Hairpin Vortex Identification using Template Fitting on Vortex Corelines

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Problem Statement

- Hairpin vortices are vortical structures that are formed due to turbulence near the boundary layer in fluid flows.
- Identifying and visualizing hairpin vortices provides useful insight about the transition process of fluid flows from laminar to turbulent around the fluid boundary layers [1].
- Hairpin vortices have irregular shapes and sizes and may be tangled with other vertices (Fig. 1(c)), which makes their extraction and separation difficult. Currently, there is not a robust framework to extract and separate hairpin vortices.

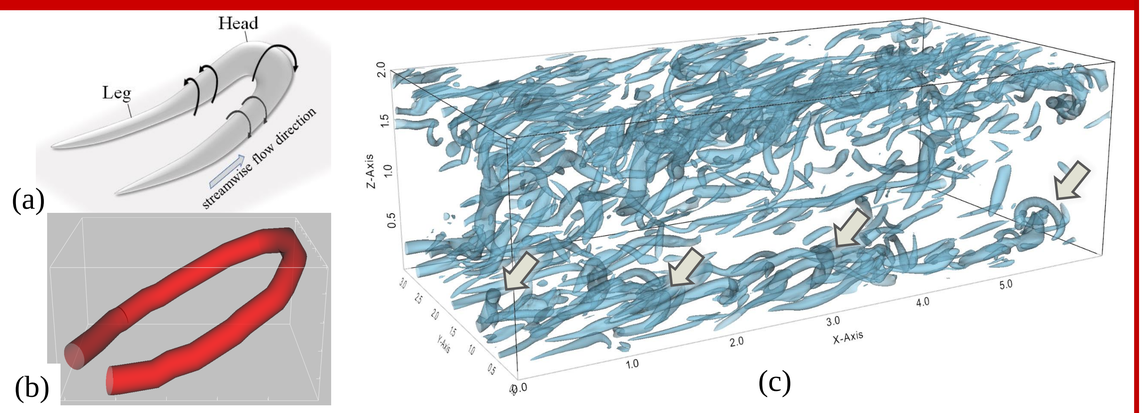

Figure 1: (a) Illustration of a hairpin vortex, (b) isosurface of a hairpin vortex using λ_2, and (c) isosurfaces of λ_2 of a stress-driven turbulent Couette flow [3]. Arrows point to places that hairpin vortices may arise.

Contributions

- To address this challenge, we make use of the geometric properties of vortex corelines to identify and extract hairpin vortices.
- We apply an improved method of coreline extraction that removes noise and disconnected corelines to improve the quality of vortex corelines.
- We propose a framework that performs vortex coreline extraction followed by a template fitting step to identify candidate hairpin vortices.

Proposed Methodology

- First, we use the “Parallel Vectors” operator [2] to extract corelines by finding the points where velocity and acceleration of the fluid are parallel.
- To extract contiguous corelines while reducing outliers (i.e., small disconnected segments), we merge two sets of output corelines which are filtered using the combined Q and Delta criteria and the combined Delta and Lambda2 criteria, respectively (Fig. 3).
- Next, we perform a pre-filtering by removing corelines that are straight, followed by a template fitting.

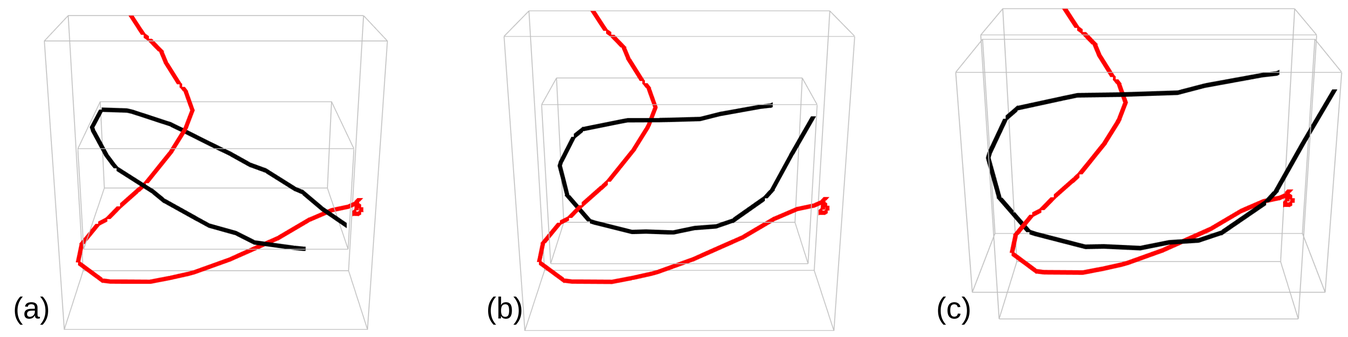

Figure 2: (a) shows the template (black) and target (red) corelines in their original scale and orientation. (b) and (c) show the aligned orientation and scaling after transformation, respectively. The template has the minimum distance with the target in this orientation and size.

- To achieve that, we select a coreline resembling the shape of a hairpin vortex as the template (black curves in Figure 2). We then align and scale the bounding box of the template with the one of a candidate coreline. Corelines with Hausdorff distance less than a threshold from the template after the alignment are identified as candidate hairpin vortices.

Results and Applications

- Fig. 3 shows the results of our corelines extraction method. In Fig. 3(a), the default VTK results show disconnected corelines in green. Fig. 3(b) uses only Delta and Lambda2 criteria for filtration which shows some false positives in red. Fig. 3(c) shows the merged results where disconnected and false corelines are removed.

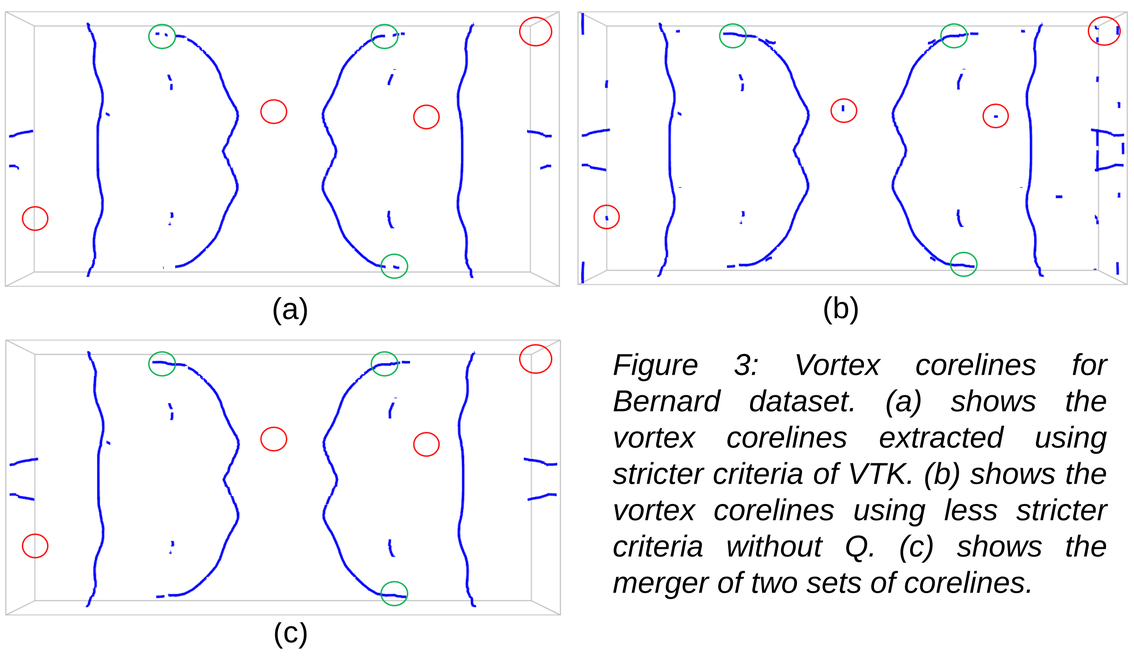

Figure 3: Vortex corelines for Bernard dataset. (a) shows the vortex corelines extracted using stricter criteria of VTK. (b) shows the vortex corelines using less stricter criteria without Q. (c) shows the merger of two sets of corelines.

- Fig. 4 shows the results of our method applied to the numerical simulation of stress-driven turbulent Couette flow from [3]. Fig. 4(a) shows the results of our vortex corelines extraction applied on the dataset and Fig. 4(b) shows the candidate hairpin vortices identified by applying our method.

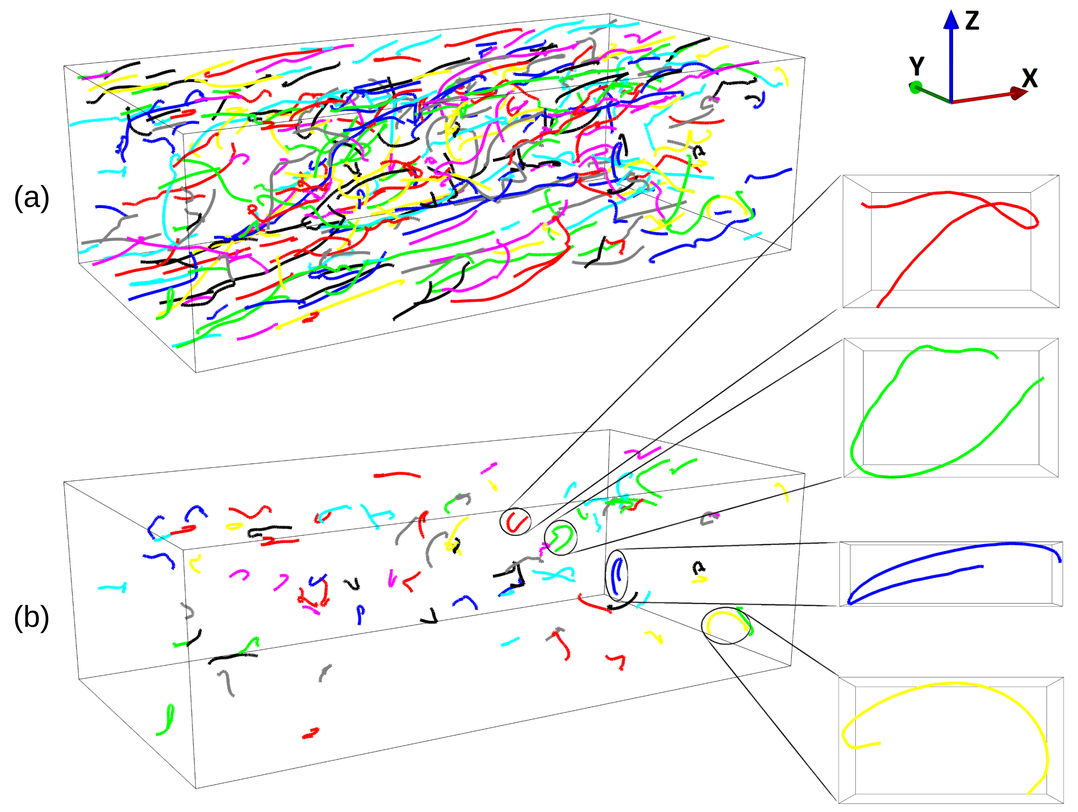

Figure 4: (a) shows the result of the vortex corelines extraction. (b) shows the result of the extracted hairpin vortices. We use different colors for each coreline to differentiate different vortex corelines.

- Our method identifies some candidate corelines that may correspond to hairpin vortices. However, the result still contains quite many false positive and some missing hairpin vortices, which we plan to address in the future.

Conclusion and Future Works

- We propose to identify hairpin vortices using template fitting on vortex corelines. We demonstrate the results by applying our method on the vector field of a wall-bounded turbulent flow.
- Given the complexity of coherent vortical structures in turbulent flows, hairpin vortices can take up many different shapes and sizes. One template might not fit all types of hairpin vortex shapes. In the future, we plan to use additional criteria to identify hairpin vortices.

References

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