Visualization of Vortex Core Differences between Ensemble Simulations

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ABSTRACT

We developed a set of visualization tools for analyzing the differences in stall development of three Computational Fluid Dynamics (CFD) simulations in a centrifugal pump. We developed a hybrid method to identify and track vortices over time, visualization techniques for reducing occlusion introduced by non-vortical flow within centrifugal pumps, encoding the evolution of vortex positions, sizes and orientations for a single data set across time, and comparing the evolution of these features between multiple data sets across time. Finally we built a head-tracked stereo visualization system that allows the interactive exploration of our visualization techniques.

KEYWORDS: Vortex, Streamline, Ribbon, Flow Visualization.

1 INTRODUCTION

We developed a system to visualize the flow of three CFD simulation data sets provided by the 2011 IEEE Visualization Contest. These simulations, from the SST, DES and SAS methods, dealt with flow within a centrifugal pump [1]. In centrifugal pump design, efficiency during part-load operations is limited by instability caused by the increased separation of flow from the pump blades due to the low flow-rate. This flow separation causes unsteady vortices on the suction side of the blades, known as "stalls" [1].

The primary goal of the contest is the display of stalls, characterized by unsteady vortices and the efficient visualization of the movement of vortical structures in the flow, focusing on larger structures. Thus, the primary design goals of this system are: (1) identification of the unsteady vortices, (2) observation of the structure, position and axis of rotation of these vortices across time, and (3) observation of the flow structure surrounding the vortices.

To answer these questions, we developed (1) a hybrid method to identify and track vortices over time, (2) a visualization technique that displays vortex structures within contextual flow for individual time steps, (3) a visualization technique that encodes the evolution of vortex positions, sizes and orientations for a single data set across time, (4) a visualization technique that encodes the evolution of vortex positions, sizes and orientations for comparison between multiple data sets across time and (5) a head-tracked stereo visualization system that allow the interactive exploration of our visualization techniques.

2 VISUALIZATION TECHNIQUE DESIGN

Section 2.1 describes a visualization technique for displaying vortical structures with contextual flow with the goal of to minimizing occlusion and enhancing shape perception. Section 2.2 describes our custom single-data-set time-summary visualization technique to enable fast tracking of vortex position, size and orientation evolution across time for a single data set. Section 2.3 describes the ensemble data set time summary visualization technique we developed to enable fast comparison of the evolution of vortices between multiple (ensemble) data sets. Section 2.4 describes the vortex-identification algorithm used.

2.1 Single-Data-Set Time-Varying View

The complex geometry of a centrifugal pump introduces complex flow patterns. The design must enable the user to accurately perceive the shape of the coherent structures ("spatially coherent, temporally evolving vortical motions" [2]) within the flow but not introduce occlusion, which would prevent shape perception at a global extent. We (1) removed the display of flow in structures outside the rotors (which do not seem to contribute to stalls) and (2) de-emphasized and removed the display of flows in regions outside of vortices.

Figures 5-7 show time-varying vortex-flow overviews of each data set. Figures 8, 12(b) and 12(c) show close-up views of a single vortex. Figures 10,11 and 12(a) show regional views. The streamlines in this system are seeded at the pump blade geometry using forward interpolation and 5th order Runge-Kutta method with adaptive step size control from The Visualization Toolkit (VTK).

The prevalence of non-vortical flow in the pump causes occlusion of the vortical structures. To overcome this, we removed regions of streamlines with small winding angles [5]. Streamlines that were identified as being part of vortices are displayed using very thin tubes. Tubes were chosen over unlit lines because they enable clear occlusion (which shows relative depths of different vortices) as well as shape from shading (which shows the shape of a given vortex).

The tubes are colored by velocity or by winding angle with nearly isoluminant color maps to prevent shape distortion. When a red-green color map is used, a slight luminance variation between the red and green was included to account for color blindness.

Contextual flow: To enhance the perception of contextual flow while minimizing occlusion, streamlines originating from the pump blades are displayed using unlit white lines with low opacity. The opacity of these unlit streamlines is set to a very low

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value to render regions with coherent structures with higher intensity than regions without coherent structures – providing good shape perception of the global flow. This reduces self-occlusion as much as possible while still providing continuity of the flow vector field.

Only flow that originates from the area surrounding the pump blades are displayed; non-vortical flow in non-critical parts of the pump are eliminated.

2.2 Single-Data-Set Time-Summary View

Continuous vortex movement in animation as seen in the video can let the user follow a vortex, but it does not provide a good summary view. The appearance and motion of other vortices can be distracting and the user must remember the earlier locations and orientations of the vortex.

We developed a visualization technique to encode the evolution of position, orientation and size of the vortices within a single image. The vortex cores timeline encodes this information in the form of a very thin ribbon parameterized by time and vortex directions, with attached glyphs, which are scaled by vortex size.

Figures 2-4 shows a series of vortex positions over time. Figure 9 shows a close-up view of a single vortex. Rather than using point clouds of positions, a very thin ribbon provides the continuity over time, and provides cues indicating directional changes. To add perceptually-salient direction indication, cone glyphs are added. The variation in rotational axis is shown by the series of cones. By attaching these glyphs to the very thin ribbon, the change of rotation is associated with the corresponding time step.

2.3 Ensemble Time-Summary View

While the single-data-set time-summaries enable single-glance study of side-by-side views from the three data sets, the user is forced to hunt all over the image to compare each location separately. Research has shown that image details across separate scenes cannot be remembered except where viewers have most recently focused their attention [4]. When the viewer switches attention from one image to the other, change blindness occurs.

We developed a single-image summarization technique that displays the entire time series of each data set in one image. The time-line path of the vortex cores produced by the each simulation is visualized using ribbons. Each ribbon center moves from the initial time step through the final time step, tracking a single vortex. The local surface normal of the ribbon is aligned with the vortex core direction, and its length is proportional to the distance between vortex cores at adjacent time steps. Color is used to nominally code the vortices from each simulation and saturation is used to indicate time, enabling the viewer to study both spatial and temporal variation between simulations (Figure 1).

2.4 Vortex Identification

We applied the winding angle vortex extraction method [5] to streamlines segmented at the points where the distance along the streamline from its seed location switches between increasing to decreasing and vice-versa. Each segment is projected to the plane perpendicular to its rotation axis [6].

Spatial overlap and feature-matching were used in [7] and [8] to track vortices across time. We adapted these methods to cluster streamline-segments into individual vortices. We implemented two filtering passes: in the first pass, segments with overlapping axis-aligned bounding volumes are clustered into individual vortices; in the second pass, the axis-aligned bounding volumes are resized by the standard deviation of the x, y and z components of each segment's "neighbors"' geometric mean positions. Each segment's "neighbors" are defined as other segments with overlapping bounding volumes and similar vortex core direction, winding angle, and size across the x, y and z axes.

Iterating through each time step, we matched each vortex core at that time step with the nearest neighboring vortex core from the next subsequent time step. Vortex cores that do not have a neighboring vortex core within a predefined distance threshold in the next subsequent time step are not matched.

3 System Design

To maximize the comprehension of the complex 3D flow structures, a visualization system including head-tracked stereo (NVIDIA 3D Vision, 3rdTech HiBall), a 3-degree-of-freedom pointing tool (SensAble Phantom Omni) for streamline placement, and a 6-degree-of-freedom navigation tool (3DConnexion SpaceNavigator) were provided. These were integrated into a customized version of the open-source ParaView visualization tool along with custom filters for an interactive display of the visualization techniques.

The system enabled the rotation and translation of the dataset using the "world-in-hand" model to enable shape perception through motion parallax and kinetic depth perception [3].

Standard ParaView control panels enable the user to display the data sets using subsets of our visualization techniques. As seen in the video, the user can use the pointing tool to generate additional streamlines to explore regions that were not automatically selected based on vortex and rotor location. Natural motions of the head enable zooming in to study regions in detail and zooming out to see an overview.

4 Conclusion

We presented a set of custom techniques for visualizing ensemble simulations of complex flow. We integrated these visualization techniques into an immersive visualization system, allowing the user to observe the development of vortices, track the vortex directions and positions over time, and analyze the contextual flow around the vortices to understand why they developed. The attached images and video describe these insights.

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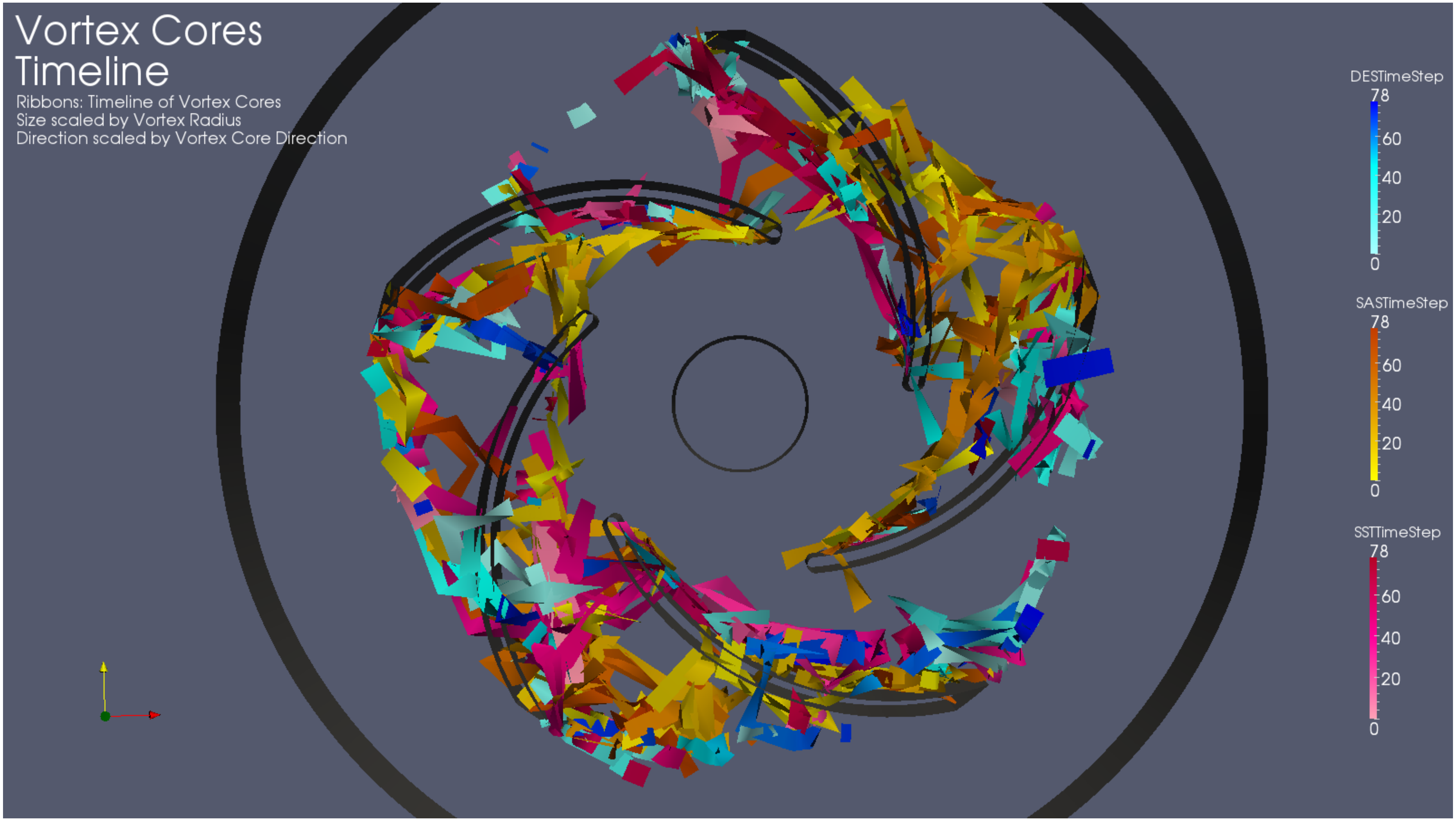


Figure 1: A ribbon-summarization technique displays the entire time series in one image with minimal geometry. The time-line path of the vortex cores produced by the each simulation is visualized using ribbons. Each ribbon center moves from the initial time step through the final time step, tracking a single vortex. The local surface normal of the ribbon is aligned with the vortex core direction, and its length is proportional to the distance between vortex cores at adjacent time steps. The SST ribbons are colored from light pink (early in the simulation) to dark red (near the end). The DES simulation is colored from light to dark blue and the SAS simulation is colored from light to dark yellow. This summary over time shows that the SAS simulation has a number of vortices in regions that the others do not (upper right) and that all three have vortices near the rotors.

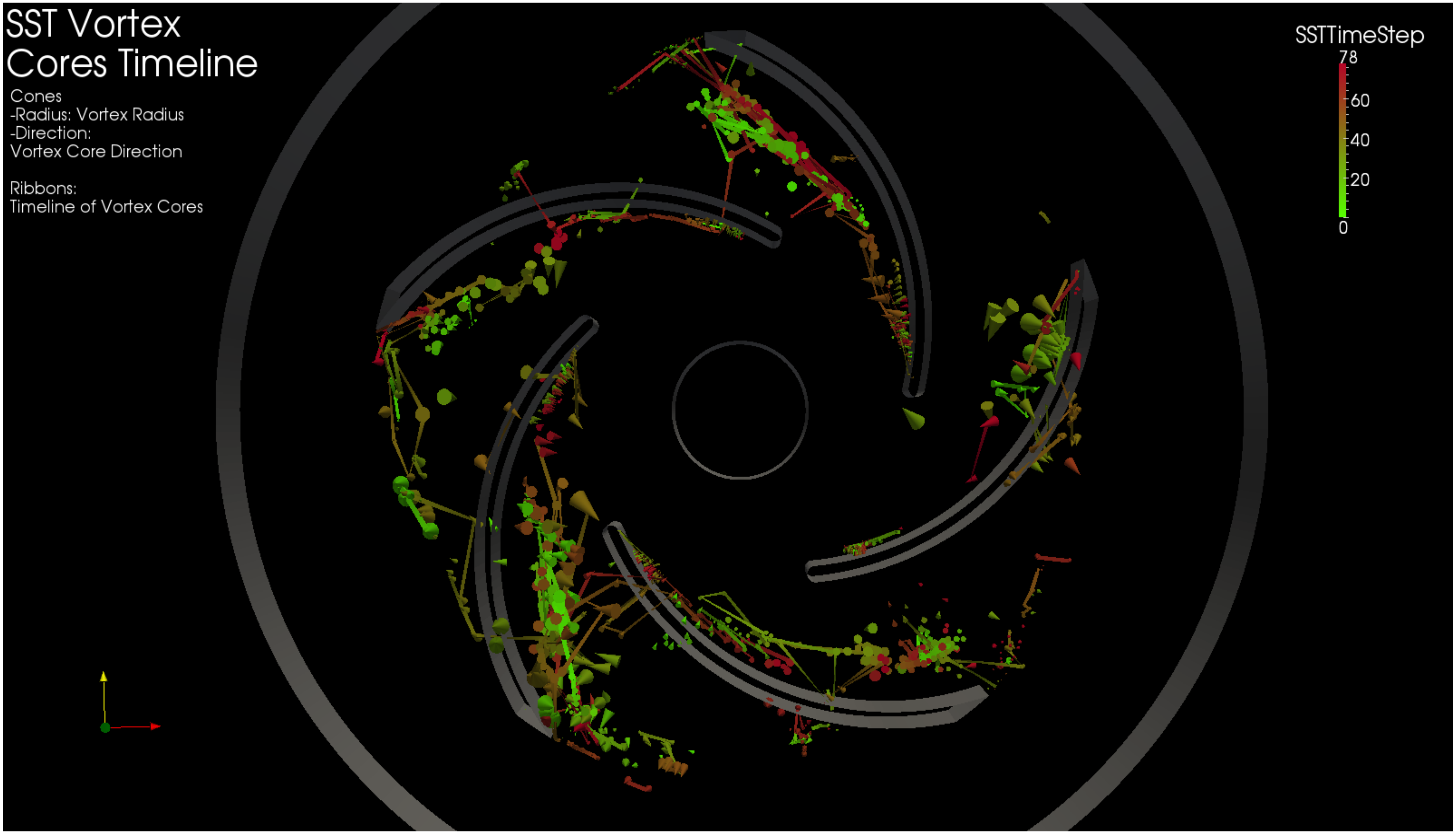


Figure 2: SST vortex core time-line summary. Each cone marks the position and orientation of a vortex core and the size of the cone is scaled by the vortex radius. Very thin ribbons connect vortex cores- each ribbon's center moves from the initial time step, colored in green, through the final time step, colored in red, tracking a single vortex. The black background is chosen because high contrast between the red-green color map and the background is needed to allow tiny vortex cores existing in the data set to be clearly visible. This summary can be applied to each data set individually and provides an instant overview of vortex location and motion. This summary display shows at a glance that there is more vortex activity near some rotors than the others and that the distribution along each rotor varies.

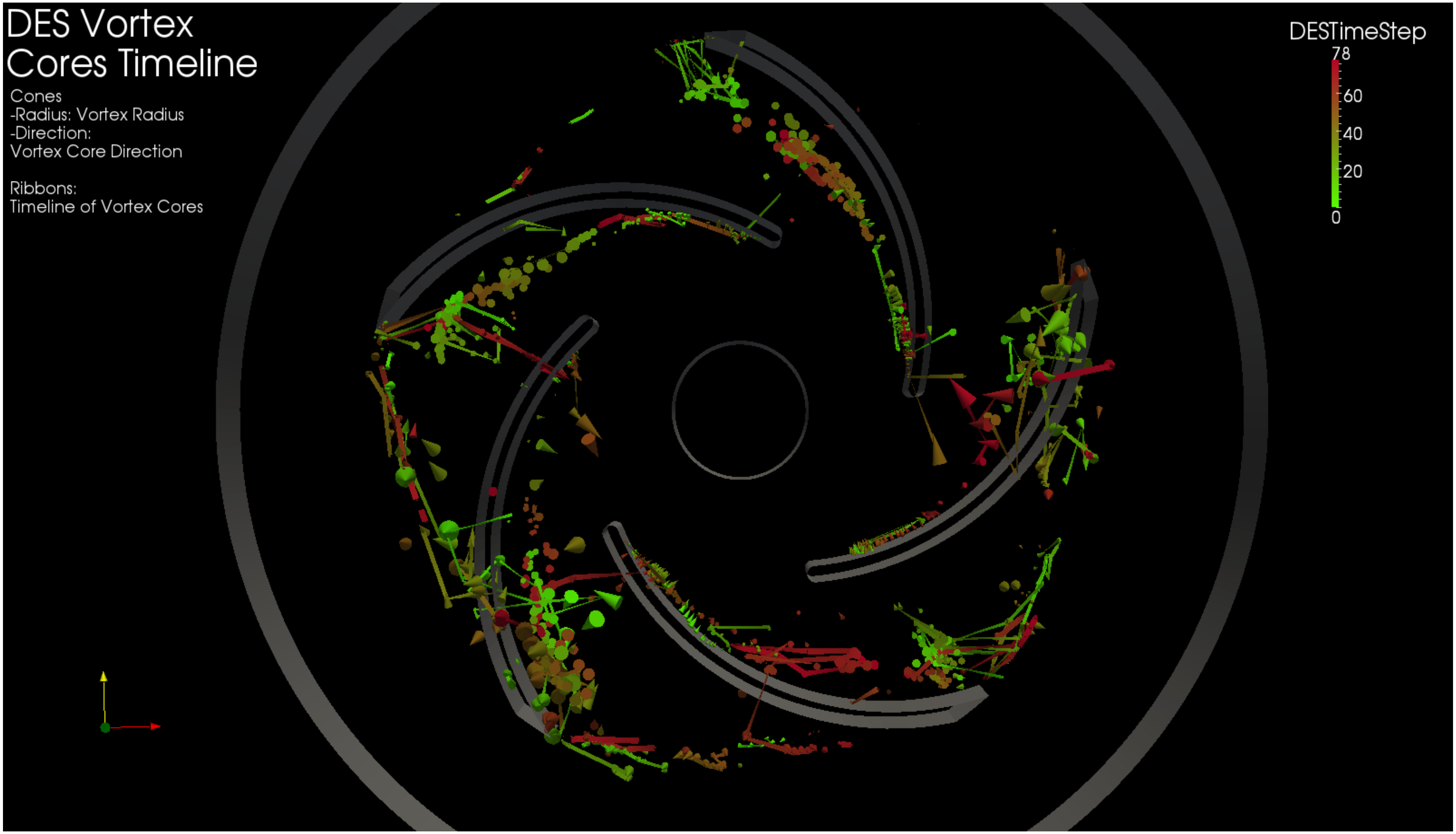


Figure 3: DES vortex core time-line summary, shown using the same technique. A vortex can be seen to move from the upper-left rotor to the leftmost rotor. Heterogeneity among the rotors is also clearly seen in this simulation.

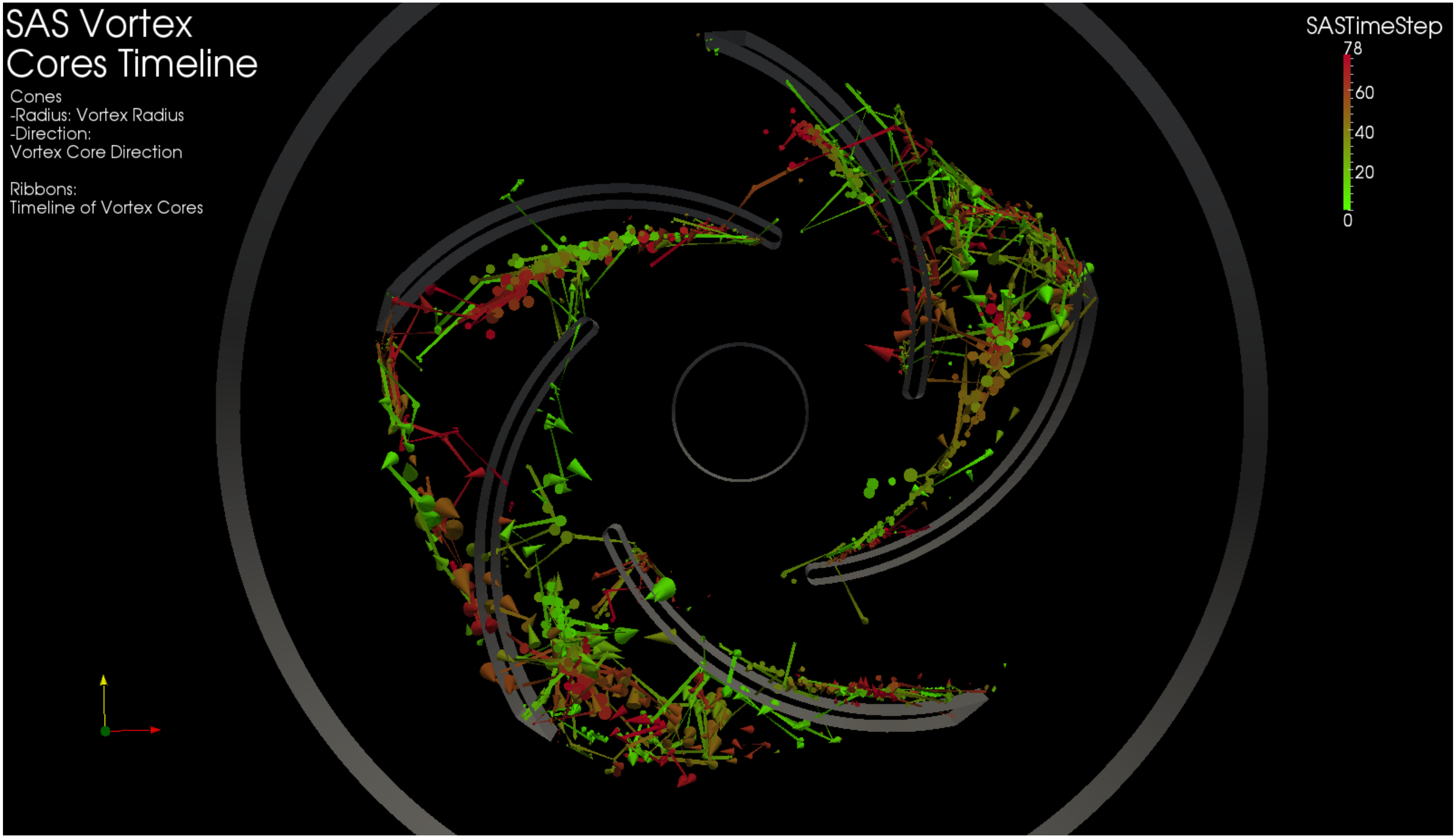


Figure 4: SAS vortex core time-line summary, shown using the same technique. This simulation has vortex motion bridging three of the gaps between the rotors and has two large regions between rotors almost completely filled by vortices during the course of the simulation.

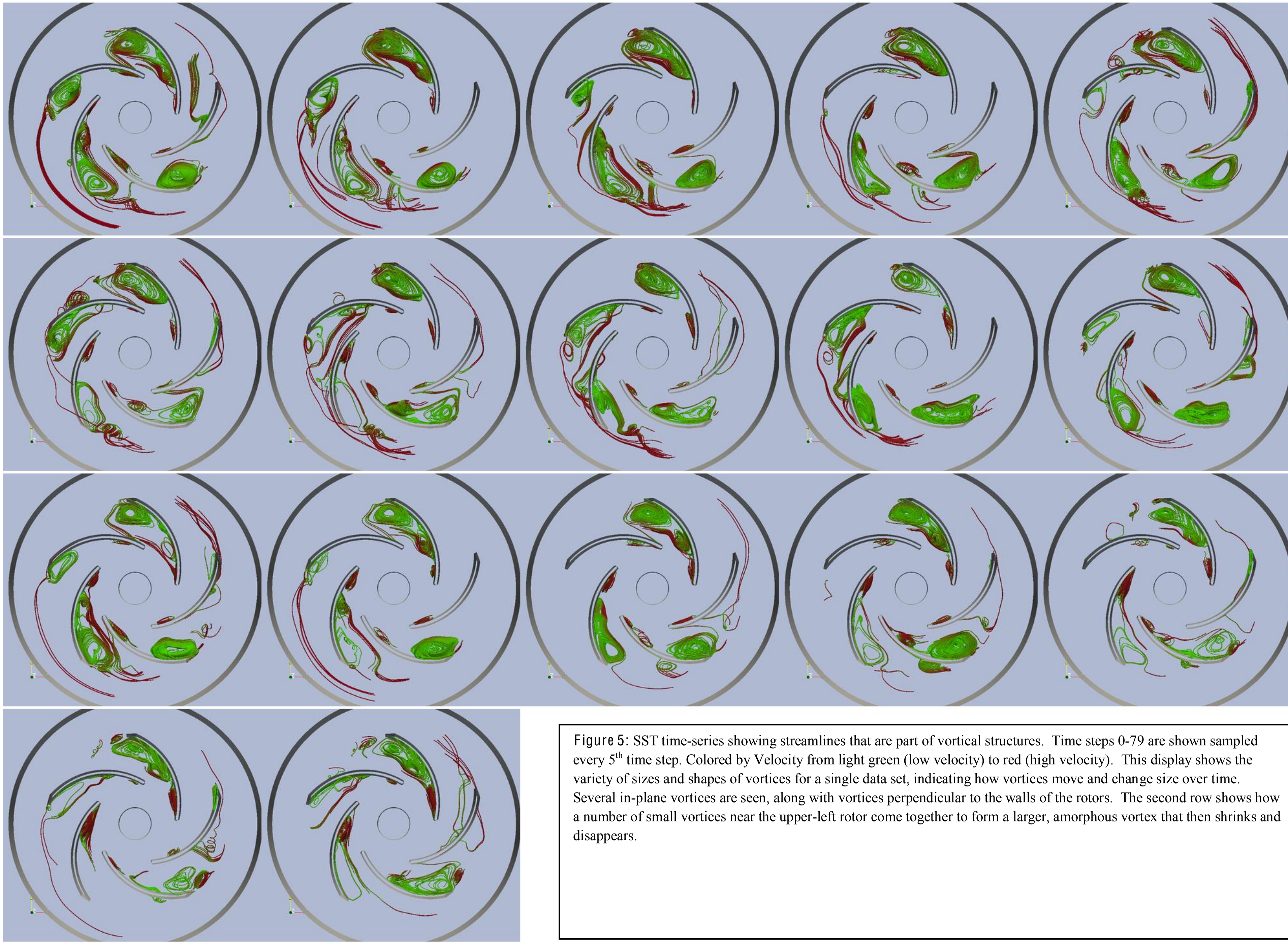


Figure 5: SST time-series showing streamlines that are part of vortical structures. Time steps 0-79 are shown sampled every 5th time step. Colored by Velocity from light green (low velocity) to red (high velocity). This display shows the variety of sizes and shapes of vortices for a single data set, indicating how vortices move and change size over time. Several in-plane vortices are seen, along with vortices perpendicular to the walls of the rotors. The second row shows how a number of small vortices near the upper-left rotor come together to form a larger, amorphous vortex that then shrinks and disappears.

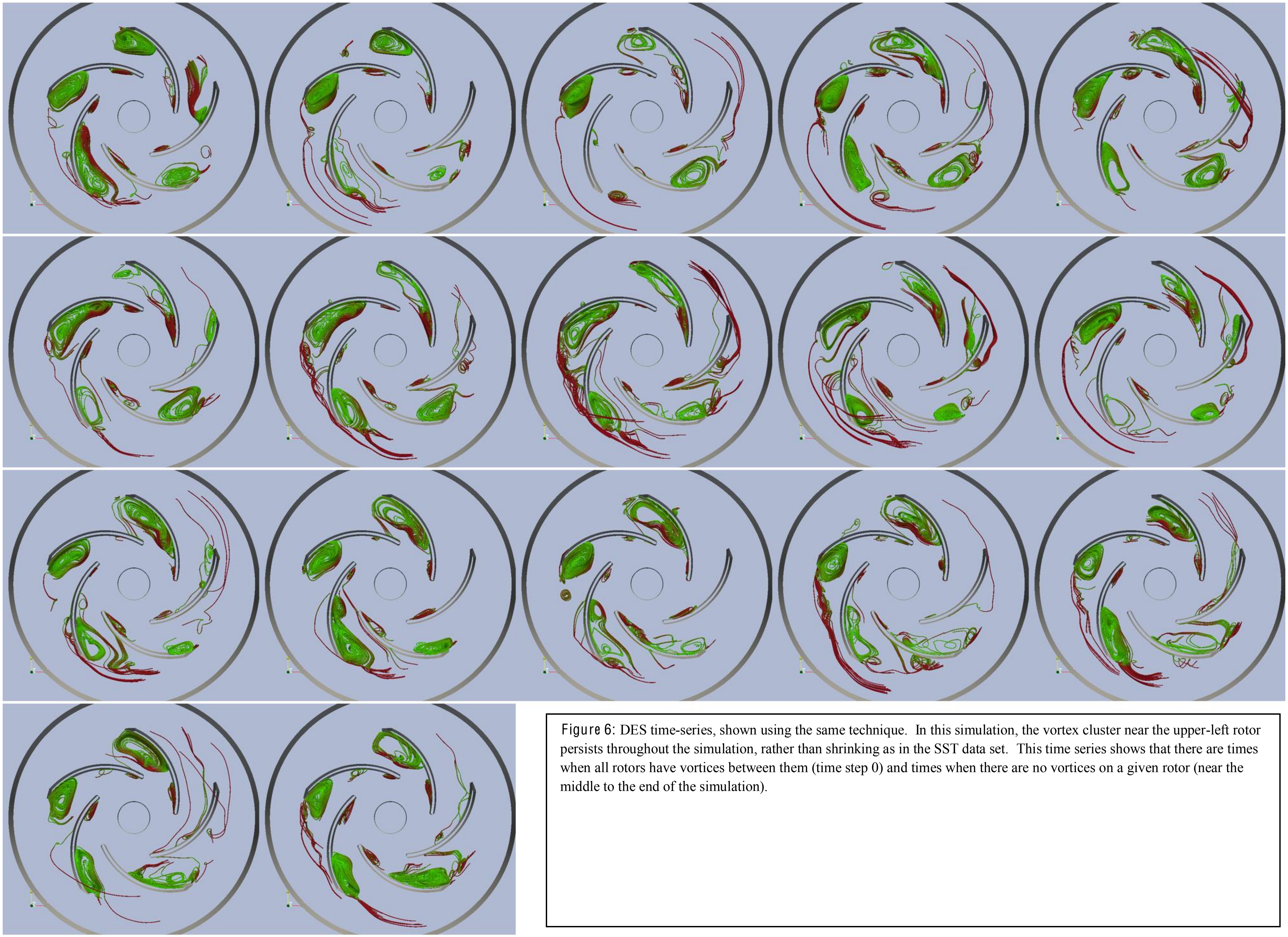


Figure 6: DES time-series, shown using the same technique. In this simulation, the vortex cluster near the upper-left rotor persists throughout the simulation, rather than shrinking as in the SST data set. This time series shows that there are times when all rotors have vortices between them (time step 0) and times when there are no vortices on a given rotor (near the middle to the end of the simulation).

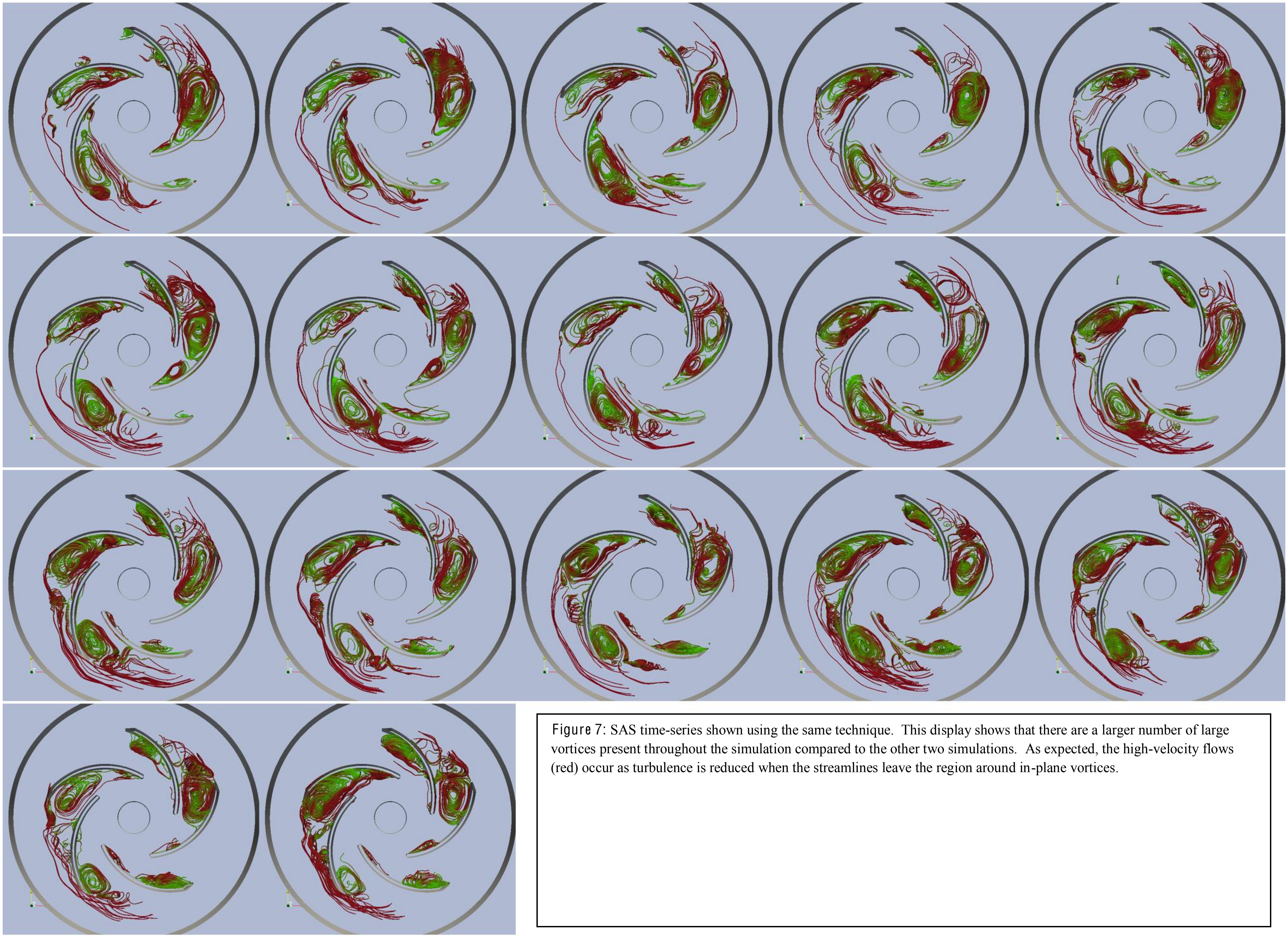


Figure 7: SAS time-series shown using the same technique. This display shows that there are a larger number of large vortices present throughout the simulation compared to the other two simulations. As expected, the high-velocity flows (red) occur as turbulence is reduced when the streamlines leave the region around in-plane vortices.

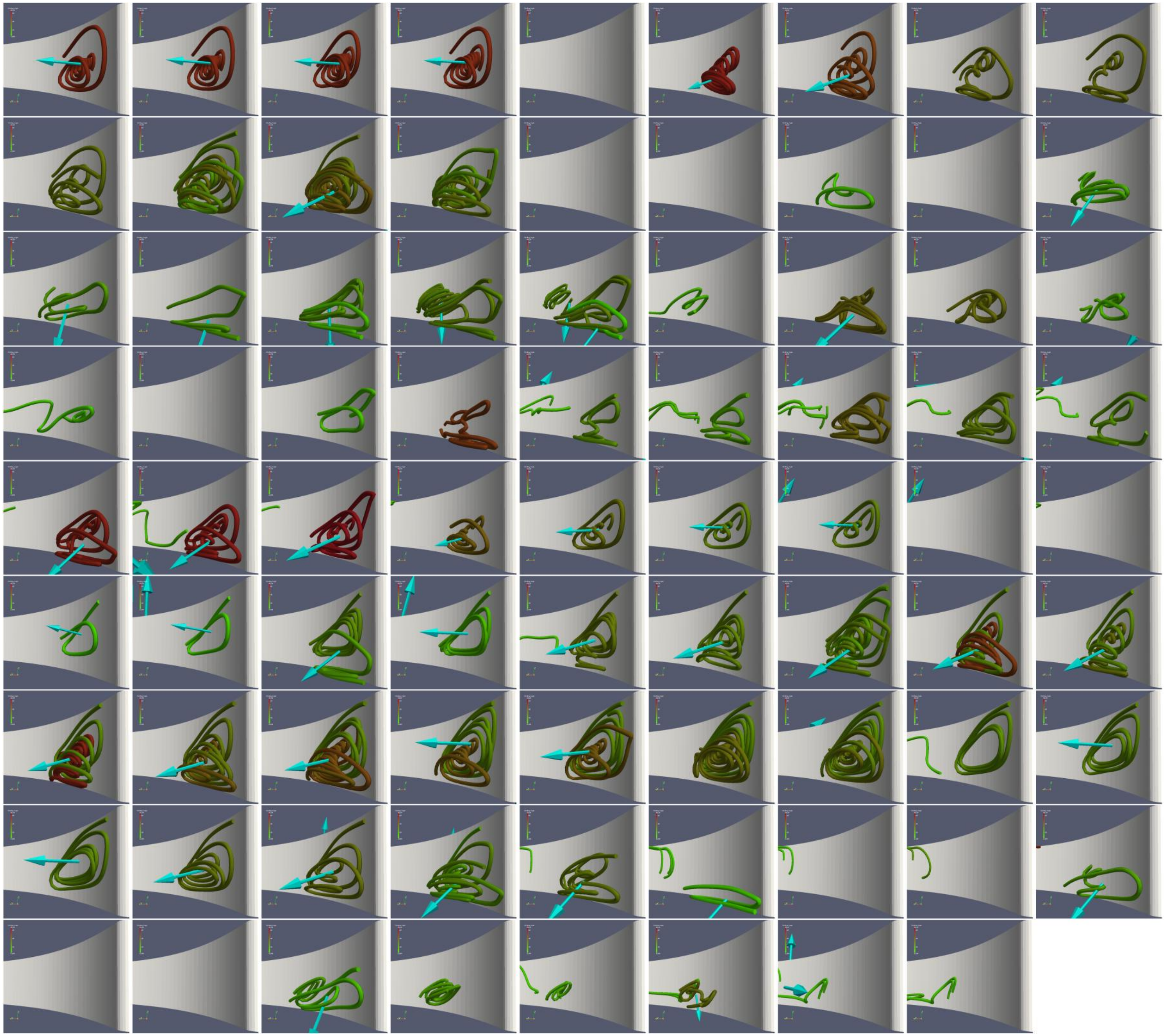
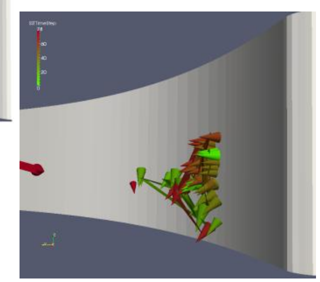


Figure 8: Close-up.

From left to right, top to bottom, time-series of the SST simulation zoomed in at 1 turbine blade. Timesteps 0-79. Vortices are visualized using very thin tubes. Light green indicates low winding angle and red indicates high winding angle. Blue arrows represent vortex cores. This shows the interesting curved shape of this vortex and how it goes from parallel to the rotor to in-plane.

Inset (bottom right): Ribbon & cone time-line summary of the SST simulation at the same turbine blade. (see Figure 9 for larger view).



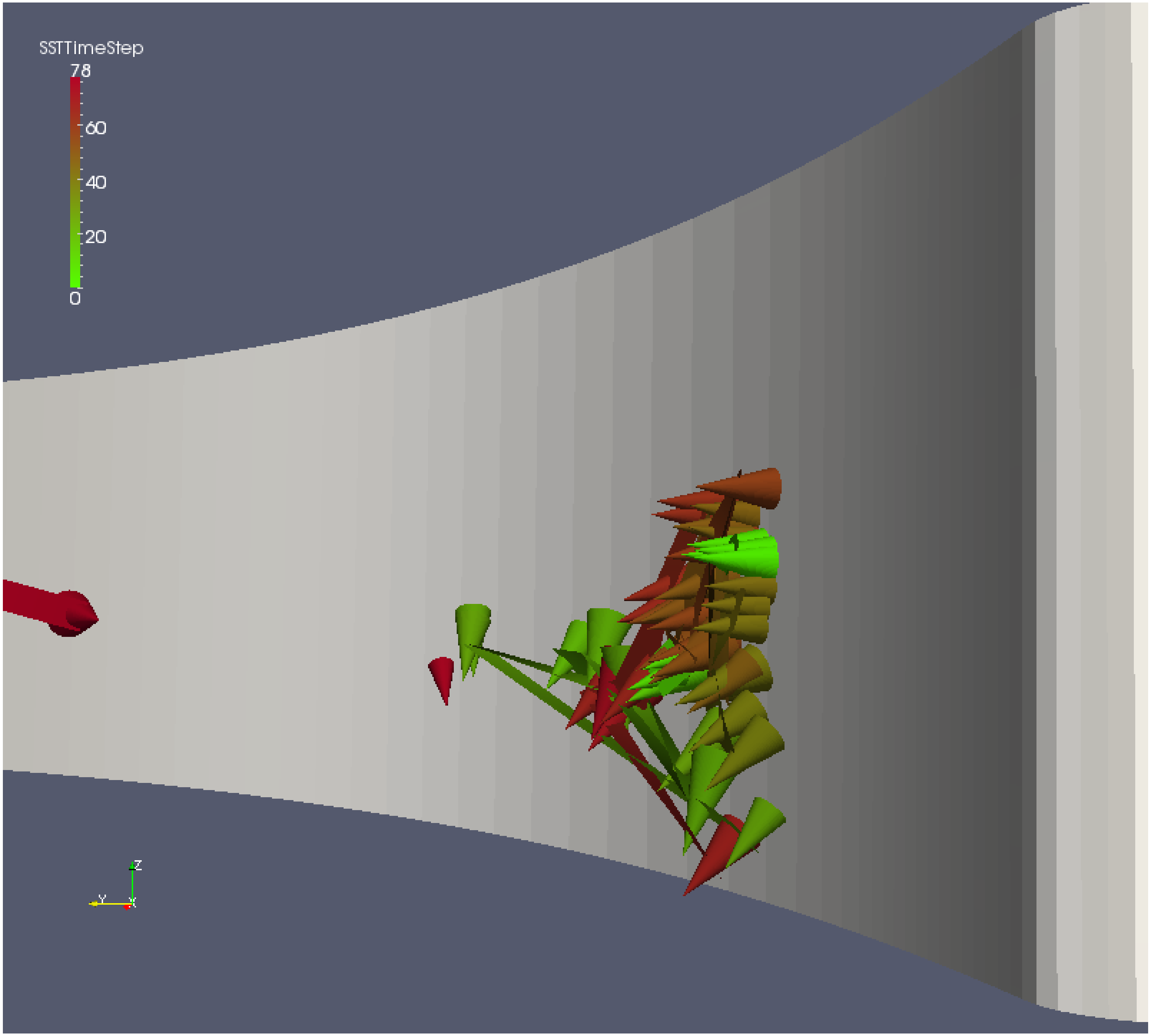


Figure 9: Close up

Ribbon & cone time-line summary of the SST simulation at a turbine blade. The different angles of the cones show instantly the dynamic orientation changes seen in the time-series view.

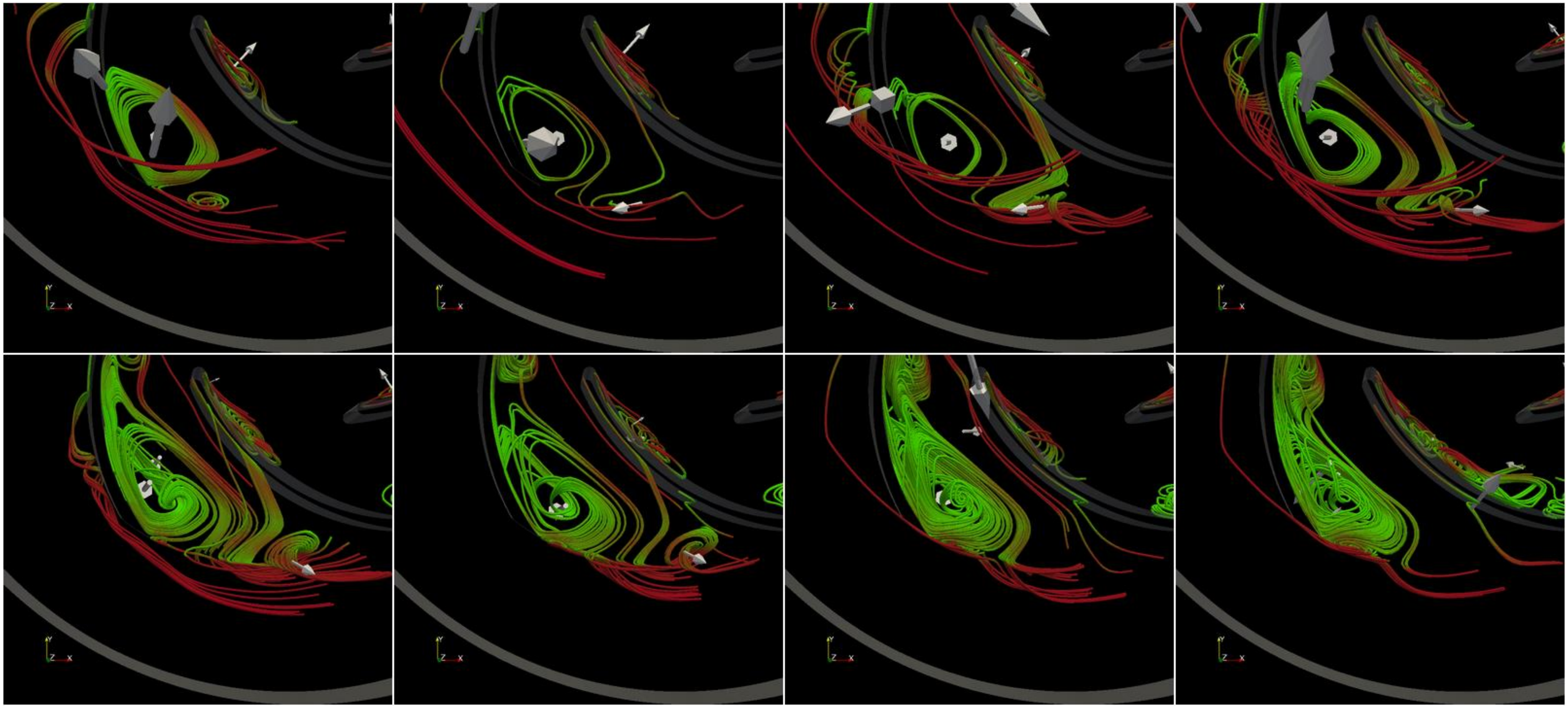


Figure 10: Close up SST simulation at time step 43 to 57, sampled at every odd-numbered timestep (from a total of 80 time steps indexed 0-79). Bright green indicates low velocity and red indicates high velocity. White arrows represent vortex cores scaled by vortex radius. The variation in orientation, size, and complexity of vortices near one particular rotor blade are apparent. This region goes from two fairly simple straight vortices to an amorphous set of intermingled turbulence.

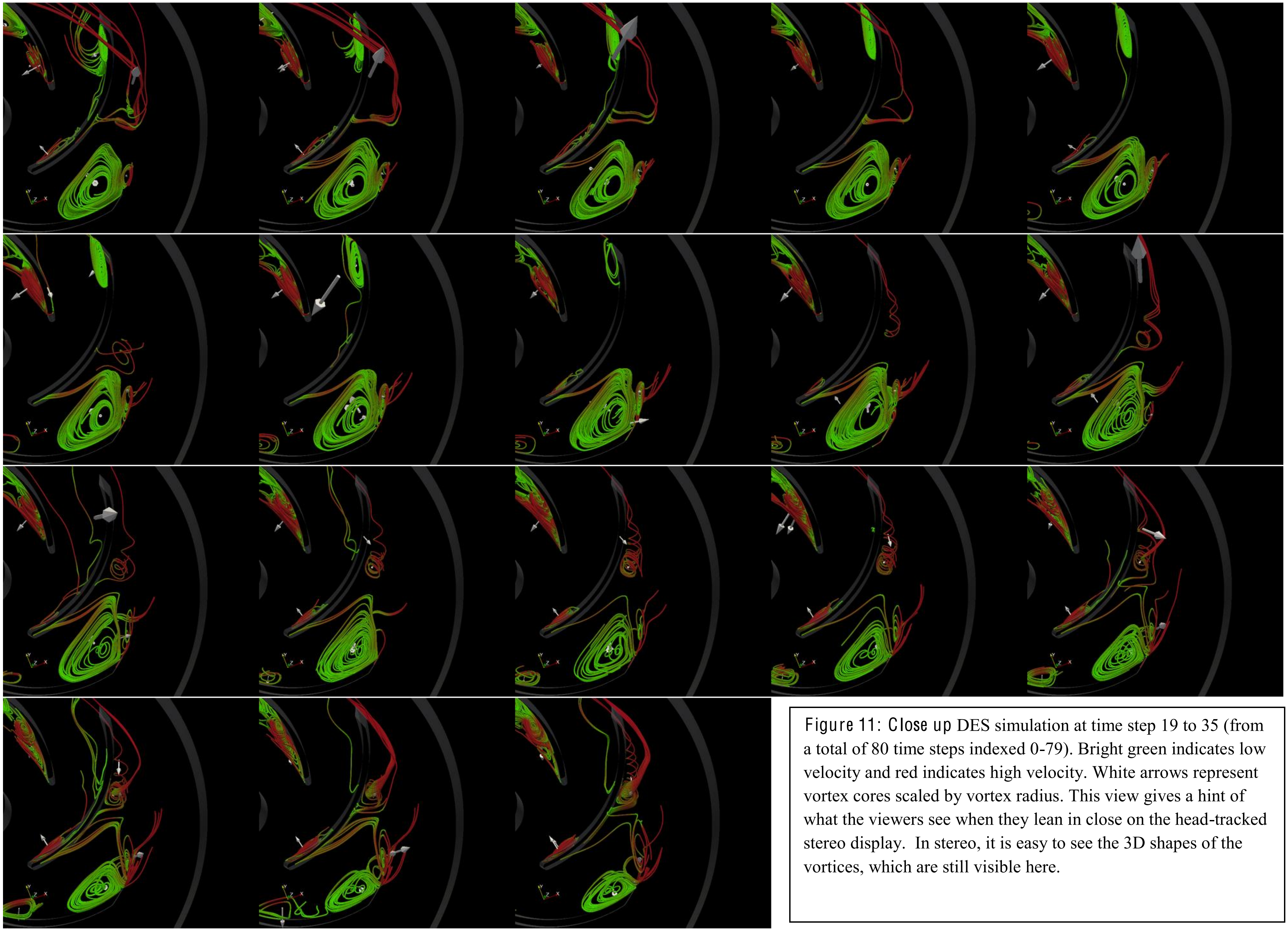


Figure 11: Close up DES simulation at time step 19 to 35 (from a total of 80 time steps indexed 0-79). Bright green indicates low velocity and red indicates high velocity. White arrows represent vortex cores scaled by vortex radius. This view gives a hint of what the viewers see when they lean in close on the head-tracked stereo display. In stereo, it is easy to see the 3D shapes of the vortices, which are still visible here.

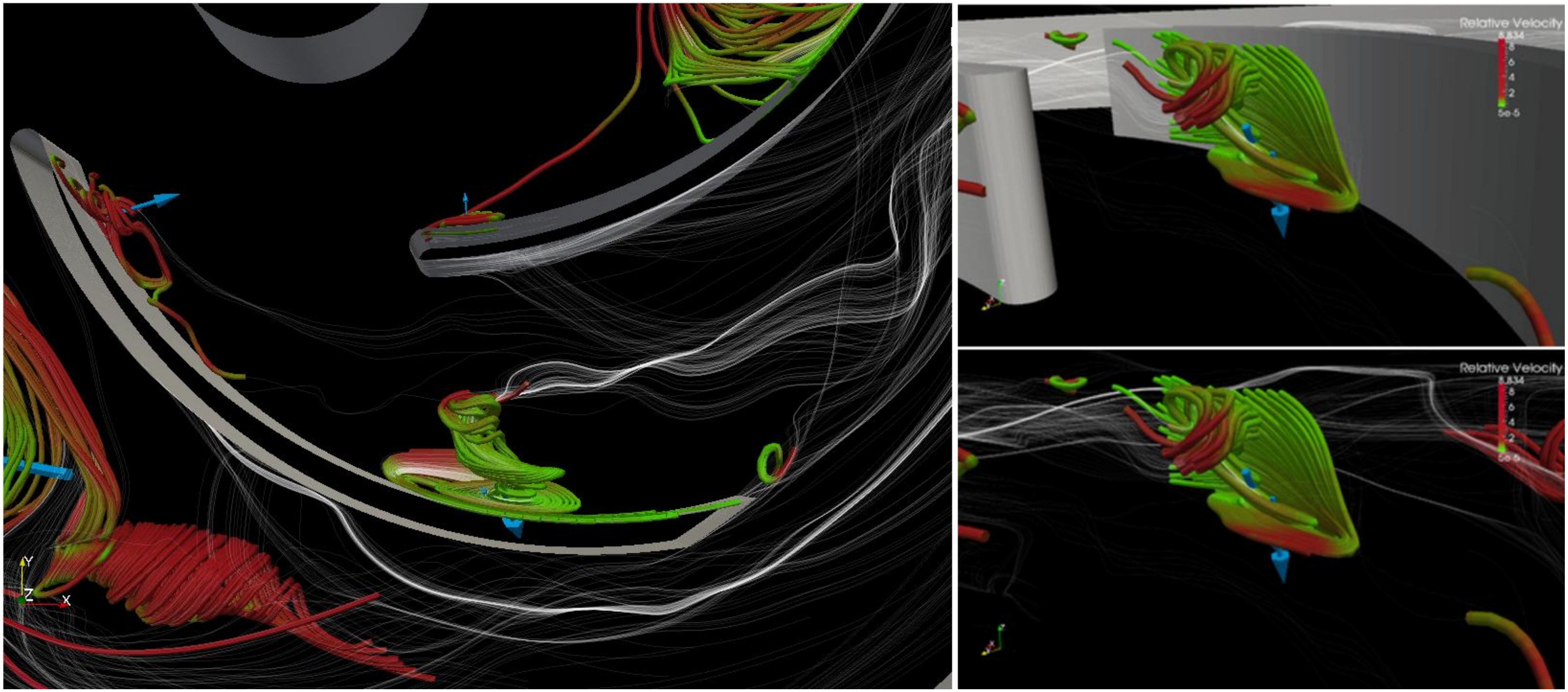


Figure 12: Close up SAS simulation at time step 56 (from a total of 80 time steps indexed 0-79). Bright green indicates low velocity and red indicates high velocity. Blue arrows are scaled by vortex core radius and indicate the vortex core direction. (a) Left: Flow surrounding the vortices are colored in unlit white lines with low opacity. The opacity of these unlit streamlines is set to a very low value to render regions with coherent structures with higher intensity than regions without coherent structures – providing good shape perception of the global flow. This reduces self-occlusion as much as possible while still providing continuity of the flow vector field. In our interactive system, this can be optionally turned on to provide contextual information (see video). (We chose white lines over a black background instead of black/gray lines over a lighter background because differences in intensity are more apparent between thin white lines than differences in intensity between thin gray/black lines.) (b) Top Right: Zoomed-in view of the vortex at the center of part (a). (c) Bottom Right: Turbine blade geometry is made invisible to enable a better view of contextual flow. This option is provided in our interactive system.