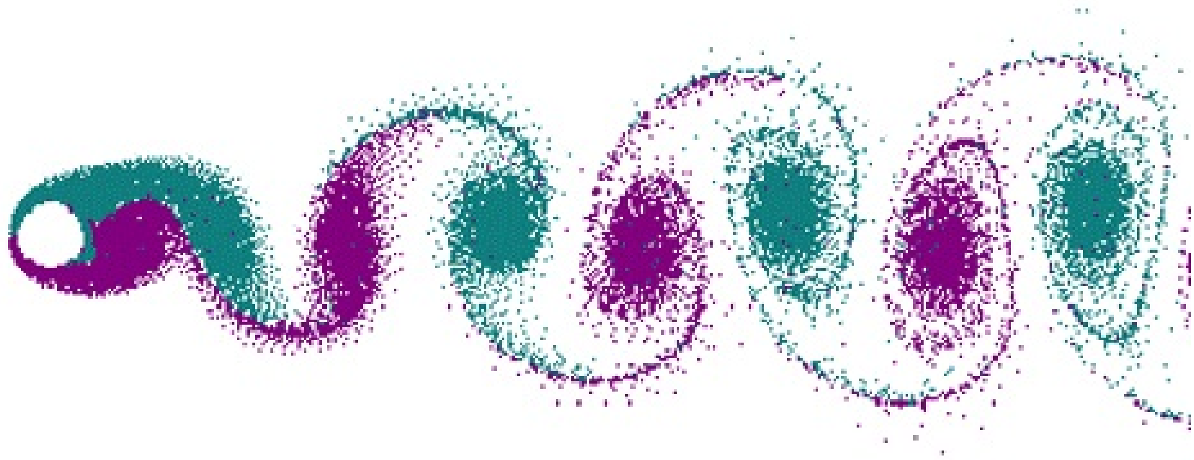

Fig. Vortex Shedding

3.4. Von Karman Vortex Street

- In fluid dynamics, a Kármán vortex street (or a von Kármán vortex street) is a repeating pattern of swirling vortices, caused by a process known as vortex shedding, which is responsible for the unsteady separation of flow of a fluid around blunt bodies.

- A vortex street will form only at a certain range of flow velocities, specified by a range of Reynolds numbers (Re), typically above a limiting Re value of about 90.

- The (global) Reynolds number for a flow is a measure of the ratio of inertial to viscous forces in the flow of a fluid around a body or in a channel which defines the flow to be either Laminar or Turbulent flow

- it may be defined as a non dimensional parameter of the global speed of the whole fluid : $R_e = \frac{\rho V D}{\nu}$

3.5. Difference between Eddy and Vortex

- **Vortex**

- Vortex is nothing but its a kind of motion of fluid which involves vorticity. Means the fluid elements rotate about its center.

- There is an angular velocity vector that is associated with that fluid element.

- Each fluid element continuously keep rotating and deforming too because of shear stress.

Fig. Von Karman Vortex Street

- **Eddy**

- In fluid dynamics, an eddy is the swirling of a fluid and the reverse current created when the fluid is in a turbulent flow regime.

- The moving fluid creates a space devoid of downstream-flowing fluid on the downstream side of the object.

- Consider a turbulent flow in which the separation is taking place.

- Due to separation, the flow downstream produces what we call eddies. it means the fluid elements are already having the vorticity but in addition these fluid elements are circulating locally downstream of the separation point.

- So these eddies are nothing but circulation or spinning of fluid elements in curvilinear fashion.

3.6. Laminar vs Turbulent Flow

- Laminar Flow: Laminar flow or streamline flow in pipes (or tubes) occurs when a fluid flows in parallel layers, with no disruption between the layers. In laminar flow, the motion of the particles of the fluid is very orderly with all particles.

- Turbulent Flow: Turbulence is flow characterized by recirculation, eddies, and apparent randomness or chaos. The presence of eddies or recirculation n alone does not necessarily indicate turbulent flow. flow regime characterized by chaotic property changes. This includes rapid variation of pressure and flow velocity in space and time.

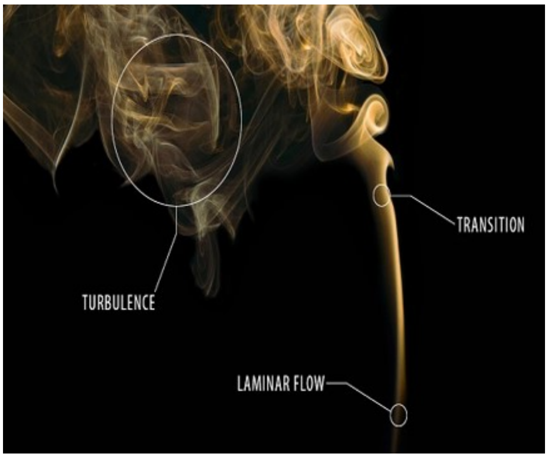

Fig. Laminar vs Turbulent Flow

Fig. Uniform vs Nonuniform Flow

3.7. Steady vs Unsteady Flow

- Steady Flow: A flow whose properties are not a function of time is called steady flow. Steady-state flow refers to the condition where the fluid properties at a point in the system do not change over time.

- Unsteady Flow: Time dependent flow is known as unsteady (also called Transient). Turbulent flows are unsteady by definition. A turbulent flow can, however sometimes, be statistically stationary.

3.8. Tracking Graph

- One natural representation of large data is tracking graphs, i.e., constrained graph layouts that use one spatial dimension to indicate time and show the "tracks" of each feature as it evolves, merges or disappears.

- Conceptually, the most natural representation of such data is a tracking graph showing the evolution of all features across time as a collection of feature tracks that may merge or split.

- Given some feature definition a graph is constructed by first extracting all features from all time steps and then correlating those features across time, for example, by considering their spatial overlap

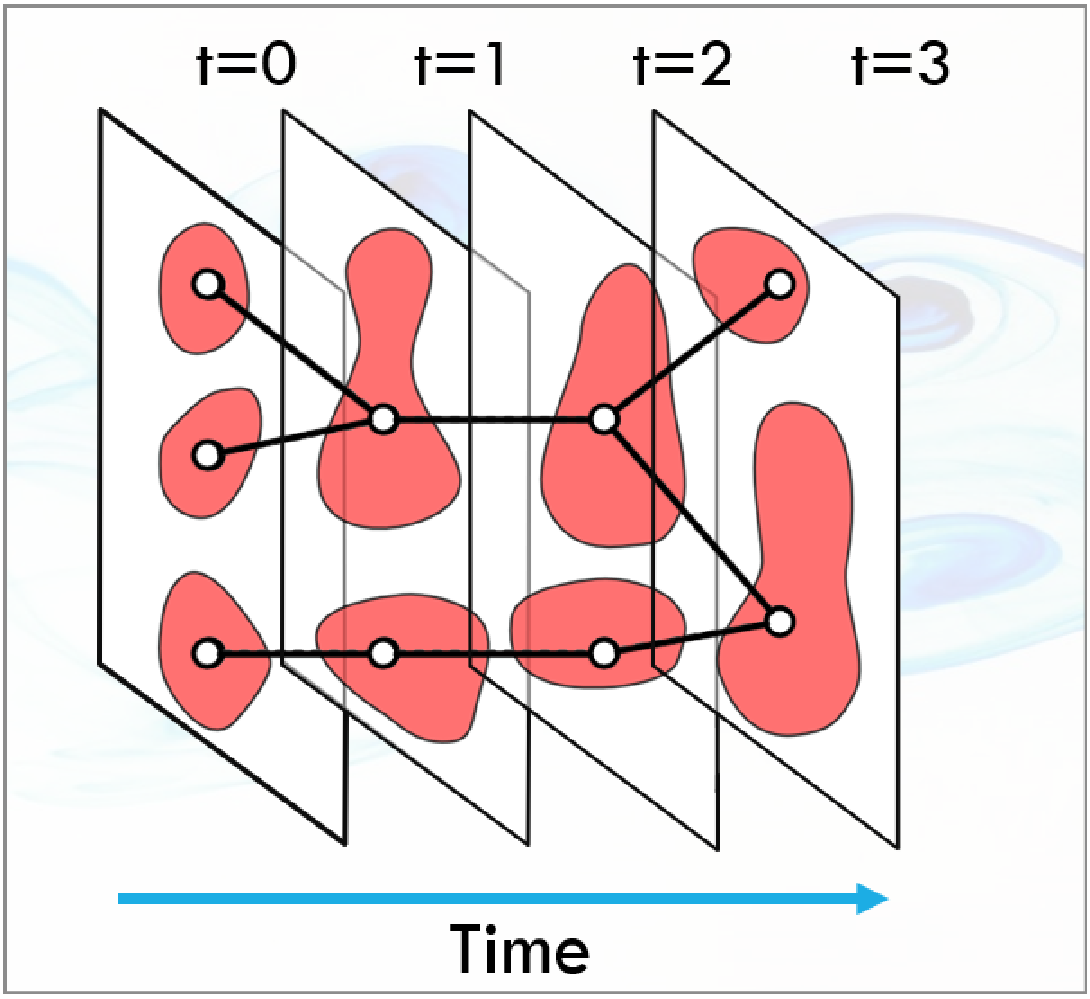

Fig. Tracking Graph

3.9. Contour Plot vs Merge Tree

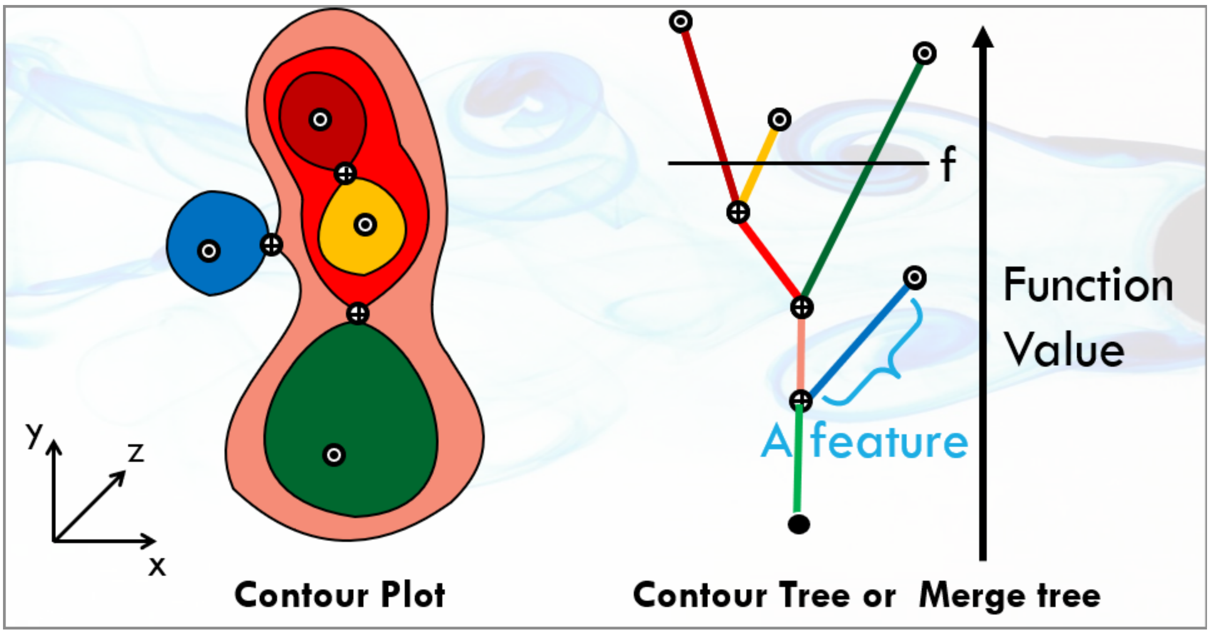

Fig. Contour Plot vs Contour Tree

3.10. Tracking Graph with Merge Trees

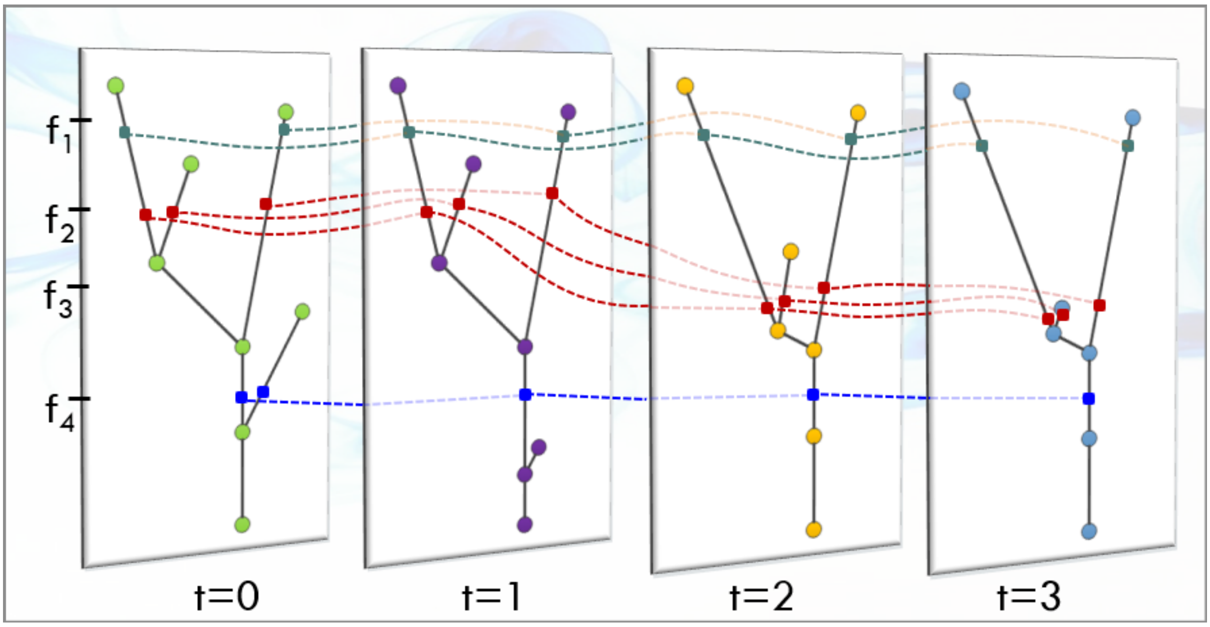

Fig. Tracking Graph with Merge Trees

4. References to related work

- A new framework that couples hierarchical feature definitions with progressive graph layout algorithms to provide an interactive exploration of dynamically constructed tracking graphs.
- The system enables users to change feature definitions on-the-fly and filter features using arbitrary attributes while providing an interactive view of the resulting tracking graphs
- Furthermore, the graph display is integrated into a linked view system that provides a traditional 3D view of the current set of features and allows a cross-linked selection to enable a fully flexible spatio-temporal exploration of data
- Abstract model showing the time evolution of features with interactive modification of their characterization

A system which allows

- Exploration of features
- Progressive layouts of Graphs
- Modification of feature attributes and correlation criteria

- Interactivity for TB size data
- Mapping dynamics of the dataset with the visualization
- Identification of region of interest

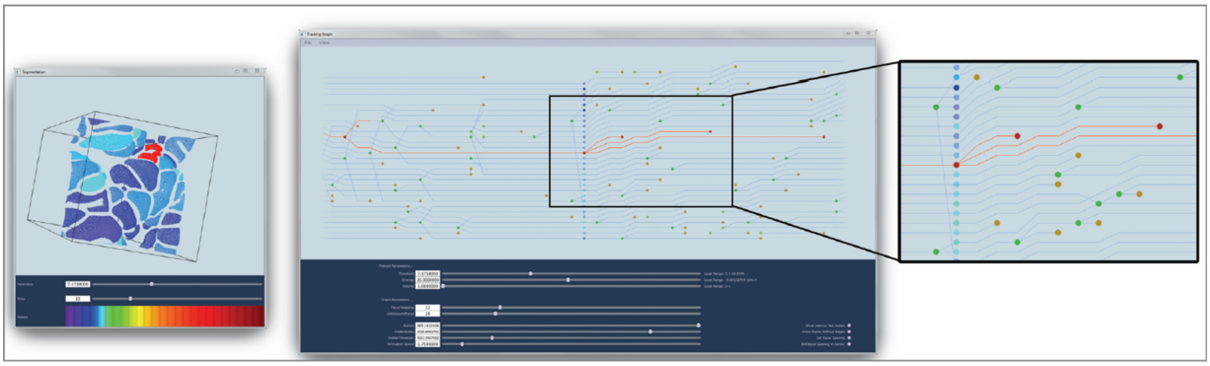

Fig. Interactive Exploration of Large scale Time-varying data using Dynamic Tracking Graph

5. Tasks Accomplished

- **Exploring Dataset – 3D Flow around a confined Square Cylinder:**
  This was done to read the Amira mesh format and convert to data files and then covert to VTK file format. Here we used C++ and Amira mesh to accomplish this task.

- **Contour Plot** for all the 102 timesteps with span of 192 x 64 for a mid plane Z slice = 24:
  This was done to identify the various feature regions in the dataset including vortex and visualize the Von Karman Street Phenomenon. Here we used python and matplotlib to accomplish this task.

- **Image Processing of all the Contour Plots:**
  This was done to identify and track the movement of each and every vortex separately. Here we used python and OpenCV to accomplish this task.

- **Tracking Graph in 3D:**
  This was done to plot the birth and death of vortex and visualize the Vortex Shedding. To do this task we used Python and Matplotlib.

- **Vector Field Plot:**
  We did this to deduce the region of interest to focus more on to identify the behaviour of one vortex. This task was also done by python and Matplotlib.

- **Tracking Graph in 2D:**
  To identify the critical timestep and region of interest and the pattern of repetitive behaviour of the Vortex tracking graph is 2d was plotted. Python and Matplotlib was used to do this task.

- **VTK File Dataset:**
  This was done to convert the data files created earlier into VTK file format – Structured Points + Vector Field. C++ was used to accomplish this task.

- **3D Visualization of Vector Field and Streamlines:**
  By this task we Visualized the Behaviour of Laminar and Turbulent flow behaviour at a particular timestep. Tools used here were VTK, Paraview.

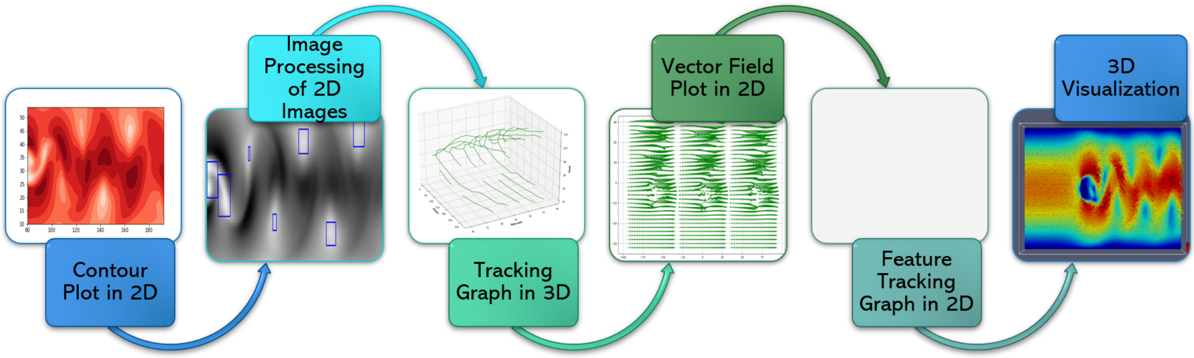

Fig. Methodology or Approach Followed

6. Results and Evaluation

6.1. Contour Plot

- A 2D Slice along the Z axis was taken at the midplane section as the flow has periodic boundary conditions in the spanwise direction

- A 10 level iso contour plot was plotted and animated to see the generation of vortex and the vortex shedding behaviour leading to a Von Karman Vortex Street.

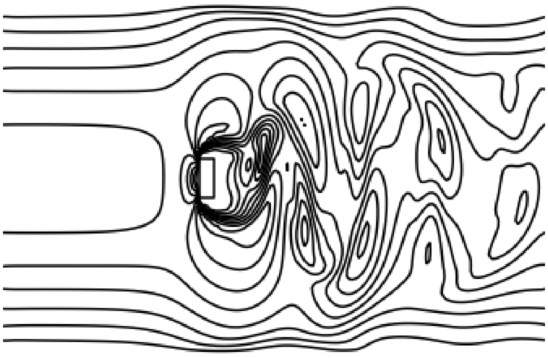

Fig. Binary Contour Level 10

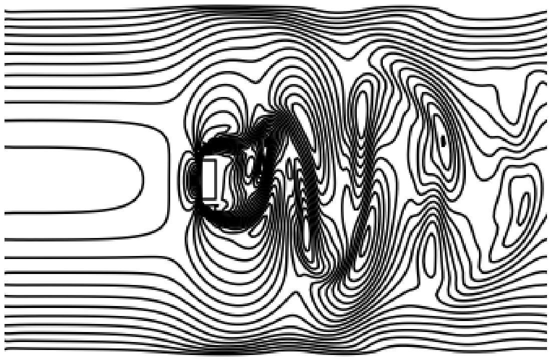

Fig. Binary Contour Level 20

- Vortex have higher velocity vector close to the axis of rotation which is evident from the dark patches at the centre of each vortex being generated.

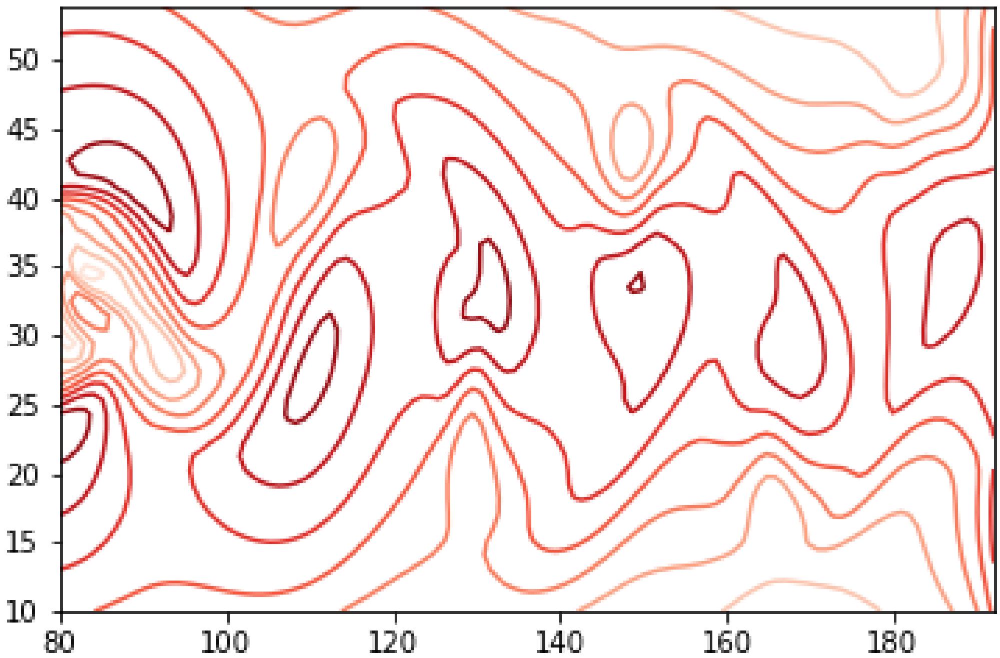

Fig. Coloured Contour Level 10

- As the fluid hits the square cylinder a sudden drop in velocity can be seen by the white region in front of the block.

- The top and bottom region of the square cylinder experience maximum velocity and the separation of flow can be visualized by the large formation of dark region.

- As the vortex loses its energy, the velocity vector field can be observed to be dissipating seen by the lightening of the dark regions towards white.

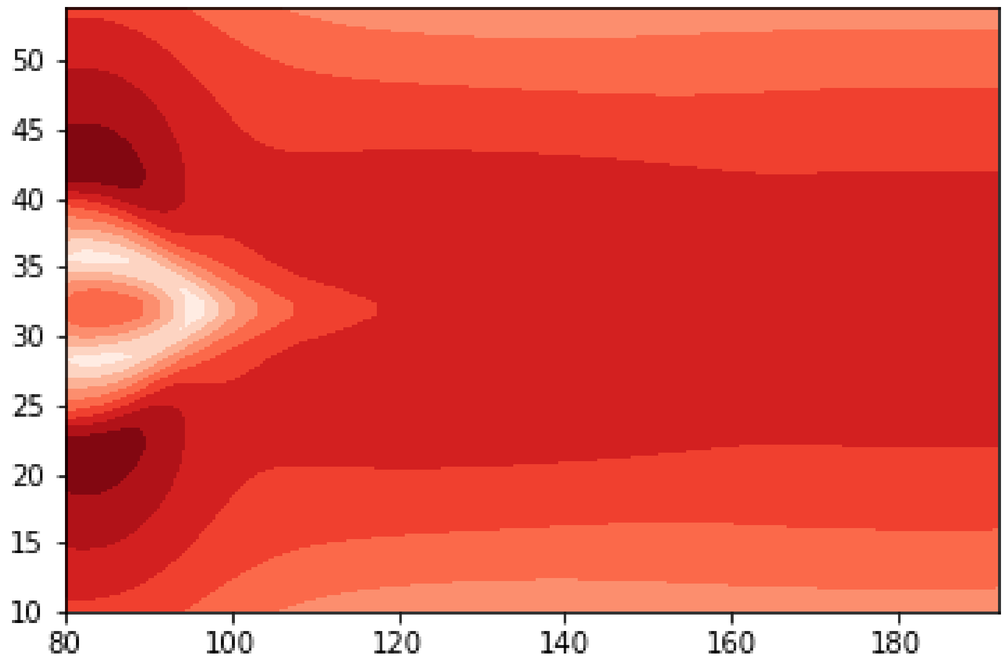

Fig. Timestep 10

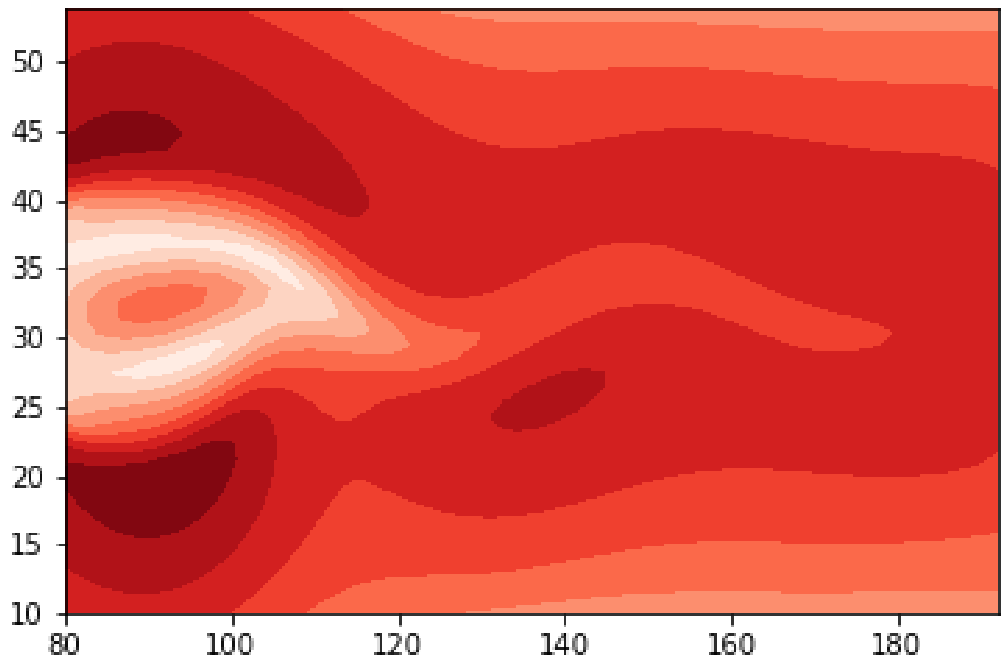

Fig. Timestep 40

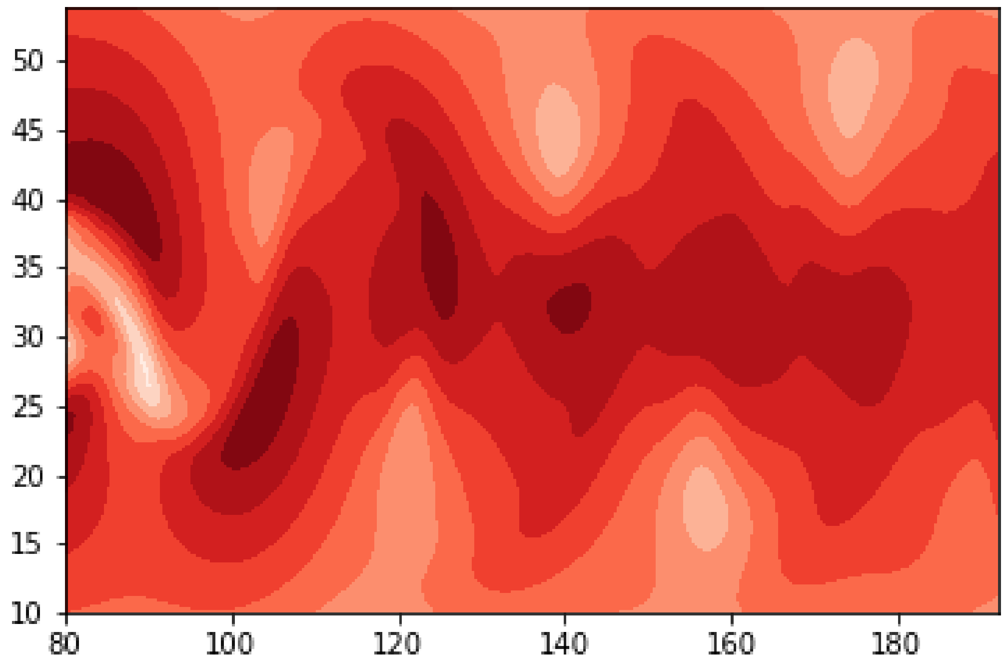

Fig. Timestep 80

6.2. Image Processing of Contour Plots

- The alternating behaviour of vortex formation and the respective circular eddy motion can be clearly seen here
- The Binary surface plot was taken to track the eddy.
- Image Processing was performed on these images using OpenCV.
- A Threshold value of 215 was given to separate the vortex by identifying the eye of the vortex
- As the vortex starts dissipating its energy the rectangular region of recognition is enlarged
- A parabolic motion of the eddies can be seen here.

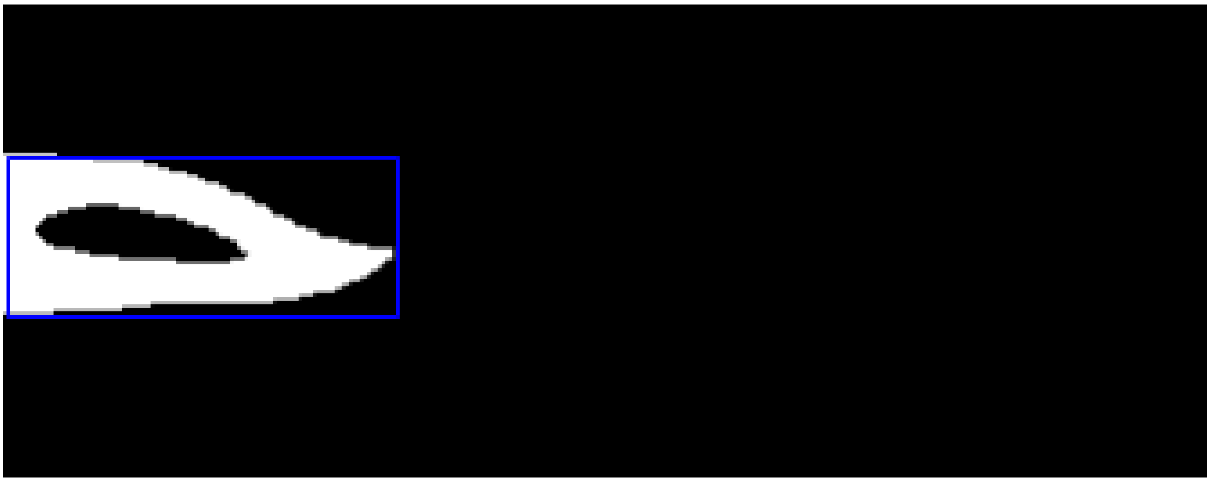

Fig. Time step 10

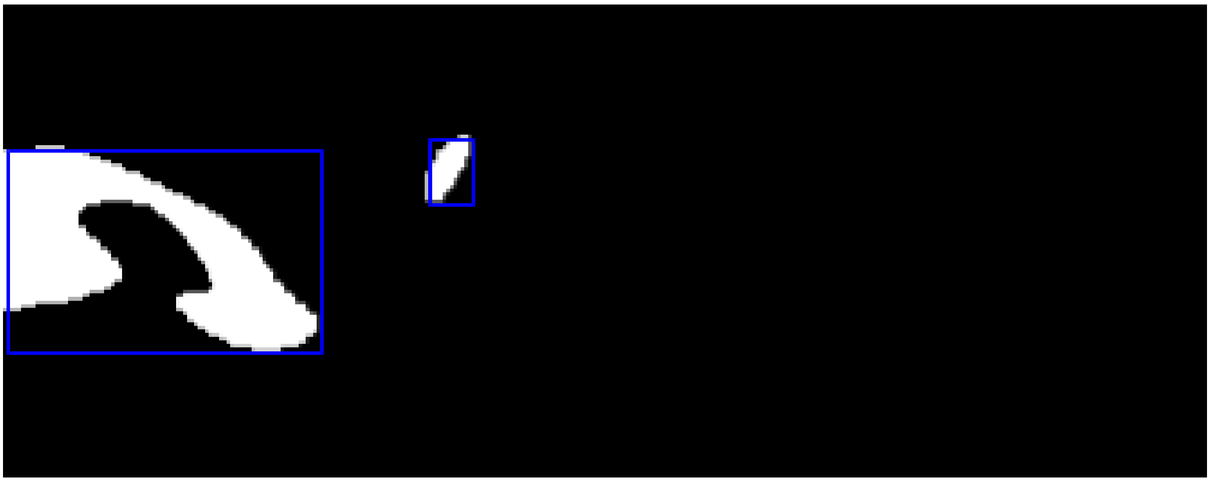

Fig. Time step 25

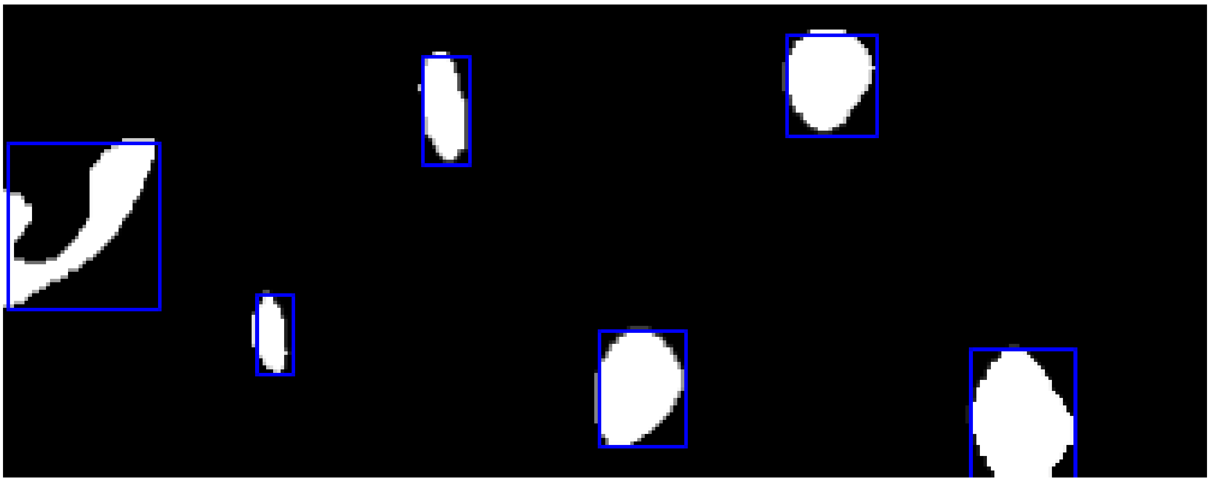

Fig. Time step 57

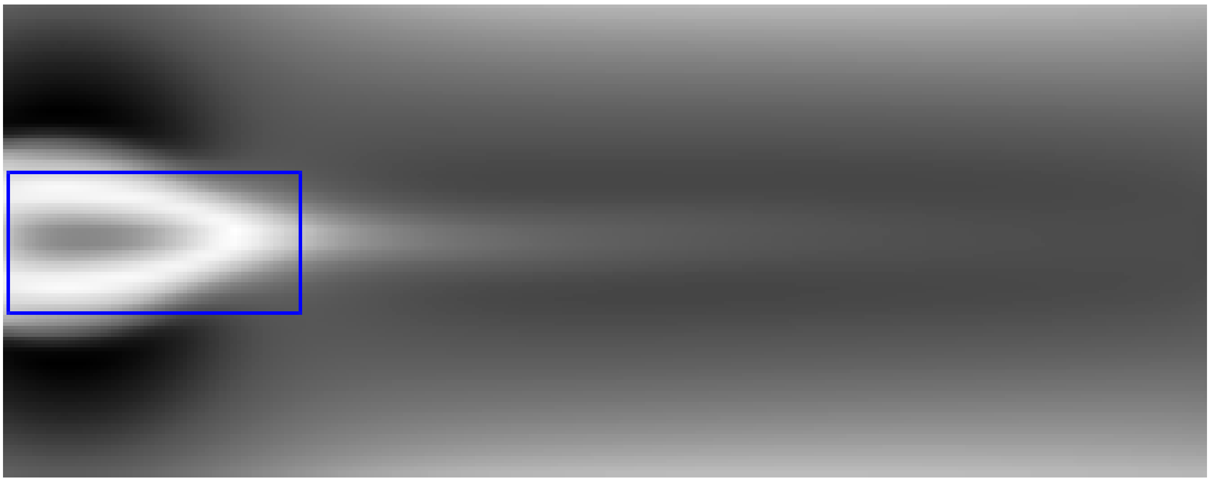

Fig. Time step 10

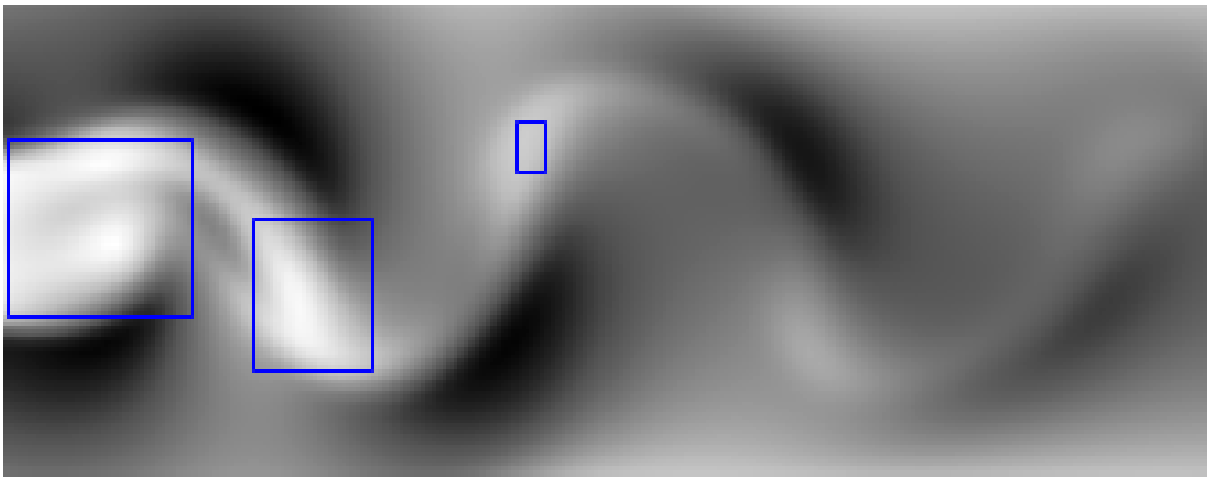

Fig. Time step 25

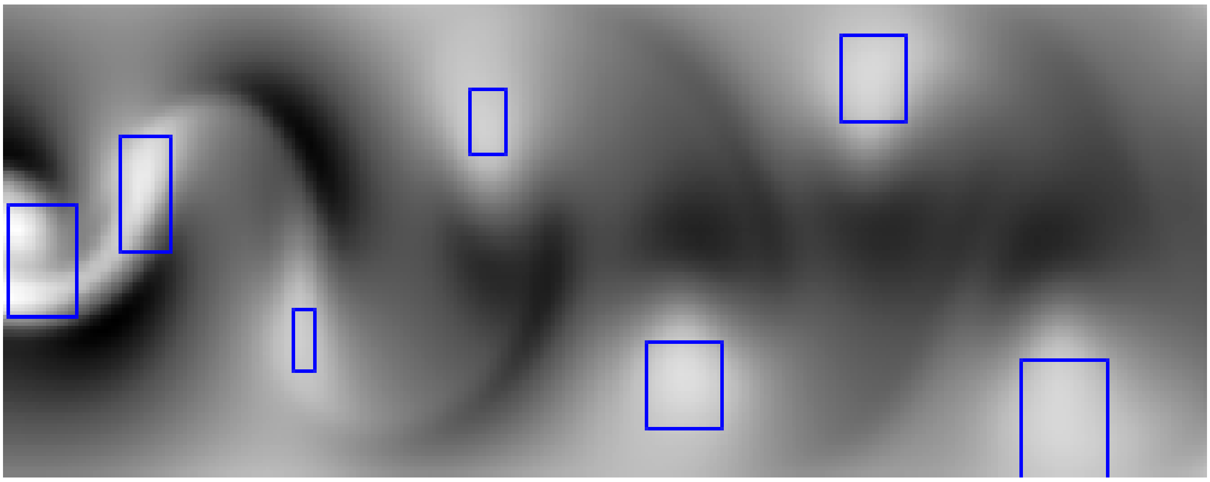

Fig. Time step 57

6.3. Tracking Graph in 3D

- In order to track the motion of vortices which were identified in the previous slides over the entire period of timestep

- The centroid of the rectangular region for subsequent timesteps are plotted over a 3D axis, where X and Y represents the XY Plane as in the contour plot and the Z axis represents time.

- It is very clear that several vortices starts forming from the central location i.e. around the square cylinder block and traverses outwards towards the wall in a parabolic fashion.

- There are certain intermittent gaps in the formation of vortices which signifies a loss in energy of those small eddies.

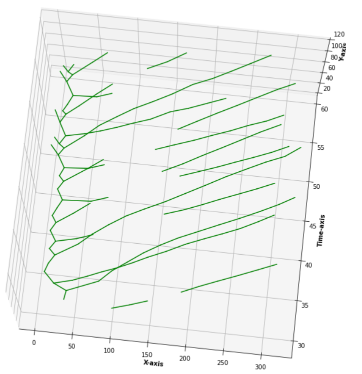

Fig. X vs time

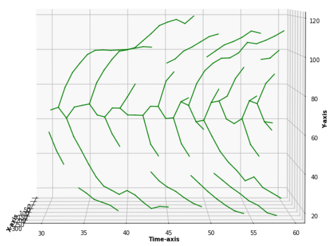

Fig. Y vs time

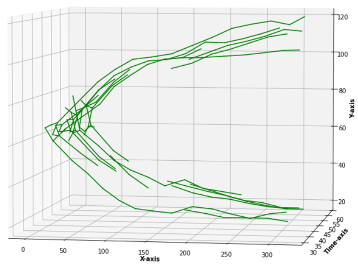

Fig. Y vs time

6.4. Vector Field Plot

- A Vector field plot was drawn for a another timestep where the vortices have grown fully.

- Equal spacing of grids on both positive and negative axes were taken.

- As the loci of each arrow mark can be joined together, it will show the Streaklines of the flow.

- Alternating repetitive flow pattern can be seen from this plot.

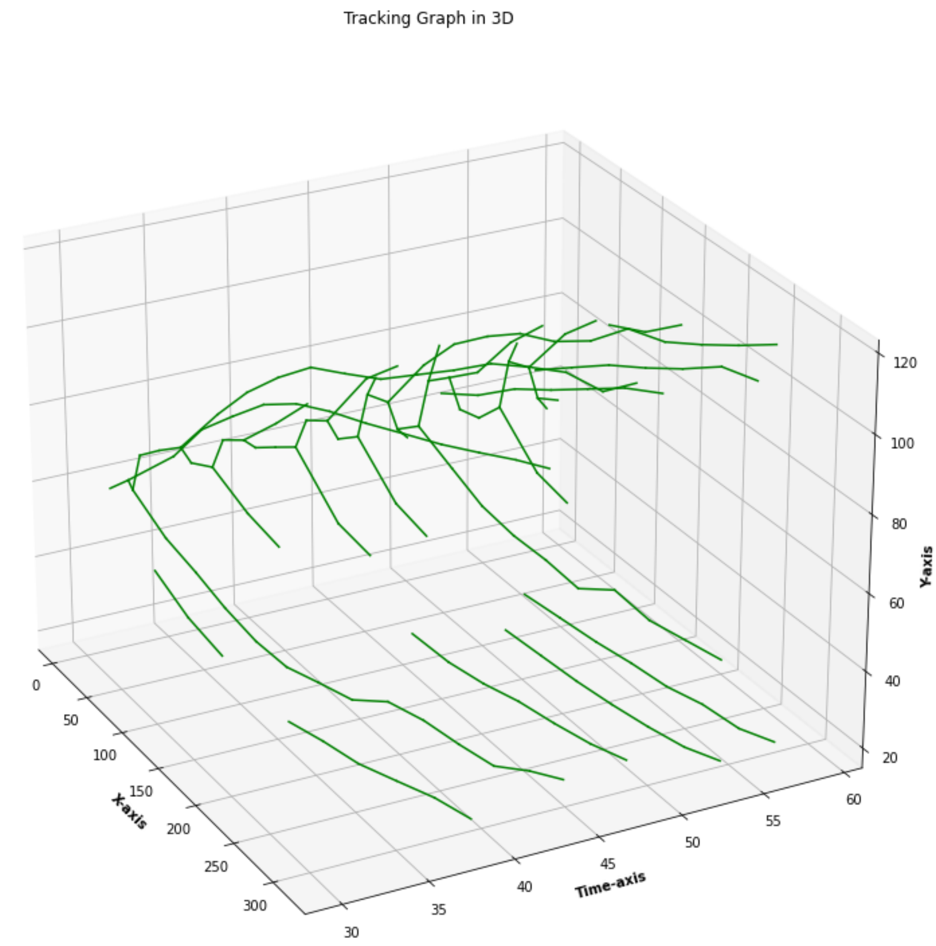

Fig. Tracking Graph in 3D

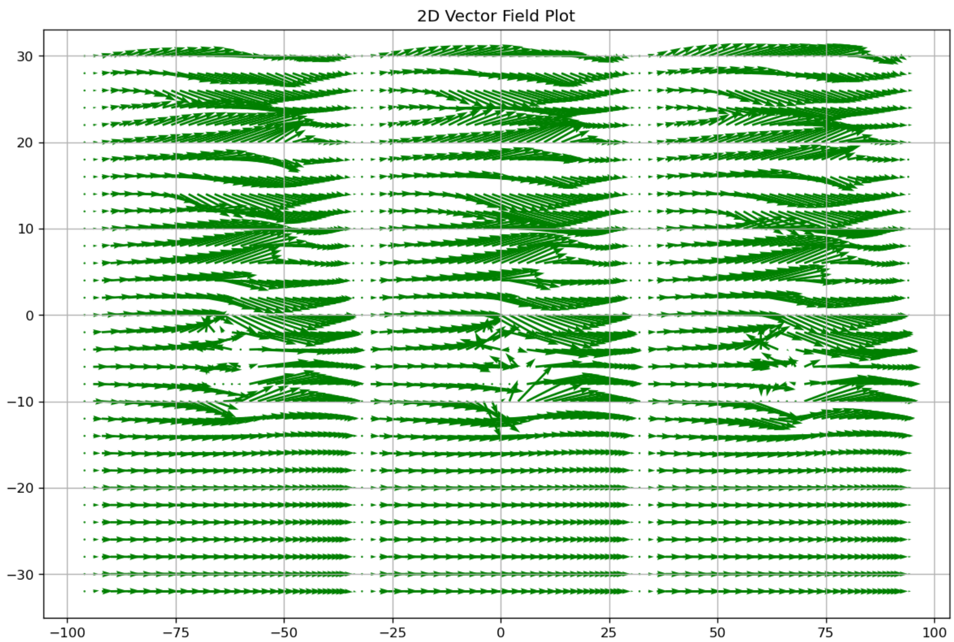

Fig. Vector Field Plot

6.5. Feature Tracking Graph in 2D

- With all the previous visualizations, a region of interest can be identified based on the expertise of the Scientist.

- Hence a region of $X_{min} - X_{max}$ and $Y_{min} - Y_{max}$ and for a certain timestep starting from $time_{min}$˘$time_{max}$ is chosen

- With these data for region selection, the vector field values are queried only for these regions from the pre-loaded entire dataset and are plotted as Tracking graphs shown here.

- The X-axis represents the timesteps and Y-axis represents the magnitude of the vector field data.

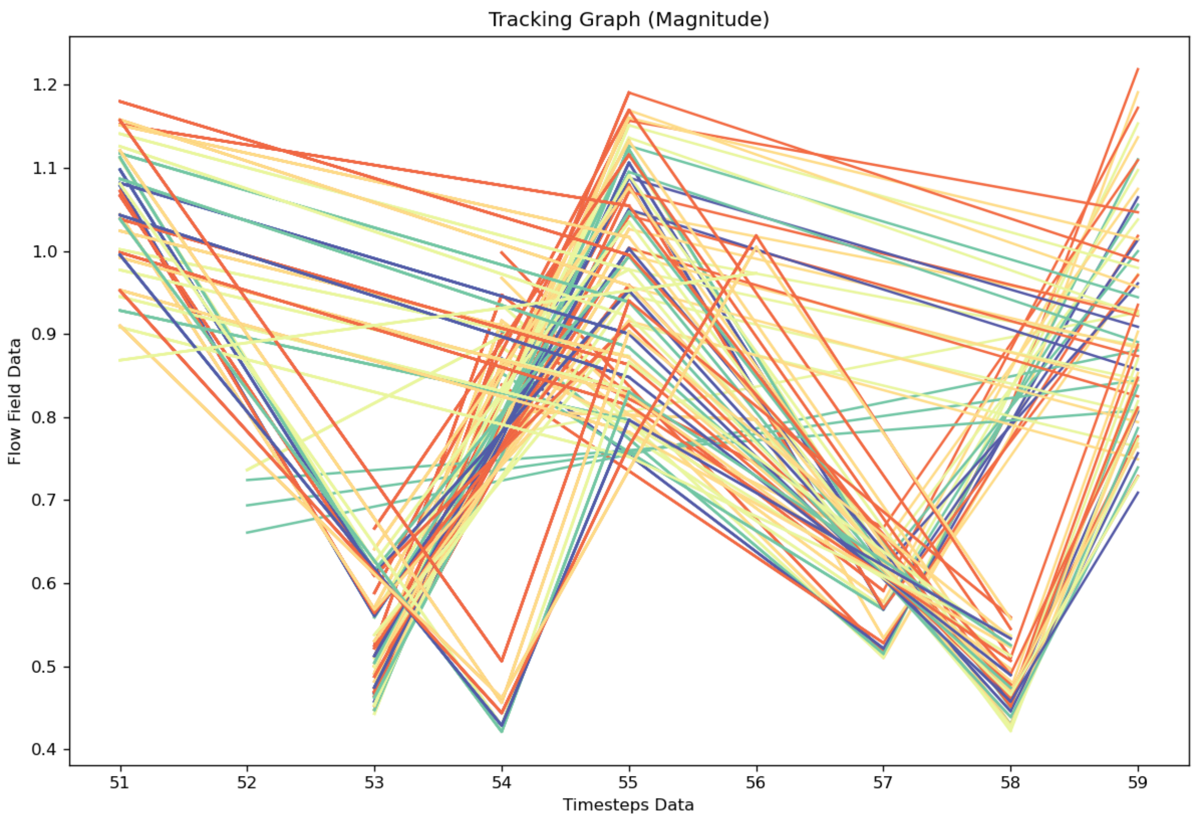

Fig. Feature Tracking Graph in 2D - 0.15

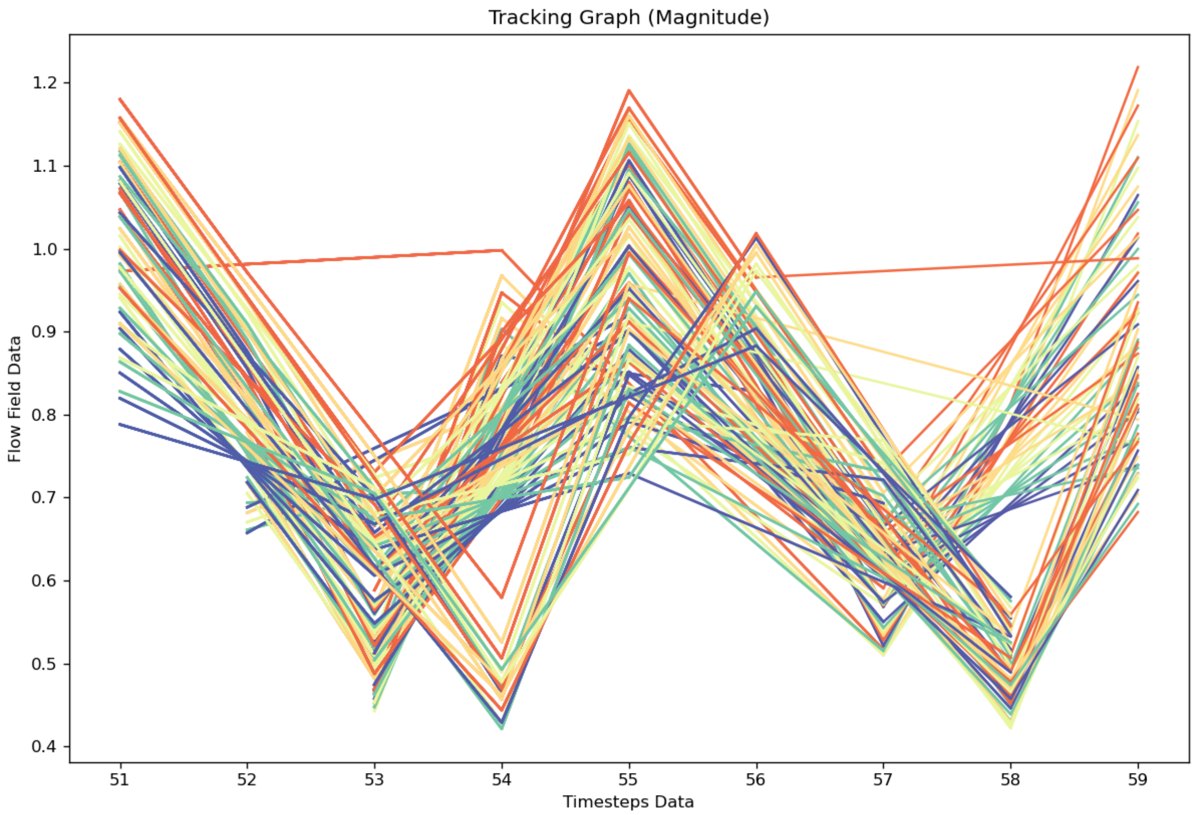

Fig. Feature Tracking Graph in 2D - 0.1

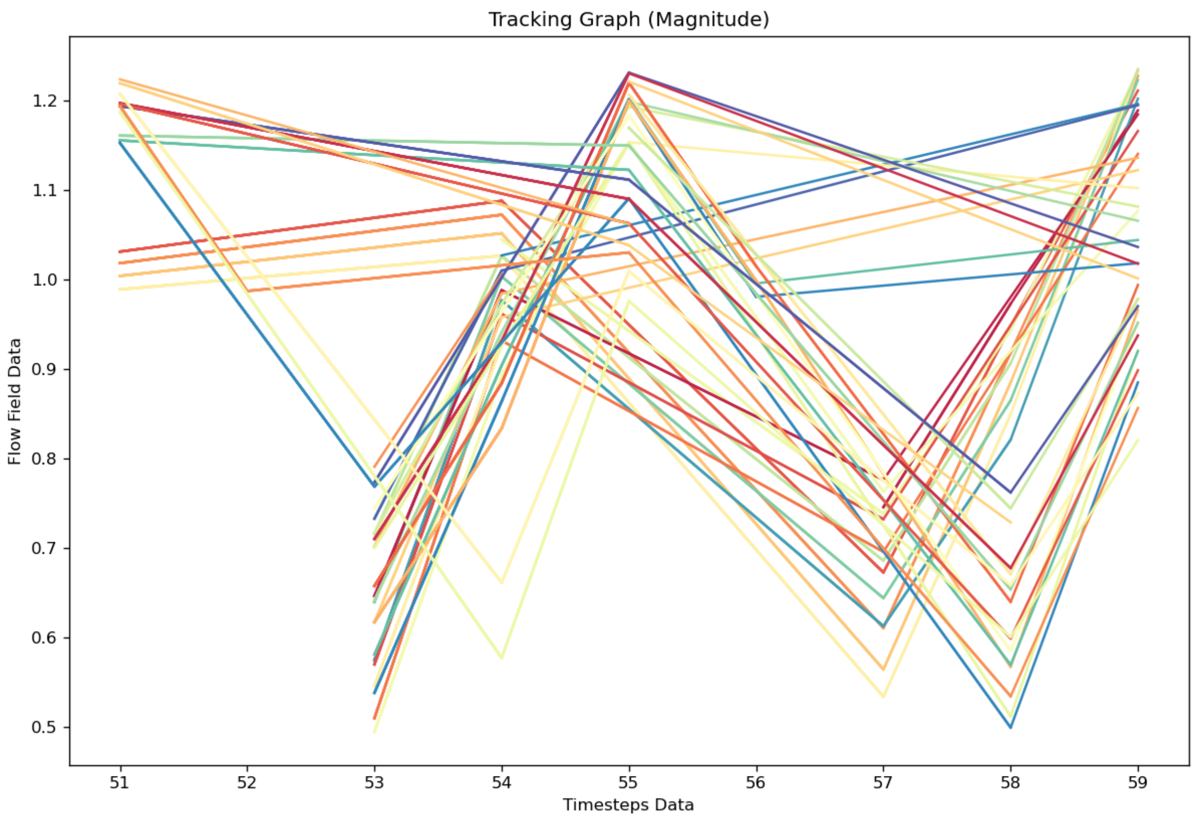

Fig. Feature Tracking Graph in 2D - 0.2

6.6. 3D Visualization

- The data file got as a result of converting from amira mesh file is now converted to VTK file format in order to be able to read it using Paraview software

- Structured Points datatype is used with vectors u, v, w is stored over the entire grid set for each time step separately.

- Once the VTK file is loaded onto the Paraview software, first a slice filter is applied and the iso surface stream for the magnitude of the vector field is visualized

- The slices is made along XY plane perpendicular to Z axis. The slice plane is moved along the entire Z axis and no significant change in the w vector can be found thereby justifying the way to visualize in 2D instead of 3D

- Then Streamlines are plotted onto the same slice.

- Streamlines are a family of curves that are instantaneously tangent to the velocity vector of the flow. These show the direction in which a massless fluid element will travel at any point in time

- The Stream lines clearly show the wavy pattern of movement of the vortex downstream

- It is clear that there is whirlpool formed adjacent to the square cylinder in the downstream region clearly indicating that there is a low pressure region formed.

- Then path lines are plotted as arrow marks.

- Path lines are the trajectories that individual fluid particles follow. These can be thought of as "recording" the path of a fluid element in the flow over a certain period. The direction the path takes will be determined by the streamlines of the fluid at each moment in time.

- The colour map shows the region of high magnitude of the vector field.

- The straight line path along the walls clearly indicate the steady streamlined laminar flow

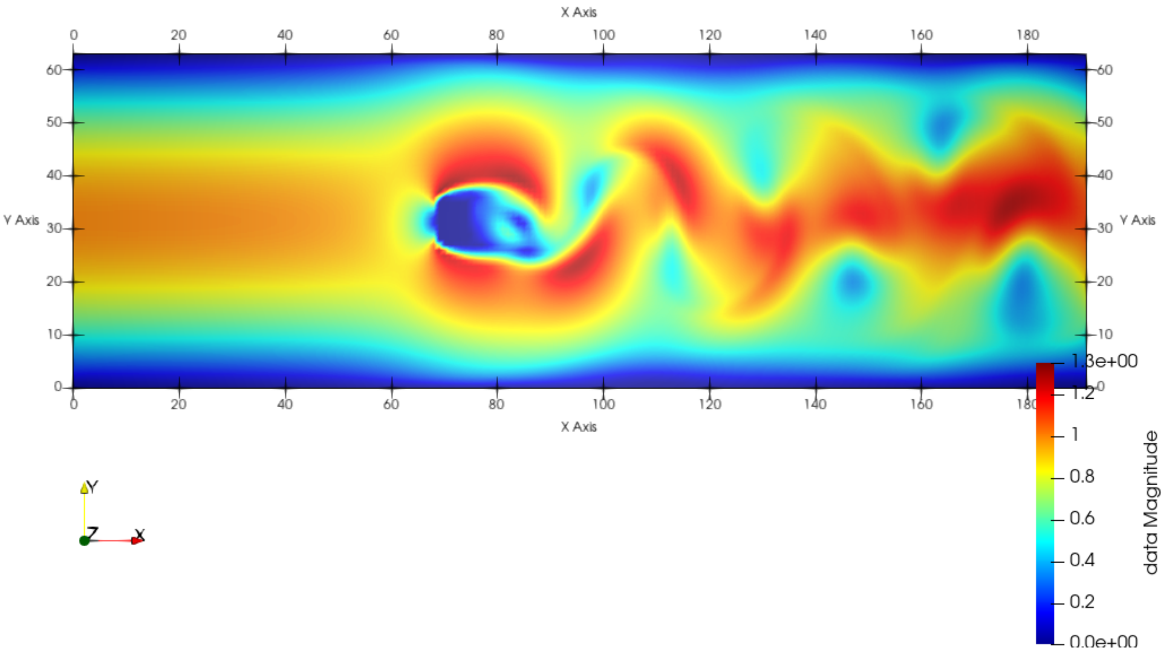

Fig. Slice Contour

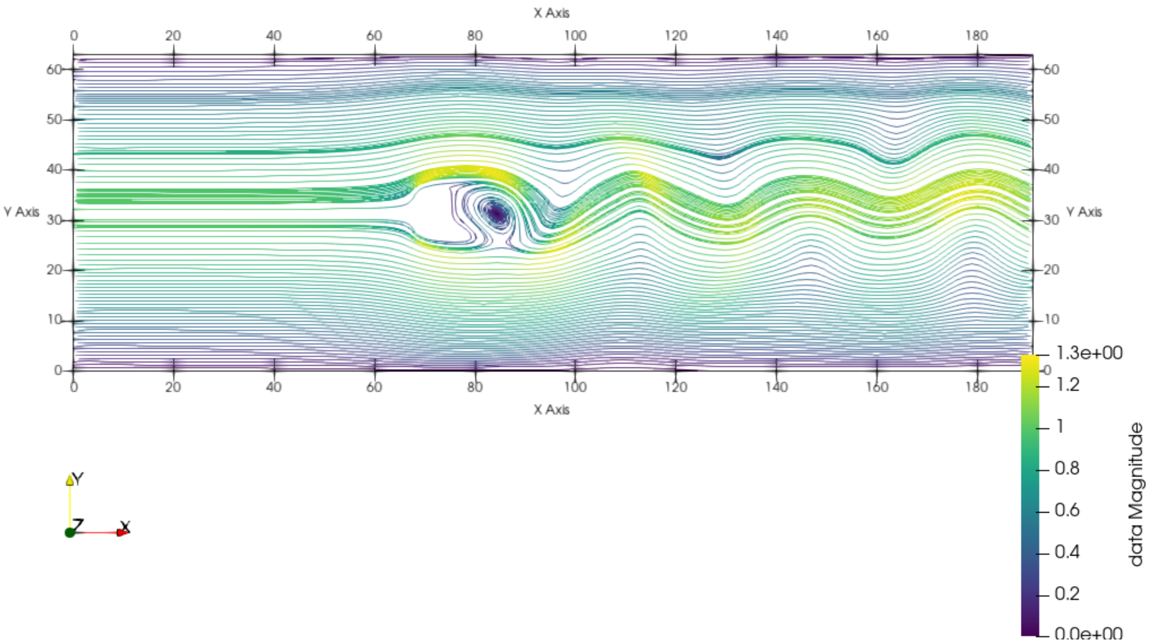

Fig. Streamlines

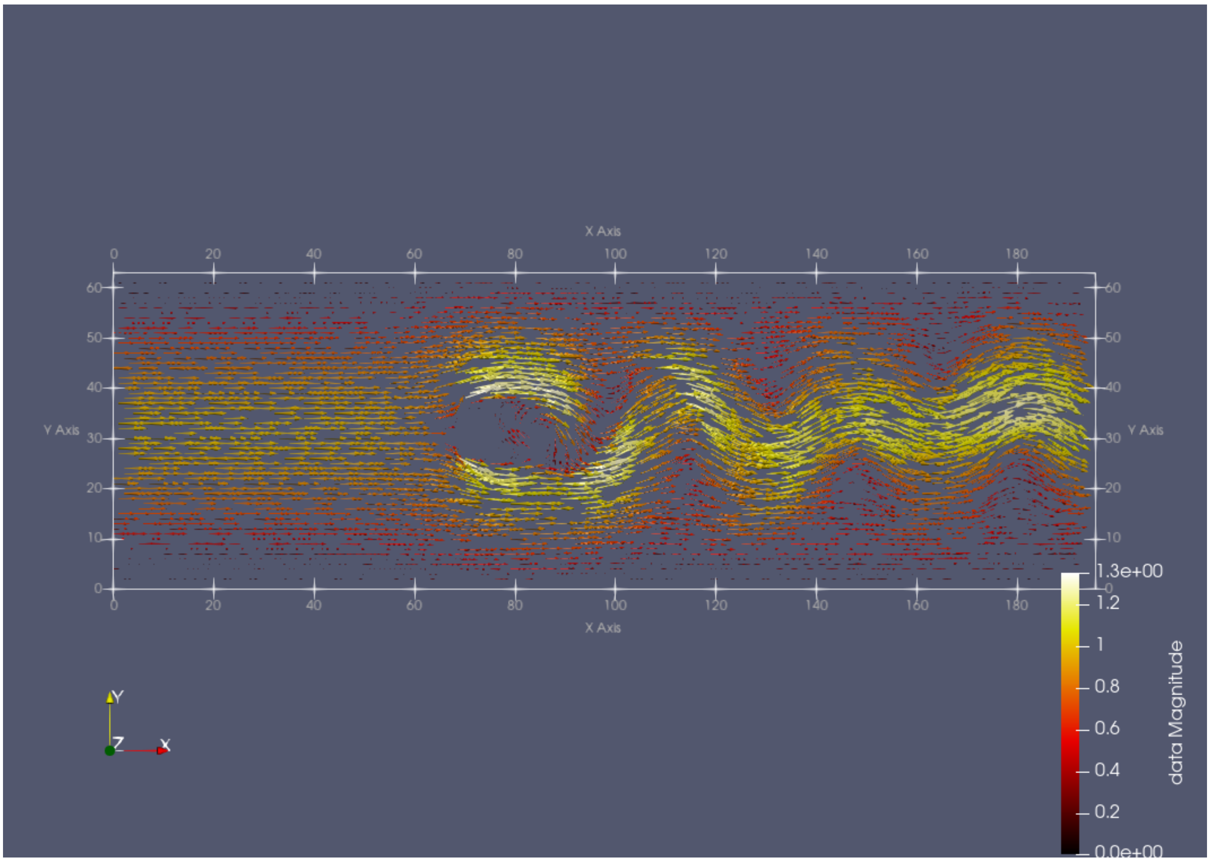

Fig. Pathlines

7. Discussion on Difficulties Challenges faced during the Work

- Drawing contour tree or merge tree.
- Combining all the dataset for different timesteps into a single dataset with time as the 4th dimension.
- Using Inviwo to create a interactive dashboard with different visualizations.
- Implementing the concept of meta graph structure.
- Tracking the centroid of the vortices detected during the image processing.
- The image processing is missing certain small vortices during its birth.

8. Conclusion

- Explored the dataset.
- Understood the formation and dissipation of Vortices and the phenomenon of Vortex Shedding (Von Karman Vortex Street)
- Visualized the Vector field flow around a bluff body.
- Able to distinguish the flow regimes from laminar to turbulent and the transition regions.
- Implement our approach on the OpenCV based Tracking Graph Plotting in 3D using Vortex Detection in contour plots.
- Understood the importance of optimization layout in the Feature Tracking graph in 2D.
- Found the critical regions downstream behind the square cylinder block where the flow becomes unsteady.

9. Scope for Improvement

- There are lots of intersections in the tracking graph in 2D even after limiting the region of interest, hence in order to minimize intersections optimization of the layout has to be carried out
- There is no connectivity between different visualizations and there is no interactive exploration in the visualization which can be added

10. Responsibilities of Each Member

All three of us worked as a team. We read the related material individually and then discussed it together. In this way we got better understanding of what we were doing.

- Sankar coming from a Mechanical background was able to understand the Fluid Mechanics flow concepts better and explained to Phani and Masavir. Masavir being Computer Science Student was able to explain the algorithmic implementation in the paper "Interactive Exploration of Large Scale time varying datasets using Dynamic Tracking Graphs". Phani being an AI person was able to explain the importance of large dataset and the ways to handle them effectively. This enhanced our overall understanding.

- Phani implemented the first two tasks on drawing the contour plots and using Image processing to identify the vortices. Phani also wrote the script to convert the Amira mesh file to the data files. Sankar was able to draw the Tracking Graphs and do the Vector field plots using Python. Masavir wrote the script to convert the data files to VTK files. He then used paraview to visualize the data in 3D.
- Finally each one of us contributed to other's work by providing constructive comments on improvements and scrutinizing the work in such a way that the overall outcome what we have presented above were able to be achieved successfully.

11. References

1. Wathsala Widanagamaachchi, Cameron Christensen, Peer-Timo Bremer, Valerio Pascucci: Interactive exploration of large-scale time-varying data using dynamic tracking graphs. LDAV 2012: 9-17
2. Background: https://www.csc.kth.se/ weinkauf/notes/squarecylinder.html
3. Dataset (102-time steps, velocity): https://www.csc.kth.se/ weinkauf/notes/squarecylinder.html
4. F. Reinders, F. H. Post, H. J. W. Spoelder, "Visualization of time-dependent data using feature tracking and event detection". The Visual Computer, 17:55-71, 200l.
5. R. Samtaney, D. Silver, N. Zabusky, and J. Cao. Visualizing features and tracking their evolution. Computer, 27(7):20-27, July 1994.
6. Topological structural analysis of digitized binary images by border following
7. Quadtree Algorithms for Contouring Functions of Two Variables
8. Plotting Vector Feilds
9. Contour Detection using OpenCV
10. Three-Dimensional Plotting in Matplotlib

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