Visualization of Flow Past a Marine Turbine: the Information-Assisted Search for Sustainable Energy

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Abstract

Interest in renewable, green, and sustainable energy has risen sharply in recent years. The use of marine turbines to extract kinetic energy from the tidal current is gaining popularity. CFD modeling is carried out to investigate the surrounding flow behavior and thus develop effective marine turbine systems. However, visualizing the simulation results remains a challenging task for engineers. In this paper, we develop, explore and present customized visualization techniques in order to help engineers gain a fast overview and intuitive insight into the flow past the marine turbine. The system exploits multiple-coordinated information-assisted views of the CFD simulation data. Our application consists of a tabular histogram, velocity histogram, parallel coordinate plot, streamline plot and spatial views. Information-based streamline seeding is used to investigate the behavior of the flow deemed interesting to the engineer. Specialized, application-specific information based on swirling flow is derived and visualized in order to evaluate turbine blade design. To demonstrate the usage of our system, a selection of specialized case scenarios designed to answer the core questions brought out by engineers is described. We also report feedback on our system from CFD experts researching marine turbine simulations.

Keywords:
Information Visualization, Flow Visualization, Visualization Application.

1. Introduction and Motivations

As we approach the inevitable depletion of fossil fuel-based sources of energy such as oil and coal, ever increasing attention is paid to renewable energy sources. The United Kingdom has several natural resources from which sustainable energy may be generated. Solar and geothermal resources are difficult or expensive to exploit in the UK. Many believe that wind and ocean tides are rich energy resources. Currently around 1.5 % of electric energy is generated from wind, and this figure is expected to increase to 3.3 % [1]. Although much work has been invested in exploiting wind power, efforts to extract power from ocean tides are small in comparison. However, oceans contain a large amount of renewable, green, sustainable energy.

A marine turbine makes use of kinetic energy available in moving water, similar in concept to a wind turbine being powered by the wind. This application is gaining popularity because of relative advantages marine turbines offer. First, the ocean tide is a more predictable resource compared to wind. Second, marine turbines are installed underwater. Hence the visible landscape remains unaffected. Last but not least, due to the slow rotation speed of the turbine, the tidal stream system has lower ecological impact compared to barrages. Based on these premises, the marine turbine has a promising future as a renewable source of energy. However, the cost of installation and maintenance for a marine turbine is large. Therefore simulation tools are essential in order to minimize this cost.

Modeling and simulation are carried out to investigate how the flow past a marine turbine is affected and thus develop a better and more efficient marine turbine system. Some of the central questions that CFD (Computational Fluid Dynamics) engineers seek the answers to in their research are:

1. How does the flow past a marine turbine behave?
2. To what spatial extent does a marine turbine have a significant impact on the downstream flow structure?
3. What kind of blade and pylon design can both maximize the energy drawn from the passing current while simultaneously minimizing its impact on the momentum of the flow?
4. How closely can turbines be packed in a given region of the ocean floor such that each may effectively draw energy from the ocean tides?

There are multiple challenges, both technical and perceptual, to overcome to answer these questions. Challenges stem from the adaptive resolution, unstructured mesh used for the simulation as well as the high dimensionality of the CFD data. Commercial off-the-shelf tools do not always provide adequate visualization solutions for each user's needs.

In this paper, we develop, explore and present customized information-assisted interaction and visualization techniques that help engineers answer these questions. We also present approaches for the engineers to gain a fast, intuitive and helpful insight into their simulation results. Our contributions are the following:

- We present a novel application that exploits multiple-coordinated views for interactive visualization of marine turbine simulation data. Two of the information visualization views are: a novel spherical histogram of velocity, and a histogram table that provides an overview of the high-dimensional data space. Other views are an interactive parallel coordinates, and a novel streamline plot visualizations that support analysis and exploration of the CFD data.

- We describe information-based and knowledge-assisted streamline seeding to investigate the behavior of the flow past the marine turbine. Novel derived data used to evaluate blade design is computed and visualized based on swirling flow behavior.

- We report feedback from CFD experts researching the simulation of flow past the marine turbine.

By utilizing customized information and spatial visualization views which incorporate multi-threading, the simulation results can be explored and analyzed interactively and more efficiently than standard commercial software. The user can multi-select or brush any attributes deemed interesting from an information visualization view, and the corresponding 3D visualization will be updated in the spatial view simultaneously.

The rest of the paper is organized as follows: Section 2 provides an overview of related research work. The background of the simulation results is described in Section 3. Section 4 presents the detail of the application framework and its components. Section 5 discusses a selection of specialized case scenarios. The domain expert review of the application is provided in Section 6. Conclusions and suggestions for future work are presented in Section 7.

2. Simulation Data

The simulations we describe are from a CFD simulation of a tidal stream turbine [2][3][4][5]. We focus mainly on two representative simulations: a simulation with a single turbine and one with multiple rotors. We briefly describe the purpose of each and the adaptive resolution meshes used to generate each. We discuss some important simulation attributes which are key to answering the engineer's questions. Some of the simulations require several days or some weeks. This visualization is a post-processing step. Thus we did not have the opportunity to provide computational steering features.

Single Turbine Simulation: To investigate the effect that the supporting structure (Figure 1(bottom)) has on the performance of a tidal stream turbine, the CFD simulation is carried out in a (length) 426 m $\times$ (height) 25 m $\times$ (width) 60 m underwater domain with a flat base [4]. The dimensions of the bounding domain for a rotor with 10 meters diameter are shown in Figure 1(top). The width of the domain is six times the diameter

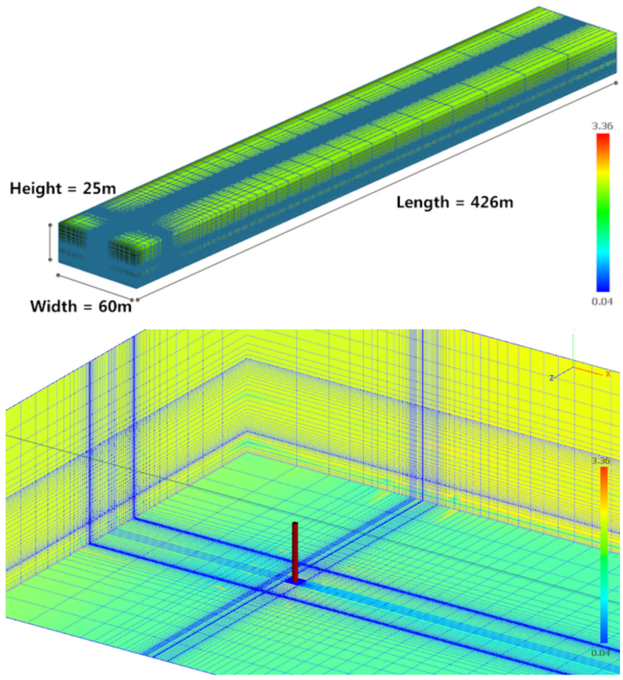

Figure 1: Schematic of the flat-bed geometry (top) dimensions of the domain. Lines highlight the adaptive resolution properties of the mesh which is much denser near the rotor area. (bottom) Detail of the mesh close to the pylon.

of the rotor in order to minimize the effect of the side boundaries on the flow past the turbine. The length of the downstream channel is 400 meters, while the height is taken from bathymetry data at the actual turbine site in the Bristol (UK) Channel whose depth is 25 meters below low astronomical tide. The tidal stream turbine model consists of a 12 meter high vertical supporting tower - the pylon as illustrated in Figure 1(bottom). The center of the rotor is 25.5 meters downstream from the in-flow boundary and is positioned on the middle plane in the width dimension. The mesh is constructed of approximately 350k hexahedral elements. Engineers are most interested in the behavior of the flow near the pylon and blades. Thus the resolution of the mesh is highest there. Mesh resolution then drops off with distance from the blade.

The simulation employs the boundary element momentum (BEM) [4] method. This method considers the time averaged influence of the rotors on the water. This results in the addition of a force term in the momentum equation which is only a function of radial and axial position relative to the rotor axis. The rotor shape is built into the source through its geometry and characteristics rather than the mesh. This method is unsuitable for predicting transient effects of blade motion but does allow time average effects to be resolved.

Multiple Turbine Simulation: In order to explore the impact from other turbines and determine how closely multiple turbines can be placed in a region so that each may effectively draw energy from the tidal flow, a simulation with four turbines is carried out in a 448m $\times$ 30m $\times$ 180m domain whose initial conditions are similar to the single turbine simulation. Three turbines are evenly spaced along width-axis at 100.5m downstream from the inlet-flow boundary. The fourth one is placed

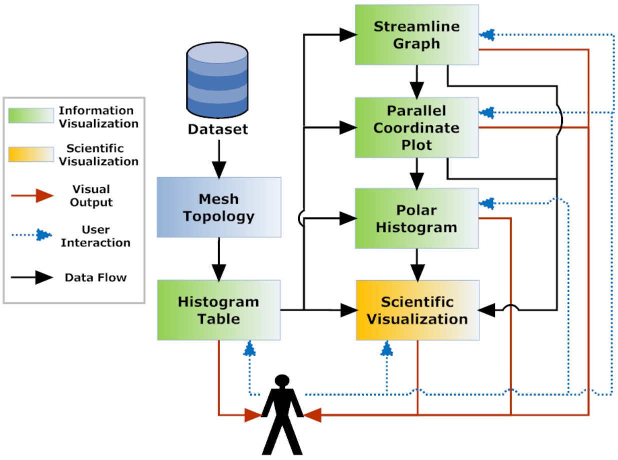

Figure 2: An overview chart illustrates the design and work flow between the user and our application framework.

132m directly after the front middle turbine. In contrast to the single turbine simulation, this simulation does not feature pylon structure embedded in the mesh since the focus of this simulation is on the influence on the flow from multiple turbines rather than the pylon itself. The mesh consists of over 2.37 million hexahedral elements.

Both simulations compute several parameters to describe the flow. Some of the important simulation attributes are: (1) Flow Velocity. (2) Relative Pressure: this describes the water pressure value relative to the out-bound flow boundary. Rapid change of the water pressure can seriously affect marine life. (3) Density: this attribute represents the density of water. This attribute may vary due to pollutants such as sediment. (4) Turbulent Kinetic Energy (TKE): the mean kinetic energy (per unit mass) associated with rotational flow. (5) Turbulent Dissipation Rate (TDR): the rate at which turbulent energy is absorbed and converted into heat. (6) Turbulent Viscosity: this describes the diffusive mixing of the flow turbulence. These attributes are deemed as key for the CFD engineers to effectively understand and describe the flow as it passes by the rotor. In addition, we derive two attributes requested by the domain experts (7) swirl flow and (8) tangential velocity both of which measure types of swirling flow behavior. These customized derived attributes are described in more detail in Section 5.1.

3. Application Framework and Visualizations

In this section, we describe the details of our research prototype system design and implementation written in C++ using Qt [6]. Firstly, an overview provides the general framework of what the system offers and how the user can interact with it. Then the linked information visualization views are described individually along with their motivation. Finally, spatial visualization options are presented based on information and knowledge-assisted queries.

Figure 2 shows an overview of the framework. The input includes the generic hexahedral meshes as the geometric representation for flow domain. Each vertex i has a position $\mathbf{p}_i = (x(i), y(i), z(i))$, a velocity vector $\mathbf{v}_i = (v_x(i), v_y(i), v_z(i))$, and other simulation related attributes such as pressure, kinetic energy etc. The mesh topology is computed in order to accelerate streamline tracing. After the topology construction, various information visualization approaches are employed to gain insight into the data. The histogram table provides an intuitive overview of the multi-dimensional attributes of the whole simulation. Based on the histogram table, the user can focus on attributes they deem interesting, while the spherical histogram and PCP (Parallel Coordinate Plot) simultaneously depict the details of the focus attributes. The spherical histogram presents an intuitive description of the flow velocity distribution. The PCP highlights the relationship between CFD attributes to support exploration. The user can interact between different information visualization approaches to obtain the final spatial visualization result. In addition, the streamline plot is used to quantify the streamline curvature so that the specific streamline which has the most swirl can be obtained. In this section, we

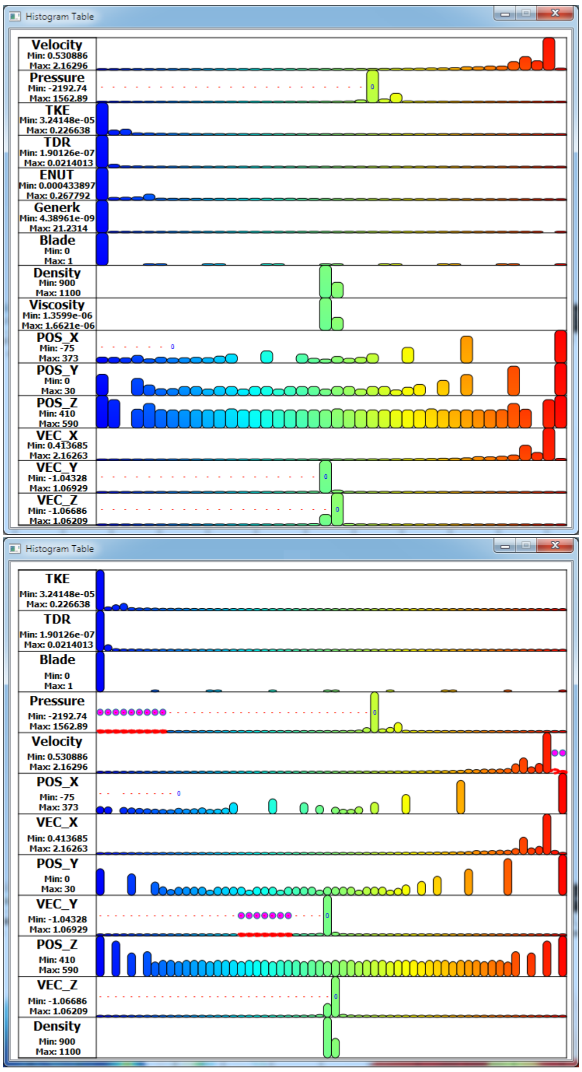

Figure 3: A set of histogram tables to provide an overview of the multidimensional information from the turbines simulation. (first) The default histogram table. (second) The sequence of attributes is reordered, and the attributes of ENUT, Generk, and Viscosity are excluded. The number of frequency intervals is increased to 60. The user selected bars are highlighted by the frame with dotted red lines and ellipses in fuchsia.

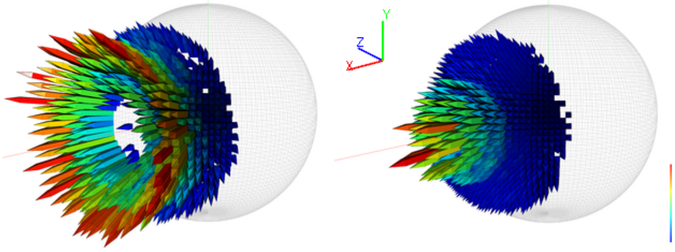

Figure 4: The spherical histogram illustrates the velocity distribution of the tidal flow around blade elements from the multiple turbines dataset. (left) The velocity distribution of the flow with negative relative pressure while (left) shows the flow with positive pressure.

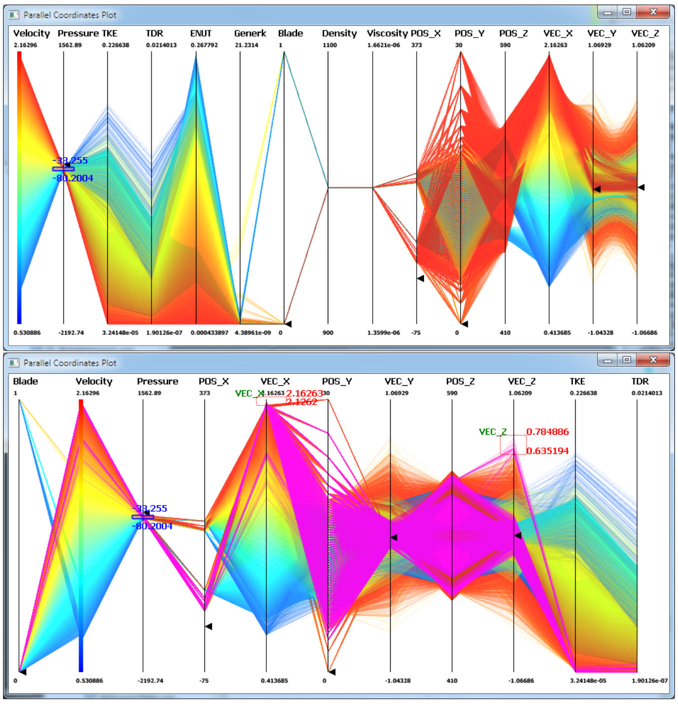

Figure 5: PCPs demonstrating the relationship among attributes when the user brushes the pressure ranging from −80.2004 to −33.255. (upper) The default view. (lower) The sequence of attributes is interactively reordered. The user brushes regions involving the flow with the highest positive velocity along x and z axes, and the selected polylines are highlighted in fuchsia. Color is mapped to velocity magnitude.

discuss these information visualization views in more detail.

3.1. Histogram Table

In order to quickly and efficiently present a large amount of multidimensional data, it is desirable to provide a quick overview of the whole data set. For this, we incorporate a histogram table. The histogram table represents the distribution of multidimensional information across the data set in an interactive visualization. As illustrated in Figure 3, the histogram table consists of a stack of histograms. Each individual histogram describes the distribution of a given simulation attribute. The name of the attribute is indicated as well as minimum and maximum values. The number of frequency intervals (bins) is defined by the user. The height of each bar is mapped to the volume of the mesh containing the data. Data range is color-mapped. Red dash labels indicate the negative values, while blue zero labels are applied to highlight the categories ranging from negative to positive.

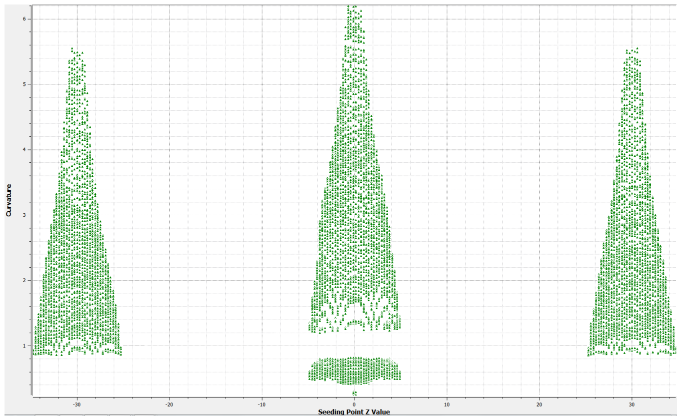

Figure 6: The streamline plot details the swirling rate of each streamline. The selected points on the plot are highlighted in red

Based on the histogram table, users can interactively brush or multi-select bars (categories) they deem interesting or important, and thus other visualization views are updated and rendered simultaneously to provide details based on the selection. A user option is implemented to render the histogram table in landscape or portrait mode for better layout of linked views. For a more detailed interaction to analyze inter-relationships between CFD attributes we provide a linked parallel coordinates view.

3.2. Spherical Velocity Histogram

We have a view called the spherical histogram for an integrated view of velocity distribution in a spherical coordinate system. See Figure 4. This is likely the most distinctive feature of our system in comparison to other state-of-the-art systems such as SimVis. The velocity distribution is useful for the user to explore the direction in which the majority or minority of velocity points. Although both the histogram table and the parallel coordinates plot have v_x, v_y, and v_z attributes to indicate the velocity distribution, a spherical representation is more intuitive because the x, y and z vector components are integrated. The spherical histogram is based on a sphere whose bin resolution can be customized by the user. Each cell of the sphere wireframe represents a direction range. The height of the stack corresponds to frequency of vectors pointing in this direction. We use a rainbow-like color mapping in order to match that of Tecplot. Users can thus compare visualizations.

3.3. Parallel Coordinate Plot (PCP)

A PCP is also integrated to help the user analyze and explore the multivariate data. The advantage of a PCP is that it facilitates identification of correlation and clusters. We can have 15 parallel axes which represent simulation attributes. See Figure 5. The axis ordering may be changed by the user. Each axis reflects the distribution of a specific attribute. The name of the attribute is labeled with minimum and maximum values. When the user brushes or multi-selects categories from the histogram table, the PCP is updated to offer a detailed view of the selection. The user can examine polylines and may find some interesting correlation of variates. For example, all the samples with high velocity magnitude are associated with low pressure. Additionally, the PCP also enables the user to brush polylines of interest. Selected samples are highlighted in the spatial visualization to offer a more precise view of the area of interest. As future work, we would like to incorporate frequency-based angular histograms [7] for better clutter reduction.

3.4. Streamline Plot

Additionally, a novel streamline plot view is added to investigate specific streamlines based on swirl. During the streamline integration, the curvature is measured at each streamline vertex based on the angle formed by the line segments joined there. Once the streamline integration is finished, the sum and the average of the curvature are stored at their respective seed positions. The higher the value is, the more swirl the streamline represents. We plot these values onto a scatter plot whose x axis is mapped to the seed's z coordinate and y axis maps to the curvature. See Figure 6. Each point on the plot presents a streamline. The user can select any point from the plot. The corresponding streamlines are rendered in the spatial view for further exploration.

3.4.1. Information Assisted Streamline Seeding

The spatial view renders the 3D result, for example the mesh, color-mapping vector glyphs and streamlines, according to the user-specified filtering in the information visualization views. To enhance the visualization clarity, knowledge-assisted and information-based streamline seeding can be applied.

One of the commercial visualization packages used by engineers at our university is Tecplot. Tecplot offers streamline seeding rakes which can be used to manually seed streamlines throughout the domain. The user manually positions and orients a seeding curve in 3D space searching for an interesting location. This is time-consuming and error-prone. A manual search does not guarantee that the users discover the features they are looking for. Although fully automatic seeding strategies exist - engineers will always want control over the seeding. This is because complete knowledge of how any automatic algorithm works is required for correct interpretation of the result. Plus, not all features of interest can be known a priori and then extracted. Our system enables the user to seed streamlines based on the knowledge of the domain expert and the information provided by the histogram table, velocity histogram, streamline plot and PCP. See Figure 7. We illustrate some case scenarios in the next section. Figure 8 shows streamlines seeded all around a rotor's periphery.

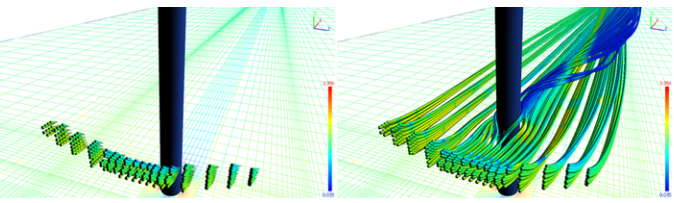

Figure 7: Glyphs (left) and knowledge-guided streamlines (right) are seeded to visualize the behavior of the flow with maximum velocity momentum in negative y direction. The flow starts down toward the bottom and then it turns upward after it passes the pylon.

4. Application Use Case Scenarios

In this section, we apply our application to specialized turbine-centered scenarios in order to answer questions raised by the engineers, and demonstrate how engineers benefit from its use during the analysis process, as well as being able to obtain new findings which conventional commercial visualization tools, like Tecplot, may overlook. To highlight the difference our application makes, a comparison to the use of Tecplot is discussed.

4.1. Visual Analysis of Swirling Flow

Swirling flow is important in this application because it indicates torque on the turbine blades. This in turn is a measure of rotor performance. Quantifying, analyzing, and visualizing swirl can aid in rotor design.

To locate where the most swirling flow occurs, the tangential velocity about the rotor axis is studied by the domain experts for the swirl quantification. In order to calculate the tangential velocity $\mathbf{v}_t(\mathbf{p})$ of the given sample point $\mathbf{p}$, the yz-plane which includes $\mathbf{p}$ is drawn. The tangential unit vector $\mathbf{e}_t$ is the normalized cross product of the rotor axis $\mathbf{R}$, and the vector $\mathbf{PA}$, where $\mathbf{A}$ is any point on the rotor axis. The tangential velocity is the inner product of $\mathbf{v}(\mathbf{p})$ and $\mathbf{e}_t$.

$$\mathbf{e}_t = \frac{\mathbf{R} \times \mathbf{PA}}{\|\mathbf{R} \times \mathbf{PA}\|} \tag{1}$$

Now the magnitude of the tangential velocity $\mathbf{v}_t(\mathbf{p})$ which we use to measure the swirling flow can be calculated by:

$$\mathbf{v}_t = \mathbf{v}(\mathbf{p}) \cdot \mathbf{e}_t \tag{2}$$

We compute equation (2) for every sample of the simulation result. The derived tangential velocity field is stored as an additional attribute of the data. We plot the tangential velocity in the histogram table and PCP so that engineers can analyze the swirling flow. In Figure 8, we simply select histogram bars representing high swirling flow about the axis of the nearest rotor from histogram table and a group of median swirling flow for comparison. The PCP is updated to reveal the relationship to the other simulation attributes. We focus on the flow about the center rotor by brushing the corresponding position from the PCP. Most of the swirling flow has comparatively high velocity magnitude. The streamline visualization depicts the origin of the swirling flow and how it evolves. When we showed the domain experts the visualizations in Figure 8, they were immediately surprised that the streamline seeds exhibit asymmetry. They expected complete symmetry. Further investigation is required to identify the source of the asymmetric swirl flow behavior. The streamline plot provides a detail view of the curvature of each streamline. The periodicity in the streamline plot obviates the periodicity of the swirl behavior in the flow domain. By selecting the point we deemed interesting, the spatial view is updated to highlight the selected streamline.

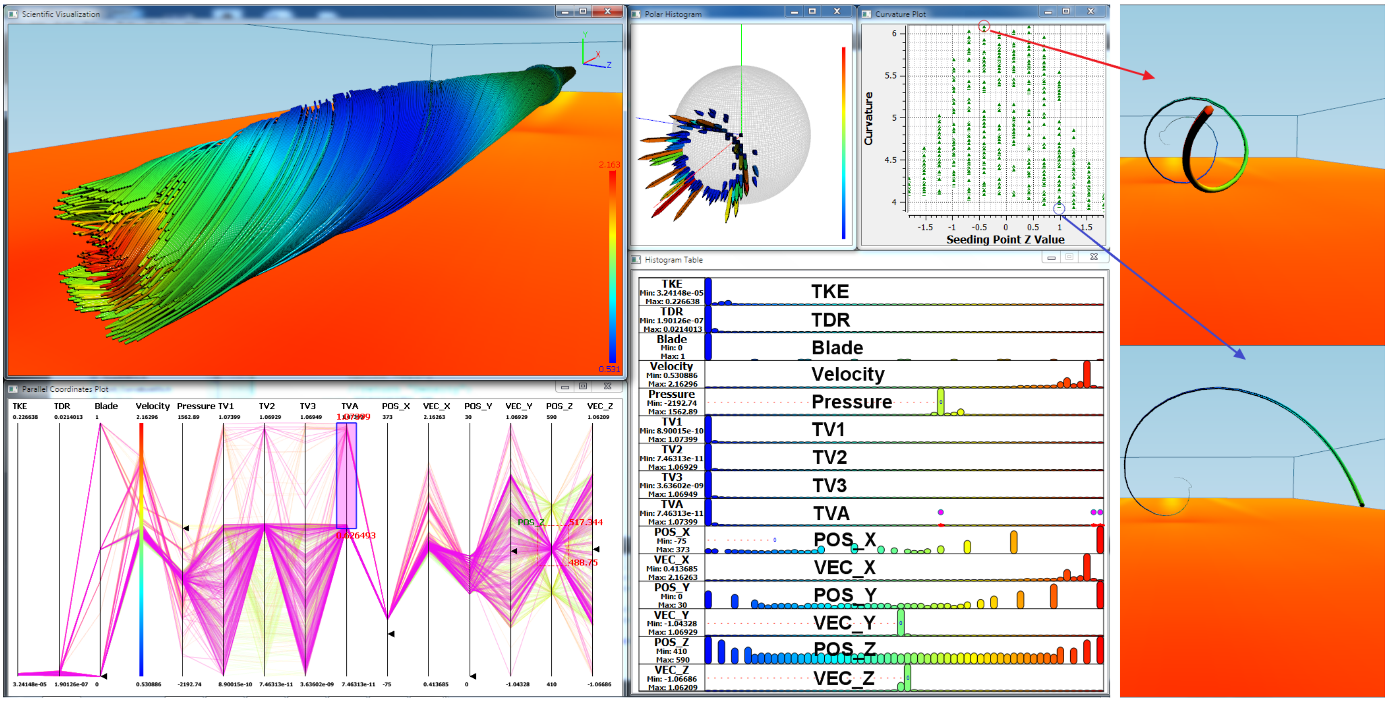

Figure 8: The swirling flow about the axis of center rotors is derived and analyzed. TVA indicates the tangential velocity of the nearest axis. TV*n* indicates the tangential velocity about the axis of rotor *n*. For example, TV2 shows the tangential velocity about rotor 2's axis, at the center in this case. By selecting the center rotor from the PCP, streamlines are rendered which demonstrate the behavior of flow about the center rotor. The streamline plot also provides a diagram showing the curvature of each streamline. By selecting the streamlines with highest and lowest curvature, the linked spatial visualization is updated.

4.2. Areas of reverse flow

To visualize how the flow past a marine turbine behaves and how the pylon design impacts on the passing current, a visual query for reverse flow is provided to illustrate the analysis process. Reverse flow is deemed detrimental because it draws useful kinetic energy from the overall flow current. Minimizing the reverse flow is one of goals for the optimal blade and pylon design. However, locating and visualizing reverse flow in the simulation result and investigating its behavior is a challenge for engineers using conventional visualization tools.

Tecplot provides a manual selection as a basic analysis approach. The user can click on the geometry to retrieve the corresponding simulation data attributes. However, it is difficult and time-consuming for the user to manually search for reverse flow. We can use its seeding rake to generate streamlines to visualize the flow. But the placement of streamlines seeds is manual. A manual search of the domain with a seeding rake is time-consuming and error-prone.

In the system we have developed the histogram table provides the user with an intuitive and quick overview of the information contained in the simulation data. The user is able to select negative vectors along x axis (reverse flow), by simply brushing the corresponding bars in the histogram table. See the highlighted bars in Figure 9 (top). The computation is concentrated on the user selection. The PCP conveys the correlation between different attributes of the reverse flow and the spherical histogram renders the distribution of reverse flow in the spherical coordinate system. Streamlines in scientific visualization view are seeded in regions which contain reverse flow and traced to depict its behavior. See Figure 9. Additionally, by interacting with other attributes from the PCP view, the initial selection can be analyzed.

4.3. Optimal Placement of Turbines

Maximizing the energy drawn from the passing tide while minimizing the number of turbines is one of the key challenges the engineer faces. The amount of the kinetic energy drawn from the tidal current may depend on where the marine turbine is positioned, especially with respect to surrounding turbines. Engineers would like to pack turbines as closely as possible to maximize the amount of energy converted from the tidal currents. However, placing turbines too close together makes them ineffective because an upstream turbine reduces flow momentum for those downstream. Thus a trade-off is made. In order to explore the impact of turbines in proximity to one another and determine how closely multiple turbines can be placed in a given region, a query concerning spatial extent of tidal current is input to explore how much energy each turbine can extract and how the flow recovers after passing each blade. In order to answer this question, we use isosurfaces to visualize the spatial extent of tide momentum.

Isosurfaces are useful in order to help CFD engineers study boundaries of the fluid flow around objects. Isosurfacing is a standard visualization tool in commercial visualization toolkits. The flow along x-axis in the positive direction is that which the turbine can draw the most energy from. Simulation experts consider flow that has recovered 90 % (or more) of its momentum with respect to the average current (represented by

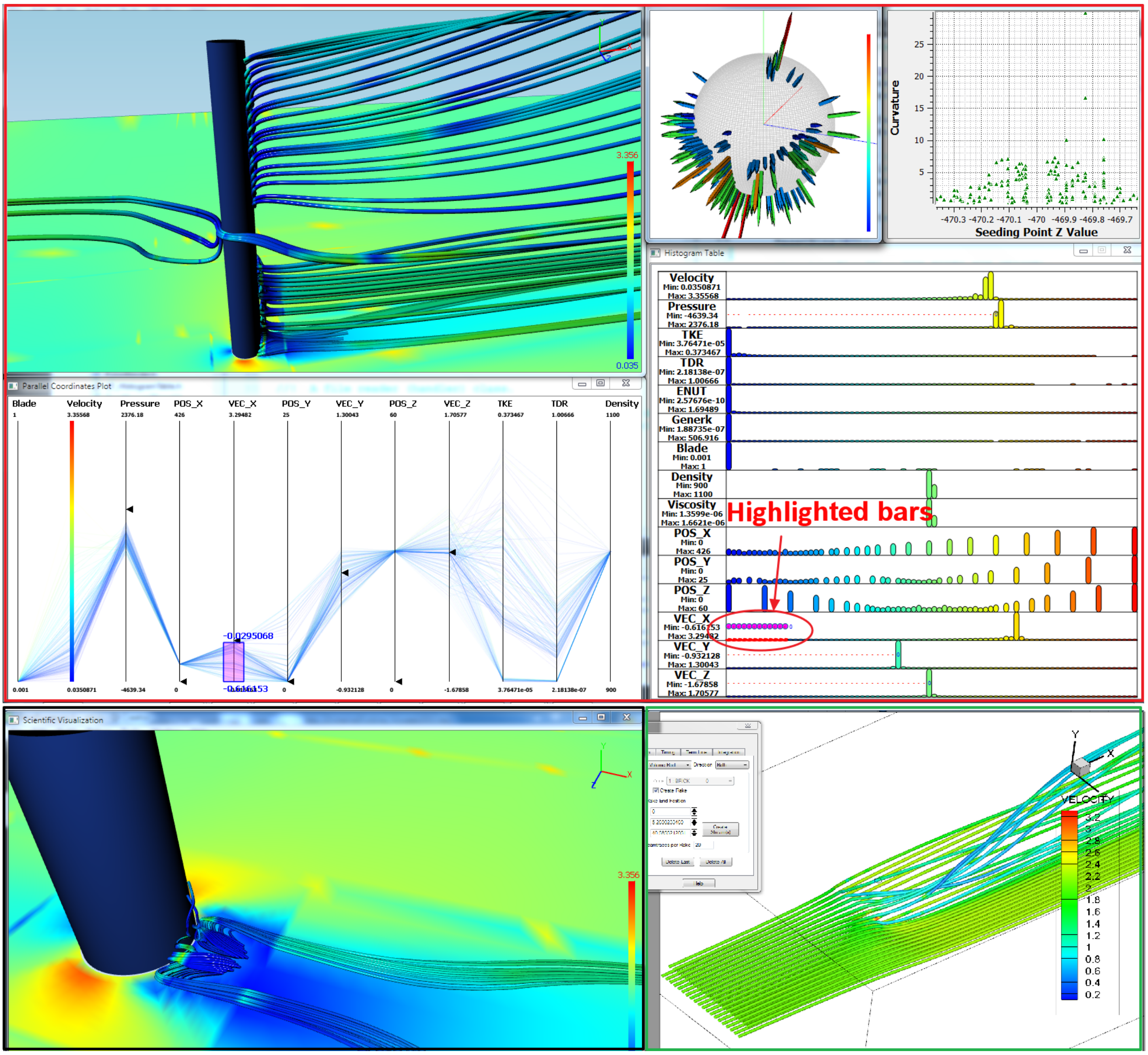

Figure 9: This scenario extracts and analyzes reverse flow. (top) In our framework, the reverse flow can be intuitively obtained from the histogram bars which contain negative velocity values. Streamline seeds are automatically placed based on the selection only in order to visualize the behavior of the reverse flow past the pylon. (bottom-left) The closeup view on the region near the bottom of the pylon. (bottom-right) Streamlines are traced from manually seeded seeding rakes in front of the flow domain in Tecplot [8].

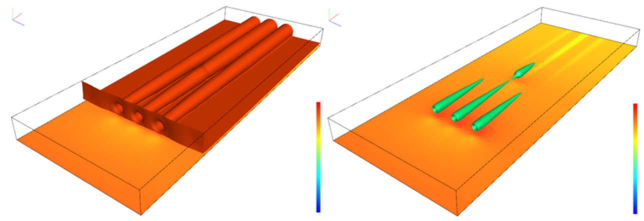

Figure 10: Isosurfaces depict the spatial extent of the tidal flow passing around turbines. (left) We choose 90 % of the inlet flow as the isovalue to trace the isosurface. We learn that the first three turbines are more efficient than the one downstream. (right) Then we decrease the isovalue to 35 %. We find the one downstream can only draw up to 35 % of the energy from passing flow.

the inlet) to be a good candidate for converting kinetic energy to be stored in the turbine. When we choose 90 % of the inlet flow as the isovalue, corresponding isosurfaces in Figure 10 depicts that three front turbines can draw most energy out of the passing flow. The flow behind the front three turbines does not return 90 % of its original momentum with the current domain. In fact, the volume of influence increases downstream in this example. The turbine downstream can not draw energy out of flow effectively. We reduce the isovalue to 35 % of the inlet flow and the corresponding isosurface. Figure 10, illustrates that the isosurface for the front-middle turbine ends just before the one downstream. This visualization illustrates the spatial extent that the marine turbines have with respect to the surrounding tidal momentum. If flow momentum has linear behavior the downstream distance between turbines must be 2-3 times greater. More simulation is necessary to confirm this hypothesis.

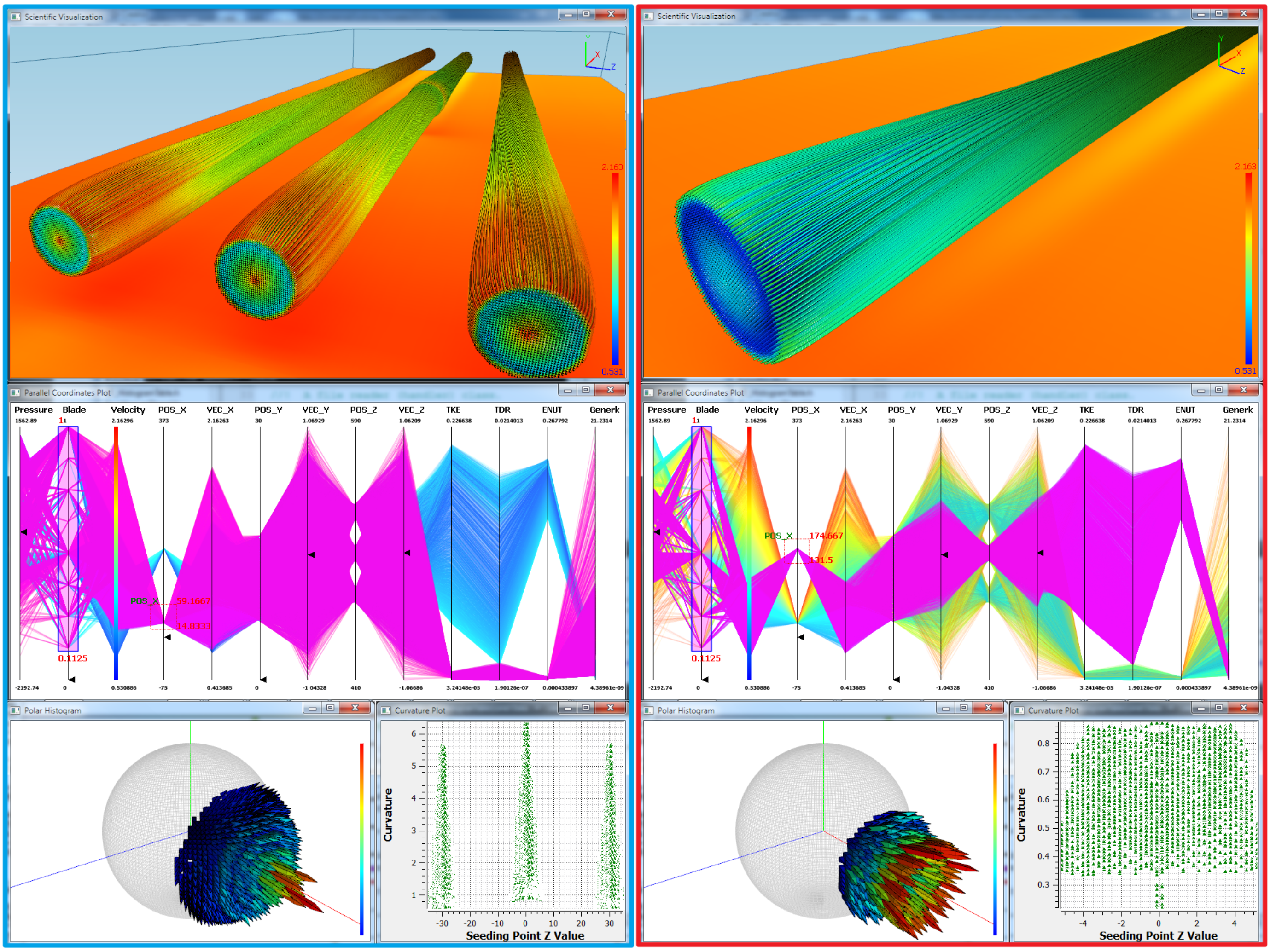

Figure 11: This scenario analyzes if the placement of turbines is optimal. We select bars representing blades in the histogram table, and blade elements are rendered in the spatial view. (left column): We brush front rotors from PCP by selecting corresponding values from *pos_x*. The spherical histogram shows most of the flow hitting blades travels in the positive *x* direction, which has high velocity but low TKE and TDR. (right column): The turbine downstream is selected. The majority of the associated flow has comparatively low energy but high TKE and TDR. Streamlines are traced to visualize the behavior of the flow respectively.

4.4. Flow Past the Time-Averaged Blades

In order to enhance the user's understanding of the correlation between attributes of each turbine, our customized multiple linked views system provides a more flexible and effective interface to the simulation data. We focus on the flow which directly contacts the turbine. We brush bars representing the blade in the histogram table and the corresponding flow is conveyed. The four blade elements are displayed in the scientific visualization. The spherical histogram shows that majority of the flow hitting the blade travels in the positive *x* direction. The PCP reveals the details of the attribute correlation for the user selection. The color legend is mapped to flow magnitude. In order to isolate and analyze the flow contacting the front turbines only, we brush front blades from the PCP. See Figure 11. The highlighted polylines illustrate that the majority of the passing flow contains high velocity (see polyline distribution for *velocity* and *vec_x*) while the turbulent kinetic energy (TKE) and turbulent dissipation rate (TDR) are comparatively low. We trace streamlines to visualize how the flow behaves in Figure 11. When we select the downstream blade from PCP we find some interesting features. The majority of flow has comparatively low energy (velocity) and the corresponding TKE and TDR are high. From the spherical histogram, we can see that the majority of the flow does not move straight toward the turbine, which is not ideal for energy extraction. Streamline seeding is also applied. See Figure 11.

4.5. Areas of Min/Max Pressure

In order to locate and analyze flow with minimum or maximum pressure, a scenario is provided to demonstrate this. We brush the minimum and maximum pressure values from the histogram table. See the highlighted bins in Figure 12. The spherical histogram reveals that most of the flow travels in the positive *x* direction. The PCP is also updated to show the correlation between each attribute with the color mapped to pressure. We start with the minimum value of the negative pressure by brushing it in the PCP. See Figure 12. The highlighted polylines reveal that the flow with high negative pressure has comparatively high velocity in the positive *x* direction. However, for the maximum

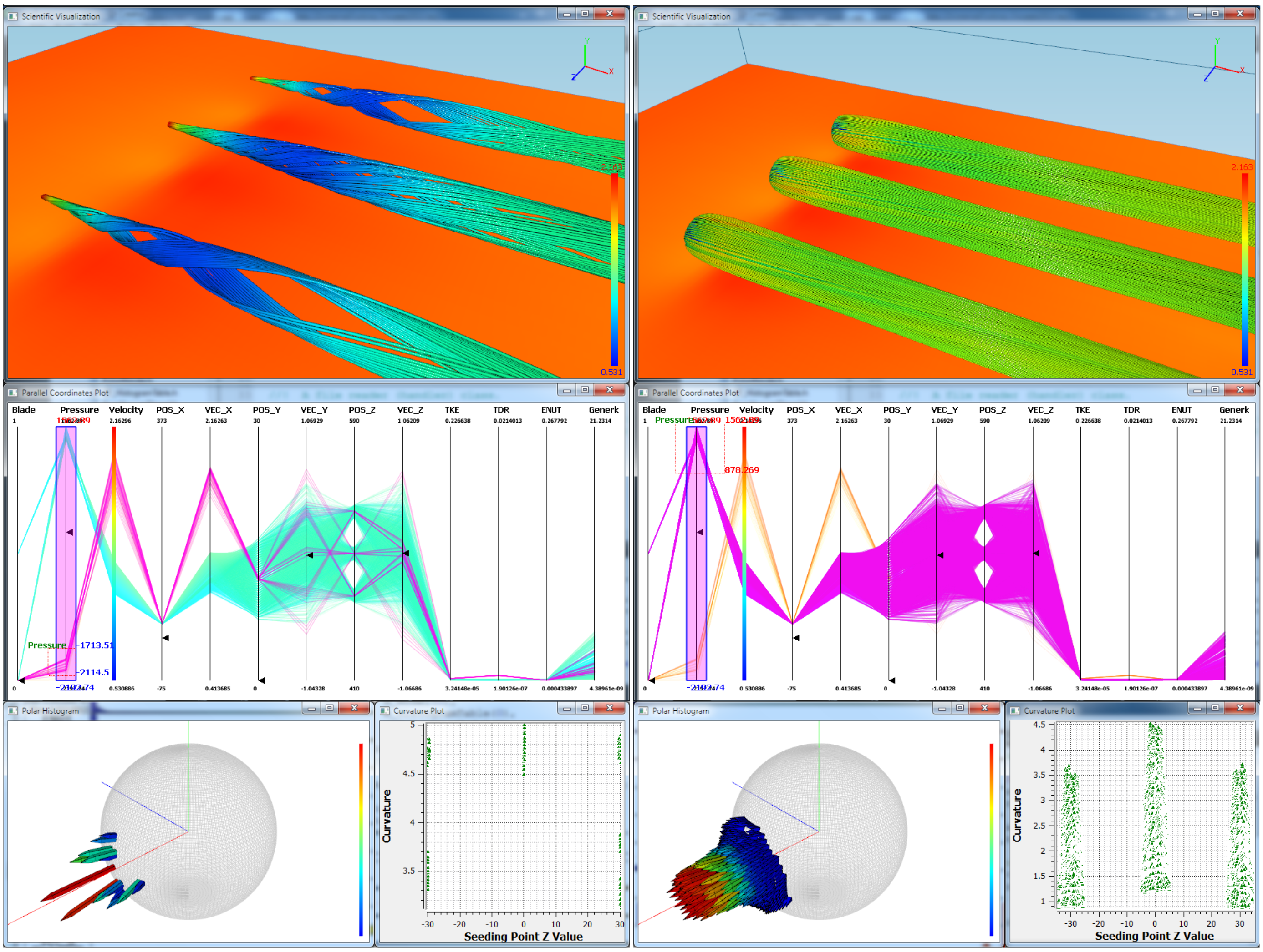

Figure 12: The flow with the minimum or maximum pressure is selected and visualized for analysis. (left column) The flow with high negative pressure is depicted, while (right column) the maximum pressure is illustrated. Streamlines are used to reveal the flow behavior. Zooming views are obtained: flow with the minimum or the maximum pressure.

pressure we find that the corresponding flow occurs around turbines and contains average energy. See Figure 12. Streamline visualization is used to depict the path of the flow.

5. Related Work

Here we present related work with the theme of coordinated, multiple, linked views. Henze presents a multiple, linked view based system, called Linked Derived Spaces [9], to visualize and analyze time-dependent CFD datasets. The objects from datasets can be interactively examined in various coordinate systems according to data attributes, such as velocity, pressure, kinetic energy etc., while the spatial connectivity and temporal characteristics are preserved. Inspired by this, we implement some customized interactive information-based views: spatial visualization views and information visualization views to help engineers gain better understanding of the marine turbine dataset.

In order to make the design of a multiple view based system more systematic and efficient, Baldonado et al. [10] present a set of guidelines for the design of multiple view systems. The first four guidelines (diversity, complementarity, parsimony, and decomposition) provide the designers with suggestions on selection of multiple views. The last four (space/time resource optimization, self-evidence, consistency, and attention management) help designers make decisions on view, presentation, and interaction. We designed our system to be consistent with these guidelines.

WEAVE [11] provides transparent linking between custom 3D scientific visualization and multidimensional statistical representations with interactive color brushing for the user to select interesting regions. WEAVE is used to analyze and visualize simulated data of a human heart to allow scientists to more effectively and interactively study the structure and behavior of the human heart.

Kosara et al. [12] present an approach called the TimeHistogram as an extension to the traditional histogram which takes time into account for large and complex data sets. The 3D histogram is generated by arranging a number of regular 2D histograms along a third time axis to give users an intuitive overview of the development of a dimension over time. This is partly the inspiration behind the histogram table view feature in this paper.

Stasko et al. [13] present a visual analytic system called Jigsaw, which provides an analyst with multiple perspectives (views) on a document collection. The system mainly focuses on exploring connections between entities across the documents and then applying a type of visual index onto the document collection for better investigation.

A technique powered by cross-filtered views is presented by Weaver [14] for visual analysis of multiple dimensional international political event data. Cross-filtering is focusing on fast and flexible interactive visual analysis on fine-grained relationships buried in massive information from multiple data sets. By cross-filtering data values across pairs of views, analysts can quickly and interactively express sequences of multidimensional set queries to obtain the relation information they deem interesting. In our work, a parallel coordinates view helps the user explore and analyze multidimensional CFD data.

Kehrer et al. [15] discuss opportunities for the interactive visual analysis of multi-run climate data. This is based on the integration of statistical aggregations with selected data dimensions in a framework of coordinated multiple views. Traditional and robust estimates of mean, variance, skewness, and kurtosis statistical moments are integrated in an iterative visual analysis process as well as measures of outlyingness. Our system also includes visualization of derived attribute data.

In order to alleviate the modifiable areal unit problem during geospatial analysis, Butkiewicz et al. [16] present a probe-based interface with coordinated multiple views for the exploration of the results of a geospatial simulation of urban growth. Firstly, the interface alerts the user if any potential unfairness is found during region based comparison. Then problem outliers are provided for user to evaluate. Lastly, semi-automated tools are provided to help the user to correct the detected problems. In contrast our work focuses on computational fluid dynamics (CFD) simulation data.

Busking et al. [17] present a technique with multiple strongly-linked views for visual shape space exploration and validation. The 3D object view provides local details for a single shape, while the high dimensional points in shape space are applied in a 2D scatter plot to offer the global aspects. They introduce a new view called shape evolution view which visualizes the shape variability along a single trajectory in shape space. We incorporate derived data that enables the user to make streamline-based queries based on shape (i.e curvature).

Piringer et al. [18] introduce HyperMoVal as interactive visualization of 1D CFD simulations to support multiple tasks related to model validation. HyperMoVal can be linked to other views and further extends the possibilities for comparing known and predicted results, investigating regions with a poor fit, assessing the physical plausibility of models also outside regions covered by validation data, and comparing multiple models. Our work is also focused on CFD simulation data.

Wang et al. [19] present an interactive visual analytics system based on multi-linked views as an extension to current bridge management systems. This system enables bridge managers to customize the visualization and data model so that it can provide interactive exploration, information correlation, and domain oriented analysis to fit different needs. Another similar work is presented by Keefe et al. [20] to visualize the biomechanical motion data.

With the exception of Henze [9] and Piringer et al. [18] all of the above systems focus on non-CFD applications. The most closely related system to ours is called SimVis. Doleisch et al. [21][22] present the SimVis application for interactive visual exploration and analysis of large, time-dependent, and high-dimensional data sets resulting from CFD simulation. Instead of the traditional automatic feature extraction, SimVis provides more freedom and user options to gain new insight into the data. Information visualizations include simple 2D/3D scatterplots, time-dependent histograms [12], and parallel coordinate plots. The application also includes a fuzzy classification to make the transition from selected to non-selected regions smoother. SimVis is used in several case studies and application examples. Many of them are automotive [23][24].

We also note the related work of Shi et al. [25] and Salzbrunn et al. [26] on the use of pathlines for flow visualization.

Comparison with State-of-the-Art In this paper, we present a framework which is comparable to SimVis, however, our system is distinct from SimVis in the following ways:

- Our system is able to process and visualize the simulation data directly from Tecplot 360 [8], the commercial visualization toolkit used by engineers at our university. No data conversion process is required. This is important due to the large data set sizes which can be several gigabytes in size. Thus we do not want to store a converted copy of the data.
- The multiple-linked views are especially customized according to the engineer's needs for interactive exploration of the simulation of flow past the marine turbine, a novel application.
- We introduce a novel streamline plot and a new 3D spherical velocity histogram (inspired by the 2D equivalent in MATLAB) to facilitate analysis on swirling flow and its behavior during evolvement.
- A histogram table provides a complete overview of the high-dimensional data.

Comparisons and references to Tecplot 360 are presented because this is the software the engineers we work with actually use. SimVis does not feature a histogram table, spherical histogram, or streamline plot. Additionally, since the size of the simulation datasets here is non-trivial, maintaining the smooth user interaction and rendering a large number of selected objects simultaneously is a challenge. In order to address this and deliver a good user experience, we develop a multi-threaded scheme inspired by Piringer et al. [27] for our system. Users can interact with the visualization result even as it is still being generated in the background.

6. Domain Expert Review

This work was done in close partnership with three CFD domain experts studying marine turbine optimization (Rami Malki, Ian Masters, and Nick Croft of Swansea University). The following domain expert feedback is provided by these three specialists.

Computational simulation often produces result files that contain relatively little data of significance. From the engineer's perspective the primary aim of visualization is to cut through the irrelevant data to highlight the important features. This highlighting comes with two main aims, to explain and to understand. These two aims come with slightly different constraints on the visualization software. Most commercial visualization software provides a solution route for the first aim. This solution requires accurate physical representation of the geometric data as well as informative representation of the data either through techniques such as contours, glyphs, streamlines or isosurfaces. For the engineer to explain data there is a requirement to understand it and this is a task that is harder to achieve through the use of commercial packages.

Understanding data often requires the loosening of the dominance of the spatial data that is fundamental to the explanation. One of the basic techniques of simulation involves the placement of many data points in areas of rapid change, which are usually areas of interest. Being able to 'see' this data often requires significant zooming into the data. This hides the relationship with the rest of the solution domain. Spatial data may play a very secondary role in some understanding where the fundamental questions concern the relationship between two variables. The PCP offers an excellent route to investigate the question such as what is the effect on other variables, specifically turbulence, of reverse flow. The multiple displays then provide a route back to the spatial relevance which will be part of any explanation.

The modeling of tidal stream rotors has beginnings in the work of Goldstein [28] who first applied this to helicopter rotors. This classical momentum theory describes the interaction of the rotor in terms of horizontal and tangential interference factors. The authors have applied this successfully to the tidal energy case [29]. It is of great benefit for the performance design of rotors to be able to describe CFD results in the same terms. However, the nature of the CFD formulation means that results are described on the individual nodes of individual cells. Therefore there is a strong motivation to recover information equivalent to the interference factors. Axial interference can be relatively easily obtained from the velocity information, defining velocity deficit as the difference between local velocity and the upstream conditions. It is obvious to see how this can be described as an additional parallel coordinate axis. Swirl is less intuitive and the results presented here have two important features: firstly the term is defined in a mathematical way that is consistent with the classical approach of momentum theory, and secondly it recovers the global rotor flow features from the discretised cells. This novel approach is of great benefit to the user and the intelligent information this provides is vital to the engineering design of these systems.

7. Conclusion and Future Work

In this paper we propose a novel application which exploits multiple-coordinated views for interactive information-assisted visualization of marine turbine simulation data such that engineers can gain a fast overview and intuitive insight. The system includes an interactive spherical histogram of velocity, a histogram table view for an overview of the CFD data, an interactive parallel coordinate visualization, and a streamline plot which provide further analysis and exploration. Information-based streamline seeding quickly and automatically visualizes the behavior of the flow deemed interesting by the engineer. The information-assisted views of the data have helped domain experts discover new properties of their data which they were previously unaware of, e.g. the asymmetric characteristics of the flow intersecting the turbine blades. Multi-threading makes the interaction between the system and the user smooth and efficient. The comparison between one of commercial off-the-shelf visualization tools – Tecplot [8] and our system is provided in the case scenarios which are designed to answer core questions brought forth by engineers in order to demonstrate that our system is more suitable for this task. We also report feedback from CFD experts researching the simulation of flow past the marine turbine.

We also would like to explore possibilities of transferring more of the computation to the GPU. Additionally, extending the work to visualize the time-dependent marine turbine flow is an interesting future direction. Future work also includes the investigation of possible applications on other domains, such as wind turbines. A more extensive user evaluation would also be a good future work contribution.

8. Supplementary Video

A complete high-resolution project supplementary video can be found from the professional video-sharing website - Vimeo. Readers are strongly encouraged to view it online. The link is: http://www.vimeo.com/21766028.

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