Topology-based Visualization of Scalar Fields Using Topology Toolkit (TTK)

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***Abstract*— Understanding scalar fields in computational fluid dynamics (CFD) is critical for analyzing complex flow phenomena such as vortex formation, boundary layer separation, and wake behavior. Traditional visualization methods often fail to capture the deep structural insights required for accurate analysis. In this project, we develop an interactive visualization system that employs topology-based visualization techniques using the Topology Toolkit (TTK) to enhance the analysis of scalar fields around a circular cylinder—a classic problem in fluid dynamics. By leveraging Contour Trees and Morse-Smale Complexes, our system provides a detailed representation of the underlying topological structures, enabling a more intuitive and meaningful understanding of flow dynamics. The integration of TTK with VTK and the Trame framework allows users to interactively explore scalar field data, adjust visualization parameters in real-time, and gain deeper insights into the fluid flow's topology. Our Python-based implementation offers flexibility and accessibility, facilitating advanced scientific visualization without extensive overhead. The web-based interface enhances ease of use and dissemination, making it a valuable tool for researchers and educators in the fields of fluid dynamics and data visualization. This paper details the methodology, implementation, and results.**

I. INTRODUCTION

Visualization plays a pivotal role in the analysis and interpretation of scalar fields, especially in the field of Computational Fluid Dynamics (CFD). Scalar fields represent quantities such as pressure, temperature, and velocity, and their accurate visualization is essential for understanding complex fluid behaviors. One of the classical problems in CFD is the analysis of flow around a circular cylinder, which involves intricate patterns such as vortex shedding and wake formation. These phenomena are critical for applications in aerodynamics, marine engineering, and energy systems.

Despite advancements in visualization techniques, traditional methods often fall short in capturing the nuanced topological structures that govern these flow phenomena. Conventional approaches focus on surface plots and streamlines, which, while visually appealing, do not provide insights into the scalar field's critical points and separatrices. This limitation hinders a comprehensive understanding of the underlying physical processes.

Topology-based visualization has emerged as a powerful approach to address these challenges by focusing on the intrinsic properties of data that remain invariant under continuous transformations. Techniques such as Contour Trees and Morse-Smale Complexes enable the extraction and representation of critical points, separatrices, and other topological features, providing a more detailed and meaningful interpretation of scalar fields.

This project addresses these limitations by utilizing topology-based visualization techniques through the Topology Toolkit (TTK), a robust library designed for analyzing and visualizing topological features of scalar fields. By applying TTK's Contour Trees and Morse-Smale Complexes, we achieve a comprehensive visualization pipeline that simplifies complex data while preserving its critical features. The proposed methodology integrates TTK with Python and Trame to develop an interactive and flexible visualization system, which not only simplifies the scalar fields but also highlights critical features such as vortex cores and pressure variations.

Our primary objectives are

- **Demonstrating the Efficacy of Topology-Based Visualization**: Showcasing how topology-based methods can reveal the structural intricacies of scalar fields in CFD datasets.
- **Interactive Exploration**: Providing a web-based interface using the Trame framework that allows users to adjust visualization parameters in real-time, facilitating an intuitive exploration of the scalar field's topological features.
- **Customization and Flexibility**: Supporting various color schemes, opacity settings, and visualization options to enhance data interpretation and cater to user preferences.
- **Scalability and Performance**: Efficiently handling large CFD datasets by leveraging the computational capabilities of TTK and the rendering efficiency of VTK.

By providing a robust and interactive tool for topology-based visualization, we aim to enhance the analysis of scalar fields in CFD and contribute to the broader field of scientific visualization. Our system not only aids researchers and engineers in gaining deeper insights into fluid dynamics but also serves as a foundation for further developments in topological data analysis and visualization techniques.

II. RELATED WORKS

Topology-based visualization techniques play a crucial role in analyzing scalar fields by capturing essential structural features such as critical points, separatrices, and level-set connectivity. Core methods like contour trees [1] and Morse-Smale complexes [2] have been widely adopted for their ability to represent scalar field topology effectively. Contour trees, as introduced by Carr et al. [1], are particularly useful for Iso surface extraction and data simplification, while Morse-Smale complexes [2] decompose scalar fields into regions of uniform gradient flow, enabling detailed structural analysis. The Topology ToolKit (TTK) has significantly advanced the accessibility of these techniques by offering efficient implementations integrated with visualization frameworks like VTK and interactive web tools such as Trame. Recent works utilizing TTK have demonstrated its efficacy in visualizing critical flow features in 2D and 3D scalar fields across domains such as fluid dynamics and geophysics. The integration of TTK with VTK and Trame enables the creation of interactive, web-based applications for scalar field exploration, marking a shift from traditional desktop tools toward collaborative, remote data analysis. Building upon this foundation, the proposed work enhances scalar field visualization by implementing contour tree and Morse-Smale complex visualizations for both 2D and 3D data, leveraging TTK's computational capabilities alongside VTK's rendering and Trame's interactivity.

III. Methodology and Implementation

The primary objective of this project is to develop an interactive visualization system for topology-based analysis of scalar fields derived from Computational Fluid Dynamics (CFD) simulations around a circular cylinder. The system integrates the Topology ToolKit (TTK), the Visualization Toolkit (VTK), and the Trame framework to visualize critical topological features such as vortex cores, critical points, and separatrices using Contour Trees and Morse-Smale Complexes

The system architecture comprises three main components: data processing and topological analysis, visualization pipeline, and interactive user interface. The data processing and topological analysis involve utilizing TTK to compute Contour Trees and Morse-Smale Complexes from the CFD dataset. The visualization pipeline implements VTK for rendering and visualizing the topological structures. The interactive user interface employs Trame to create a web-based platform for user interaction.

A. Data Processing and Topological Analysis

The system begins by loading the CFD dataset using VTK's data readers, specifically designed for VTK file formats. The dataset represents the flow around a circular cylinder and includes scalar fields such as pressure and velocity. To ensure appropriate processing, the system determines whether the dataset is two-dimensional (2D) or three-dimensional (3D). This distinction is crucial because it affects the selection of visualization techniques and computational resources.
The dataset's dimensions are analyzed by inspecting its extent in each spatial direction. If the extent in the z-direction is one unit, the dataset is considered 2D; otherwise, it is treated as 3D. The scalar field of interest, such as pressure or velocity magnitude, is extracted and set as the active scalar for subsequent analysis.

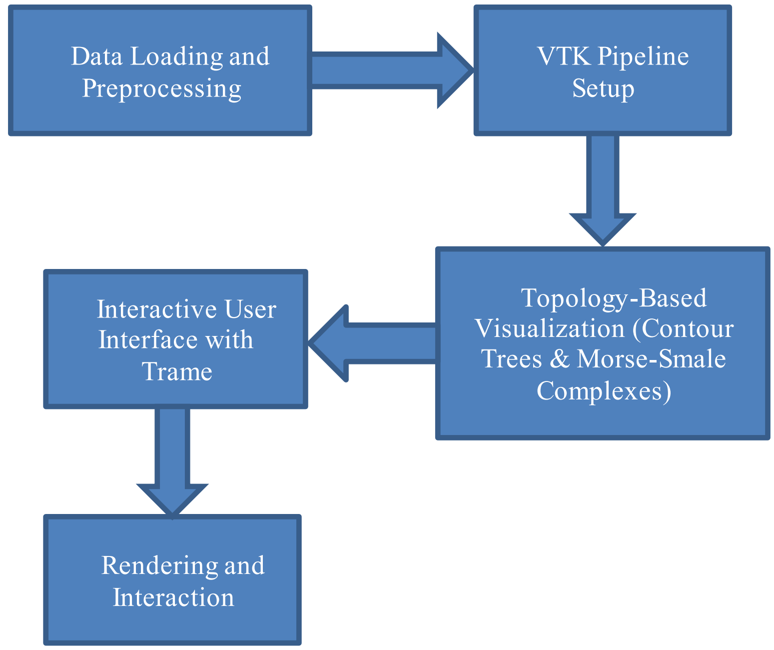

Fig. 1. Flow Chart Depicting overview of visualization system.

1. *Contour Tree Computation*

The Contour Tree is a topological data structure that captures the connectivity of iso surfaces within a scalar field. Computation involves several key steps:
Persistence Diagram Calculation: A persistence diagram is computed to identify critical point pairs (minima and maxima) and quantify their significance based on persistence values. This step helps in understanding the topological features present in the scalar field.

1. **Thresholding**: Critical point pairs are filtered using a user-defined persistence threshold. This process eliminates insignificant features, allowing the focus to be on prominent topological structures that have a greater impact on the flow dynamics.

2. **Topological Simplification**: The scalar field is simplified by removing the less significant features identified during thresholding. This results in a simplified dataset that retains essential topological characteristics, facilitating more efficient computation and clearer visualization.

3. **Contour Tree Generation**: The Contour Tree is computed from simplified data using TTK algorithms. The tree represents the hierarchical relationships among Iso surfaces, providing insights into the scalar field's topology and enabling the identification of key features such as vortices and flow separations.

2. Morse-Smale Complex Computation

The Morse-Smale Complex provides a decomposition of the scalar field based on its gradient flow, revealing critical points and separatrices that partition the domain into regions of uniform behavior. Computation involves the following steps:

1. **Data Simplification**: Similar to the Contour Tree computation, the scalar field is simplified to retain only significant features, ensuring that the Morse-Smale Complex highlights the most impactful topological structures.
2. **Morse-Smale Complex Extraction**: The Morse-Smale Complex is extracted using TTK, which involves identifying and classifying critical points (minima, maxima, and saddles). The ascending and descending separatrices that connect these critical points are computed, delineating regions where the scalar field exhibits consistent gradient behavior.

B. Visualization Pipeline

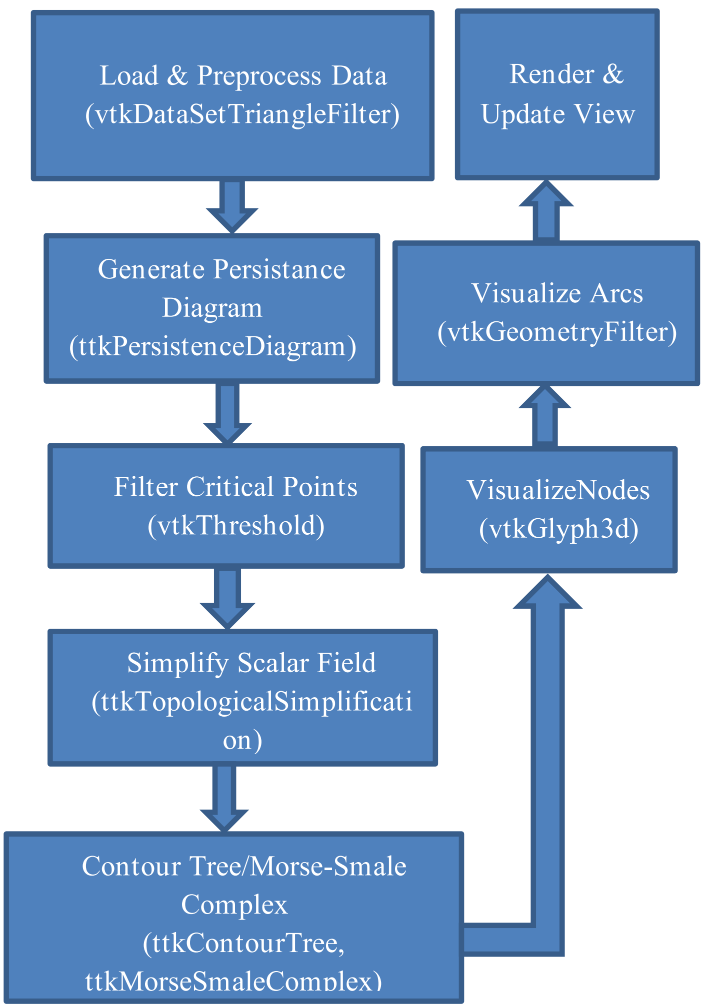

Fig. 2. Flow chart Depicting visualization pipeline used with ttk and vtk filters.

Visualization pipeline leverages VTK for rendering computed topological structures. For the Contour Trees, the arcs and nodes are mapped to graphical representations where arcs are displayed as lines connecting critical points, and nodes are depicted as spheres or points indicating the locations of critical points. Customizable color schemes and point sizes enhance visual interpretation, allowing users to distinguish between different types of critical points and the significance of various features.

For the Morse-Smale Complexes, critical points and separatrices are visualized with options to toggle the visibility of ascending and descending separatrices. Critical points are displayed with different shapes or colors based on their type (minimum, maximum, saddle), and separatrices are shown as curves or surfaces that highlight the gradient flow within the scalar field.

Various color schemes are implemented, including critical type coloring where colors represent the type of critical points, and scalar value mapping where colors correspond to scalar field values. This aids in interpreting data variations and understanding the relationships between different topological features. Users can adjust opacity settings to emphasize or de-emphasize certain structures, providing further customization for data exploration.

C. Interactive User Interface

An interactive web-based interface is developed using the Trame framework, facilitating real-time user interaction and exploration of visualization. Users can adjust parameters such as the persistence threshold to filter out less significant features, select color schemes to enhance visual differentiation, and modify opacity and point size to improve clarity.

The interface includes toggles to enable or disable visualization components like the Contour Tree and Morse-Smale Complex, as well as their individual elements such as separatrices and critical points. Real-time updates enable users to explore different parameter settings and immediately observe their effects on the visualization, providing instant feedback and enhancing exploratory analysis.

Additionally, the interface allows users to upload different datasets, broadening the applicability of the system to various scalar fields beyond the flow around a cylinder. This flexibility makes the tool valuable for a wide range of applications in fluid dynamics and data visualization.

IV. Contributions

This project was a collaborative effort where each member brought their expertise to different aspects while supporting one another throughout the process.

Sai Kiran Peruru concentrated on the Contour Trees, handling their integration with Python and ensuring the seamless visualization of hierarchical scalar field structures. He developed the algorithms and functions related to computing Contour Tree, optimized the performance of these visualizations, and assisted in integrating Contour Tree computations with the user interface.

Mohammed Adil Ahmed focused on the integration of Morse-Smale Complexes with Python, applying his knowledge to bridge complex topological concepts with practical implementation. He implemented the computation and visualization of Morse-Smale Complexes, including critical points and separatrices. His work enhanced the visualization techniques to accurately represent the complex structures inherent in the scalar fields. He also contributed to enabling interactive controls for Morse-Smale Complex components within the user interface.

Arvind Reddy Bobbili led the research on the Topology ToolKit (TTK), spearheaded the development of core code, and managed the documentation process to ensure clarity and completeness. He was responsible for integrating TTK with VTK and the Trame framework, establishing the foundation of the system architecture. He designed the overall system pipeline, ensured seamless communication between components, and authored comprehensive documentation and user guides for the system.

Although each member had distinct roles, the collaborative spirit ensured that everyone contributed to overcoming challenges, sharing insights, and refining the overall solution. This teamwork not only facilitated efficient task execution but also enriched the final output, reflecting a well-rounded understanding of topological data analysis.

V. Results and Discussions

The analysis of the 3D CFD dataset of flow around a circular cylinder using topology-based visualization techniques revealed significant insights into the scalar field's structure, with vorticity being the scalar quantity of interest. Vorticity plays a critical role in understanding rotational flow behaviors such as vortex generation, shedding, and dissipation, which are prominent in such flow scenarios. By employing Contour Trees and Morse-Smale Complexes, we were able to uncover hierarchical and gradient-driven features that provide a deeper understanding of the flow dynamics.

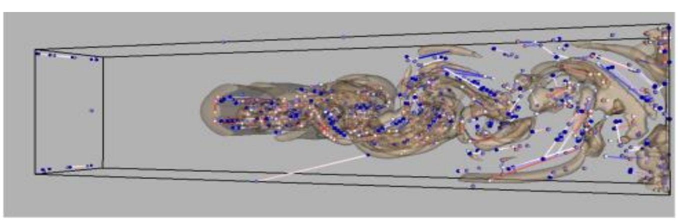

Fig. 3. Contour Tree Visualization of Cylinder CDF dataset with iso surface

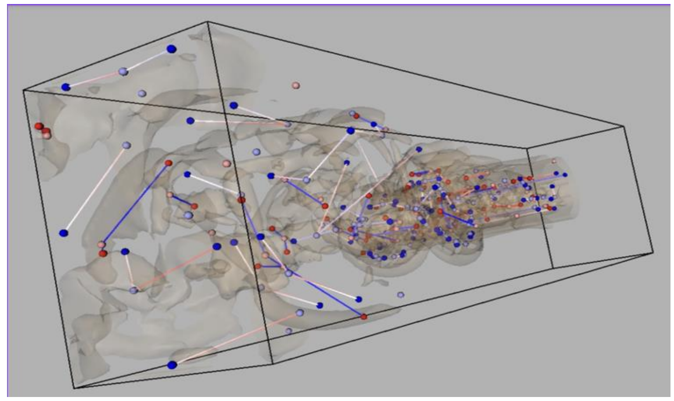

Fig. 4. Contour Tree Visualization of Cylinder CDF dataset with iso surface.

The Contour Tree visualizations effectively captured the hierarchical relationships between Iso surfaces in the vorticity field. As illustrated in Fig. 3 and 4, the critical points—minima, maxima, and saddles—served as nodes, while the arcs depicted the connectivity and evolution of scalar values. This hierarchical representation was particularly insightful in analyzing the wake region, where vortex shedding occurs. The arcs revealed how high-vorticity regions emerged, evolved, and dissipated downstream. Such hierarchical insights are challenging to achieve with traditional methods like streamlines or surface plots, as these primarily focus on local or surface-level details without emphasizing topological connectivity.

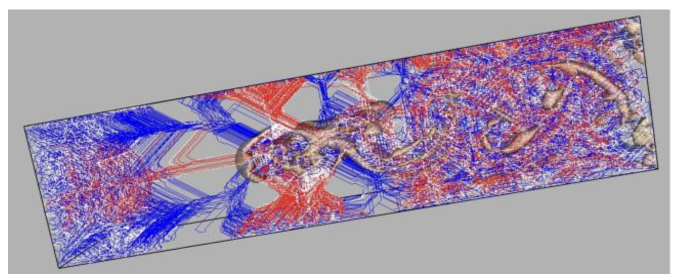

Fig. 5. Morses Smale Complex Separatrix 1 visualization for cylinder CFD dataset.

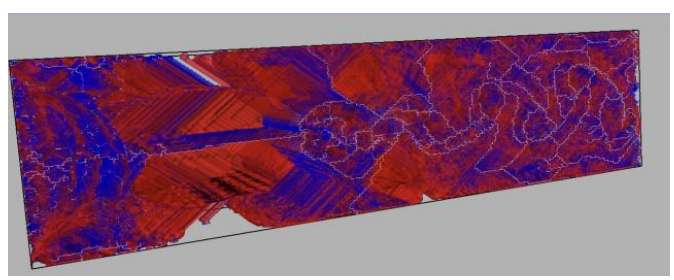

Fig. 6. Morses Smale Complex Separatrix 2 visualization for cylinder CFD dataset.

The Morse-Smale Complex visualizations, on the other hand, provided a complementary gradient-based decomposition of the scalar field. Fig. 5 and 6 showcased the separatrices, which delineated regions influenced by specific critical points, segmenting the flow field into distinct zones of uniform behavior. The ascending and descending separatrices effectively highlighted critical flow features, such as vortex cores and regions of dissipation. Separatrix 1 visualizations captured the dominant flow paths, while Separatrix 2 offered a finer-grained view, revealing secondary vortices and smaller-scale structures. This segmentation not only aids in understanding how vorticity is distributed but also provides a structured way to study interactions between vortices and wake regions.

One of the key observations from these visualizations was the ability to distinguish critical points such as saddle points, which signify regions of flow separation. These regions are pivotal in understanding how the wake structure develops and evolves behind the cylinder. The separatrices provided a visual representation of flow partitioning, delineating areas dominated by vortices and highlighting regions where the flow transitions between different behaviors. Such insights are crucial for understanding vortex dynamics, particularly in engineering applications where vortex shedding can impact structural stability and performance.

The hierarchical representation from the Contour Tree and the gradient-driven segmentation from the Morse-Smale Complex complemented each other to offer a comprehensive understanding of the scalar field. While the Contour Tree emphasized global connectivity and relationships between scalar Iso surfaces, the Morse-Smale Complex focused on local gradients and transitions, making the combined approach highly effective for detailed analysis.

We also implemented contour tree and Morse-Smale visualization for 2D scalar field data. Figure 7 presents the contour tree for the diesel field, while Figure 8 shows the Morse-Smale separatrix for the same dataset. Our visualization system dynamically detects whether the given scalar dataset is 2D or 3D and adjusts the visualization pipeline and functions accordingly to support 2D visualization.

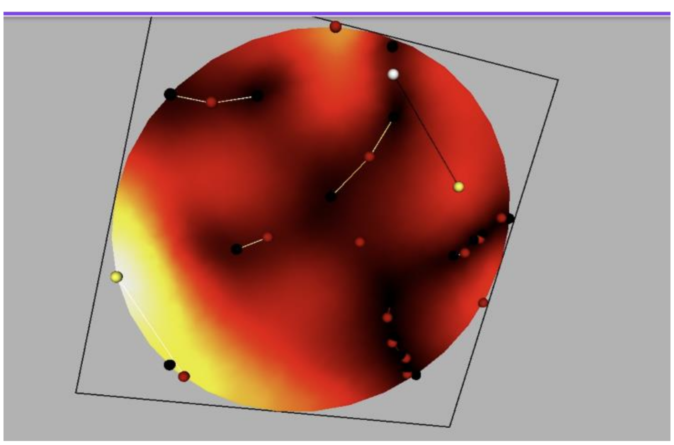

Fig. 7. Contour Tree visualization for diesel field 2d dataset.

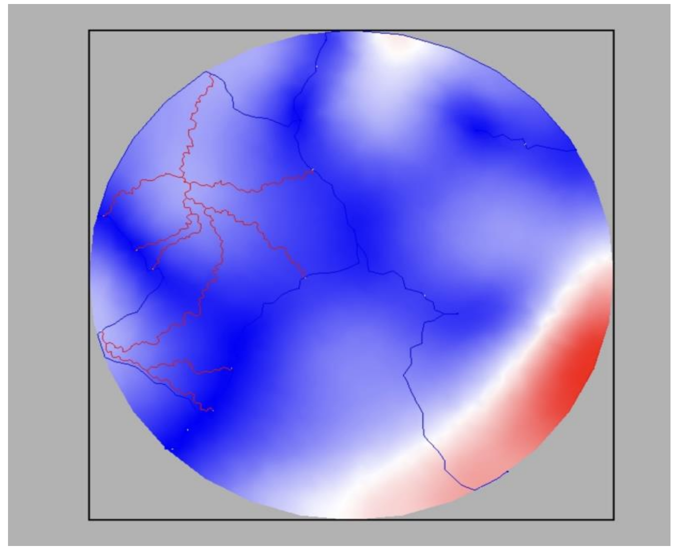

Fig. 8. Morses Smale Complex visualization for diesel field 2d dataset.

The user interface for the topology-based visualization system, implemented using the Trame framework, offers an interactive and dynamic environment for analyzing scalar fields. It includes controls for uploading datasets and adjusting parameters such as persistence thresholds, opacity, and a variety of customizable color schemes, including grayscale, heatmaps, rainbow, and bivariate blue-red (BWR). These schemes enhance the interpretability of scalar variations, critical points, and separatrices. The interface allows users to toggle between visualization techniques like Contour Trees, Morse-Smale Complexes, and isosurfaces, providing unique insights into the data. Isosurfaces highlight regions of specific scalar thresholds in 3D datasets, such as high-vorticity zones, while for 2D datasets, color plots with superimposed critical points and separatrices visually represent scalar field variations. Real-time interactivity ensures that any updates to parameters are instantly reflected in the visualization, enabling users to focus on key features and explore data efficiently. This robust and user-friendly design facilitates a comprehensive analysis of both 2D and 3D scalar fields, making the system accessible for detailed scientific exploration.

Overall, the results validate the utility of topology-based methods in fluid dynamics analysis. The ability to uncover and visualize critical topological features provides insights that are difficult to achieve with conventional visualization techniques. The system's interactivity, allowing for real-time parameter adjustments, further enhances its utility by enabling users to focus on specific features dynamically.

VI. Challenges

Despite its effectiveness, the implementation faced several challenges related to computational performance, data interpretation, and integration. The large size of the dataset required optimization of the TTK pipeline to ensure smooth visualization, as rendering complex topological structures was computationally intensive. Additionally, interpreting the results demanded a solid understanding of both topology and fluid dynamics, particularly when analyzing intricate features like vortex formations or flow separations. Another significant challenge was integrating Python with TTK, as TTK is primarily built in C++ while our codebase was in Python. To bridge this gap, we built TTK from source code using CMake and had to make sure that all the dependencies were properly configured for it to work with python wrappers. This process was complex and time-consuming, especially since we opted for a direct integration approach rather than using TTK's preview feature, which would have simplified the task but limited flexibility. Overcoming these challenges required a combination of technical expertise and collaborative problem-solving, ultimately leading to a robust and efficient solution.

VII. Future Work and LIMITAITONS

This study demonstrates the potential of topology-based visualization for analysing scalar fields in CFD. By applying TTK's Contour Trees and Morse-Smale Complexes, the project successfully visualized critical flow features around a circular cylinder. The methodology provided a robust framework for simplifying and analysing complex datasets while preserving their key structures.

The current implementation is limited to static datasets and lacks support for dynamic flow analysis. Furthermore, the reliance on domain knowledge poses challenges for non-expert users.

Future developments will focus on extending the methodology to dynamic datasets, enabling real-time analysis of transient flows. Additional features, such as side-by-side comparisons of topological visualizations and implementation of other topological visualization method, will enhance the overall experience.

References

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