Development of a flow visualization model using the transport tube method for application in vertical axis wind turbine analysis

By Vincent Laroche and Dr. Di Yang, Mechanical Engineering

UNIVERSITY of HOUSTON

Background

- After passing through a wind turbine, air emerges from the other side slower and with greater turbulence. This reduced-speed region is referred to as the turbine's wake.
- In the context of a wind farm, one turbine's wake will be directly upstream of another turbine, so it is important that the wake flow travels sufficient distance in order to recover speed (thus momentum and kinetic energy being transported).
- Studying wake flow structure will allow a greater understanding of where and how kinetic energy is recovered in downstream flow.
- Although significant wake flow research has been done on horizontal axis wind turbines, vertical axis wind turbines (VAWTs) (see image) are a newer design that need study.

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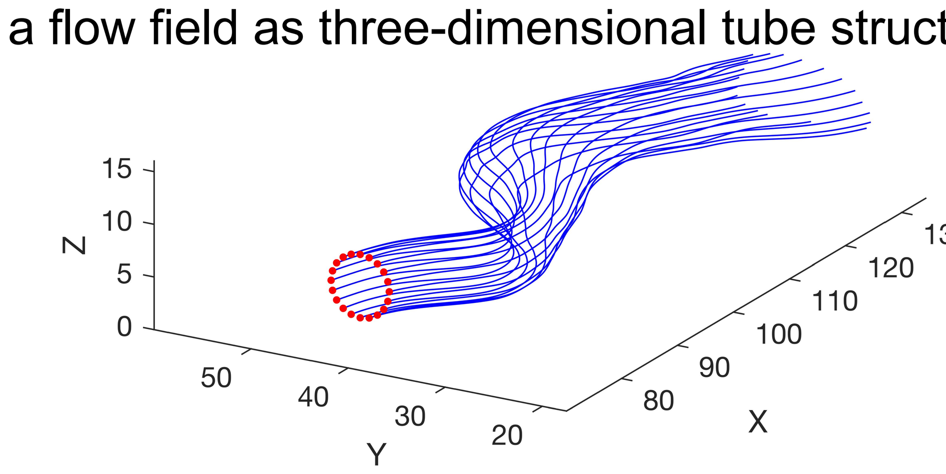
Methodology

- The transport tube method (TTM) was the primary tool used for data analysis. This method allows for the visualization of the transport of mass, momentum, and kinetic energy through a flow field as three-dimensional tube structures [1].
- In the case of mass transport, numerical integration of the velocity field was used on a circular set of start points, resulting in a set of streamlines that define a tube (see image). Physically, this tube represents a region where there is no flow of mass across its boundary.



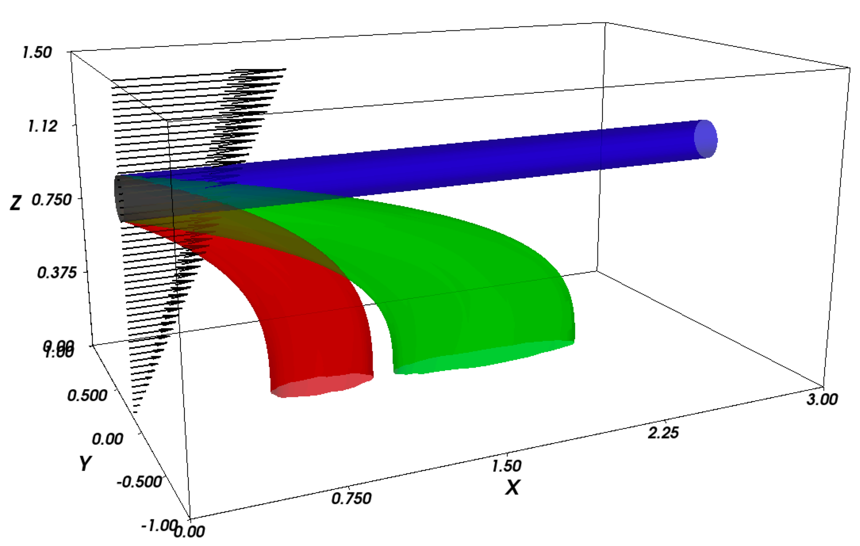
- A similar process can be used to construct transport tubes for momentum and kinetic energy by analyzing their flux vector fields. Manipulation of the Navier-Stokes equations yields two equations for mean momentum flux ($\bar{F}_m$) and mean kinetic energy flux ($\bar{F}_K$):

$$\bar{F}_{m,j} = (\bar{u}_i \zeta_i)\bar{u}_j + (\overline{u_i' u_j'} - 2\nu \bar{S}_{ij})\zeta_i \qquad \bar{F}_{K,j} = (\bar{u}_i\,\bar{u}_i/2)\bar{u}_j + (\overline{u_i' u_j'} - 2\nu \bar{S}_{ij})\bar{u}_i$$

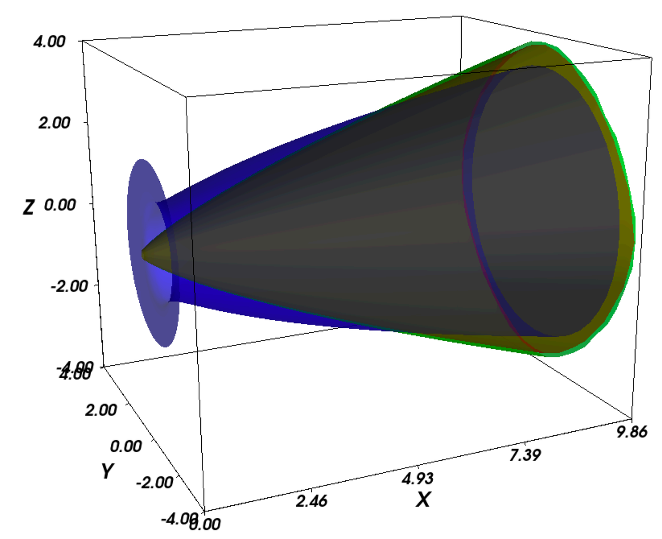
- Computer codes were developed in Matlab and Python to apply TTM to a given velocity vector field dataset.

Results

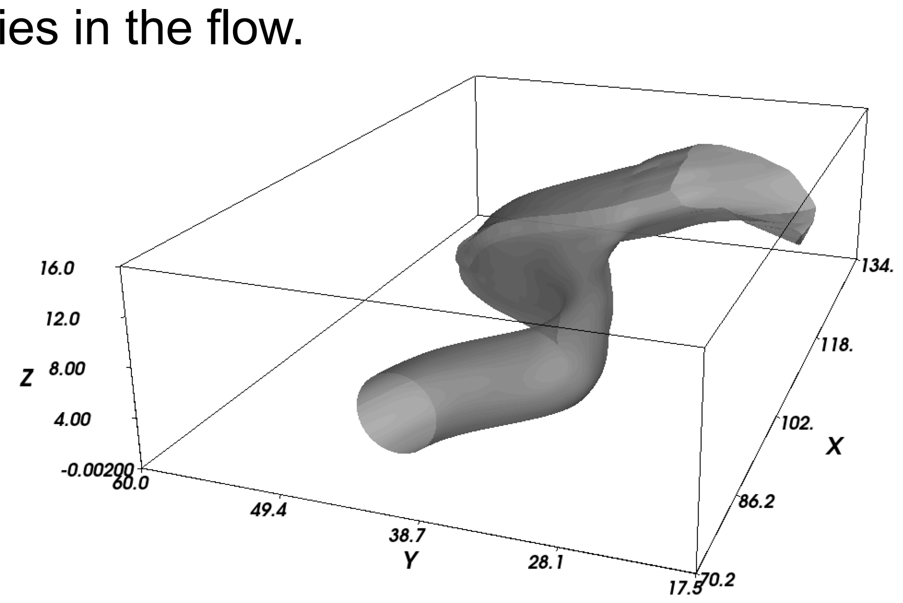
- The TTM was first applied to three simple flow fields (see below) in order to test its ability to analyze varied flow conditions.
- Couette flow is a 2D flow field that has been extended to 3D for the purpose of this visualization. Mass, momentum, and kinetic energy transport are shown in blue, green, red, respectively, with the velocity profile overlaid. Although the flow of mass is horizontal, the tubes reveal that momentum and kinetic energy are are directed into the bottom wall as they are dissipated due to friction. This is a primary example of how the TTM allows for an understanding of momentum and kinetic energy transport that would not be obvious from only observing the velocity field.
- The laminar round jet is a 3D axisymmetric flow field. The momentum and kinetic energy tubes (coincident and thus appearing as yellow) are similar in structure to the mass tube (blue), but they expand at a faster rate. This is indicative of the energy being dispersed from the flow of the jet as it loses speed in downstream flow. Again, the TTM is able to highlight smaller differences in the transport of mass momentum and kinetic energy even when they have similar trends.
- The sample wind data set represents a more complex 3D flow field with significant turbulence. In this case, all three tubes are nearly identical, so only mass transport is shown in grey for sake of clarity. Still, the TTM is able to create a visualization of the flow's characteristics; for example, the two curves in the path of the tube indicate eddies in the flow.



Plane Couette Flow

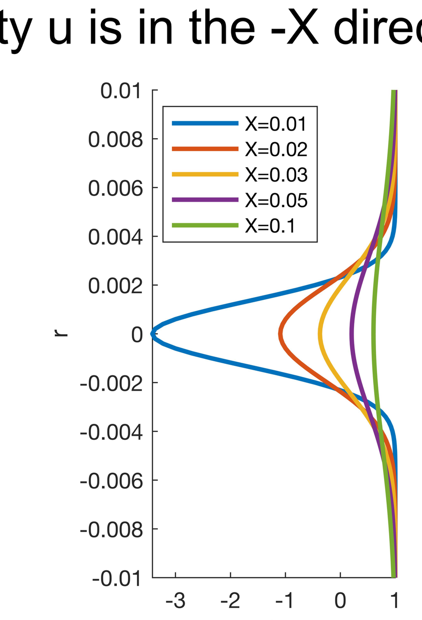


Laminar Round Jet Flow

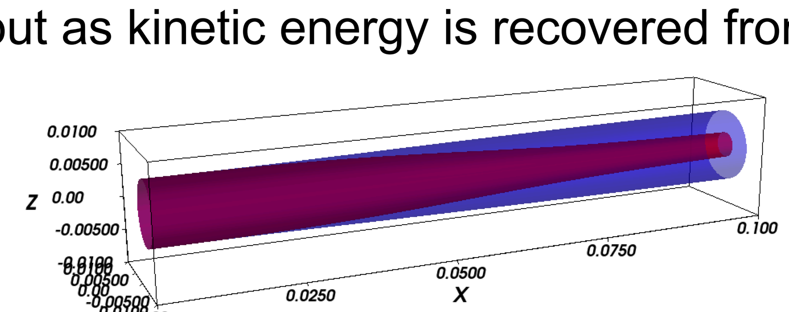


Sample Wind Flow

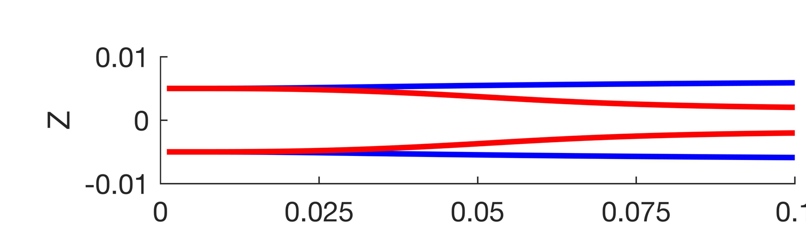
- The figures below show the results of applying the TTM to idealized wake flow. The velocity profile demonstrates the recovery to freestream velocity u_0. At the start of the wake, centerline velocity u is in the -X direction, but as kinetic energy is recovered from freestream flow, the velocity changes direction and the profile approaches u_0 throughout. The mass (blue) and energy (red) transport tubes offer an explanation of how this recovery occurs. Although the tubes begin at the same location, the kinetic energy tube quickly reduces in size, indicating flow of kinetic energy from the edge of the wake to its center. The primary direction of kinetic energy transport is still in +X, but the viscous effect causes a significant component of the transport velocity to point to the center of the wake. Kinetic energy from surrounding freestream flow is thus absorbed into the wake to restore an equilibrium state.



Wake Velocity Profile



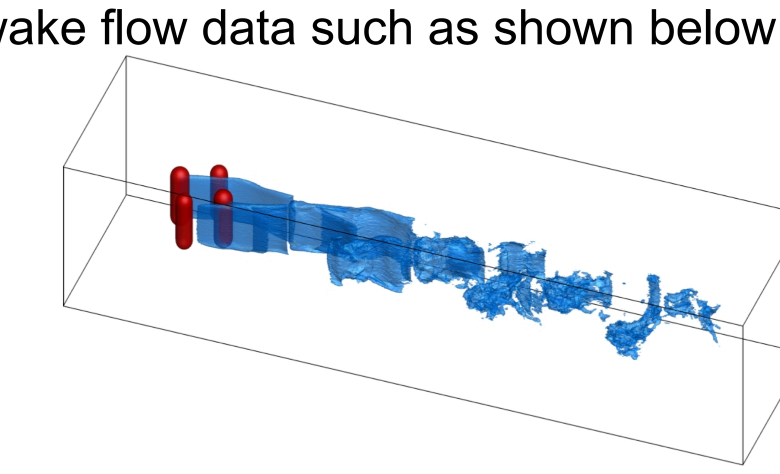
Transport Tubes



Transport Tubes Cross-Section

Conclusion and Future Work

- The TTM provides an effective tool for visualizing mass, momentum, and kinetic energy transport in a variety of flow fields both 2D and 3D as well as laminar and turbulent.
- The method is also useful for identifying features of the flow field (e.g. eddies) and non-obvious flow patterns of momentum and kinetic energy
- Transport tubes are capable of showing to what extent kinetic energy is regained in downstream wake flow.
- Future analyses will include applying TTM to simulated VAWT wake flow data such as shown below [2].



- I will continue the research of this project in the University of Houston's Senior Honors Thesis program.

Acknowledgements

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Works Cited

[1] J. Meyers and C. Meneveau. Flow visualization using momentum and energy transport tubes and applications to turbulent flow in wind farms. Journal of Fluid Mechanics 2013; 715:335-358.
[2] S. Xiao, R. Yao, D. Araya, J. Dabiri, and D. Yang. Effect of helical-shape blades on the wake flow characteristics of vertical axis wind turbines. 72nd American Physical Society Division of Fluid Dynamics Annual Meeting, Seattle, WA, USA, November 26, 2019.