Team "CUTe Flow": Information-guided Streamtube Seeding for the Visualization of Vortex Behavior in a Centrifugal Pump at Deep Part Load

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ABSTRACT

The data of the IEEE Visualization Contest 2011 consists of different simulations of a centrifugal pump. We will study the development and cause of vortices in the flow of this pump at deep part load. This will be done using the well-known tool Paraview and utilizing different seeding strategies for streamtubes.

Index Terms: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—

1 INTRODUCTION

Nowadays, simulations of extensive technical processes or complex physical phenomena are carried out on massive parallel computer systems facilitating high resolutions in spatial as well as temporal dimension. Consequently, the sizes of generated data are growing enormously and interpretation is getting more and more complex. Although a wide variety of free and commercial visualization tools exists, it is in many cases not even clear which general approach to follow nor which tool to use to get a useful insight into the relevant parts of the data. In the following we describe, how we tried to conquer the data of IEEE Visualization Contest 2011.

The provided data consists of three different data sets simulating one full rotation of a centrifugal pump [6, 7]. The data sets are simulated using different turbulence models, more precisely a LES approach (DES), an URANS approach (SAS), and a RANS approach (SST). All three models result in data sets, which show similar behavior in some parts but also significantly differ in other regions of the simulation. One challenge is to choose the best approach for the each study of a specific phenomena, as discussed in Section 2.3.

The domain of the simulations is a centrifugal pump with a single inlet, a rotor, and multiple outlets. At the datapoints in this domain a series of data values is given which are mostly scalar values as pressure, total pressure in relative system, total pressure in the absolute system, and turbulence kinetic energy. In addition, each data point holds vector-valued information representing the velocity in a relative and absolute context. This multidimensional data set with 6.7 million data points per time step leads to an enormous data size. Moreover, each simulated rotation is documented by a set of 80 time steps, resulting in an angle difference of 4.5° between consecutive time steps. This also induces the difficulty of changing geometry and domain during simulation. The strategic decisions made and preprocesses carried out to handle the challenging data are described in Section 2.2.

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2 METHODOLOGY

2.1 Visualization Approach

Today there exists a nearly unmanageable amount of different visualization approaches and ready-to-use tools. We decided to use a standard visualization tool to show the capabilities of these tools for generating real-world visualizations. Finally, we chose Paraview [1] since it is known for its good performance, utilizing parallel architectures, and its feature richness. The tool utilizes the well-known Visualization Toolkit [9] and provides various interaction mechanisms for data inspection like zooming and flying through the data visualization. All data processing and visualizations were computed using only Paraview.

For visualizing the different parameters and fields we used and combined different approaches. To give an overview over scalar fields and their behavior with respect to the surrounding area we used color-coded cutting planes [3, 4]. Additionally, we highlight areas of extremal values by extracting isosurfaces [5, 8, 11] to the scalar fields with appropriate isovalue. The flow fields of the data are visualized using streamtubes [10] which are tracked forward or backward in the flow using a standard Runge-Kutta-solver [2].

2.2 Data Preparation

As already described before, the domain of the provided massive data set is a whole centrifugal pump. The questions of domain experts concern mainly the flow and it's irregularities near the rotor. We took advantage of this fact and restricted the data to the actual domain of interest, the disc around the rotor, significantly reducing the data size.

A second preprocessing is needed because of the very special nature of the data domain. Since the rotor is moving during the simulation, the data context is changing from one time step to the other. To allow for qualitative conclusions about flow behavior over time, we decided to realign all data sets with respect to the geometry of the rotor in the first time step $t = 0$. Since the angle between consecutive time steps is 4.5°, this means that for each time step t the data set is rotated with the angle $-t \cdot 4.5^\circ$.

2.3 Different Approaches

The provided data consists of three different time-varying data sets, each one generated using a different turbulence model during simulation. To gain an overview about the relevant features of the different data sets, a series of color-coded cutting planes for each variable and turbulence model were used. Sample renderings of the cutting planes are shown in Figure 1. The visualizations gave the insight, that the DES data is well-suited for studying all variables, while the SAS data does not resolve the scalar variables as good as DES and should just be used for visualizing the velocity field and giving a rough overview. The SST data was neglected from the beginning since it does not resolve turbulences.

2.4 Performance

All experiments were carried out on an Intel Core i7 Hexacore processor with 3.33 GHz with a NVIDIA Geforce GTX 580 graphics card. The loading of each time step of a data set took 30-40 seconds. The navigation through the data and the extracted geometry was then interactive, which results from the fact, that Paraview uses a sparse preview of the data during movement. Generation of cutting planes was working in not more than a second and has proven to be a good and fast approach for initial data exploration. The integration of streamtubes needed, heavily depending on the number of seed points, several seconds to at most one minute.

3 Scientific Questions

After generating a first overview of the data, we decided to use the SAS data to study the vortices in the flow and their behavior over time. For each time step we extracted isosurfaces with respect to turbulence kinetic energy and nearly maximal isovalue to show the locations of the high turbulent regions. In addition, we seeded a set of nine streamtubes at the top of each blade of the pump and traced them following the relative velocity field. Here the radii of the streamtubes are also encoding turbulence. A visualization for two time steps is shown in Figure 2.

From the visualization it is obvious, that turbulences only occur in three of the spaces between the blades, which stay the same for the whole rotation. Furthermore, the regions of high turbulence are close to the edges of all blades, which is the normal behavior, but also between the blades ends for the spaces of abnormal turbulence.

For the investigation of the vortex development during one full rotation we concentrated on one detail of the data set and show a side-by-side comparison of 16 time steps in Figure 3. Here we see the space between two blades during the whole rotation. The regions of highest turbulence and the vortical streamtubes are moving with the time against the direction of the rotor movement, in the pictures to the upper left. In addition, it can be seen that a new vortex is developing at $t = 55$ starting a new period of the cyclic behavior. An animation of this close-up with all time steps is provided in the video `SAS_StreamTube_animation_detail.avi`. An overview of the animation of the visualization for the whole disc is given in video `SAS_StreamTube_animation.avi`.

To understand the cause of the turbulent behavior, we looked in addition into the pressure fields and concentrated on the first time step of the DES data set. The extracted isolines with respect to total pressure in stn frame show a quite abnormal structure, see Figure 4. It is obvious and clear, that the gradient of pressure is very steep close to the top of each blade and relatively flat in between. However, the isolines show also a steep gradient directly between each consecutive pair of blades. It would be interesting to investigate if this is also the case if the pump is working at higher speeds. The extracted streamtubes show, that flow behavior is most turbulent in the spaces between blades where the pressure isoline is also very "turbulent". It seems as if the low load of the pump causes pressures to fall that far, that small fluctuations in the pressure field lead to enormous turbulences in the flow.

A final insight into the phenomena of this data set we also found when studying the pressure distribution. As shown in Figure 5, we extracted the regions of minimal and maximal total pressure in stn frame. The isolines segmenting these regions were used as seed for backward tracing of streamtubes, showing regions of origin for the flow going into the extrema. Here the tracing from the maxima of pressure produced very strange streamtubes. While most of the streamtubes originate from the space between the blades of the rotor, as one would expect, there is a significant amount of streamtubes originating from outside. This means, that there is flow coming back from the outer boundary of the pump to the rotor. The fact can be nicely seen in the perspective view of Figure 5 and in a flight through the visualization, emphasizing the three-dimensional correlations, shown in video `Streamtubes-POIs.avi`. This flow, coming from outside in addition to the normal flow, produces larger regions of high pressure and seems to be a major reason for the turbulences. Taking the geometry of the whole pump into account it seems as if the outlets should be constructed in a different way to prevent this behavior and allow for a more stable operation also at lower loads.

4 Conclusion

We have visualized the data of IEEE Visualization Contest 2011 with the help of the visualization tool Paraview. For a faster insight we have reduced the data to the significant part close to the rotor and realigned the different time steps. Our visualizations show that vortices develop in some spaces between blades and regions of high turbulence move over time against the movement of the rotor.

We have identified two different possible reasons for the development of the turbulent structures. One reason could be the very high fluctuation of the gradients in the pressure between the inlet and the blades. The second possible direction of further investigation would be the flow coming back from the outer pump to the rotor, generating high pressures and possibly turbulences in the flow.

We have shown that a standard tool like Paraview is capable of handling today's real-world data and producing insights also for complex and high-dimensional phenomena.

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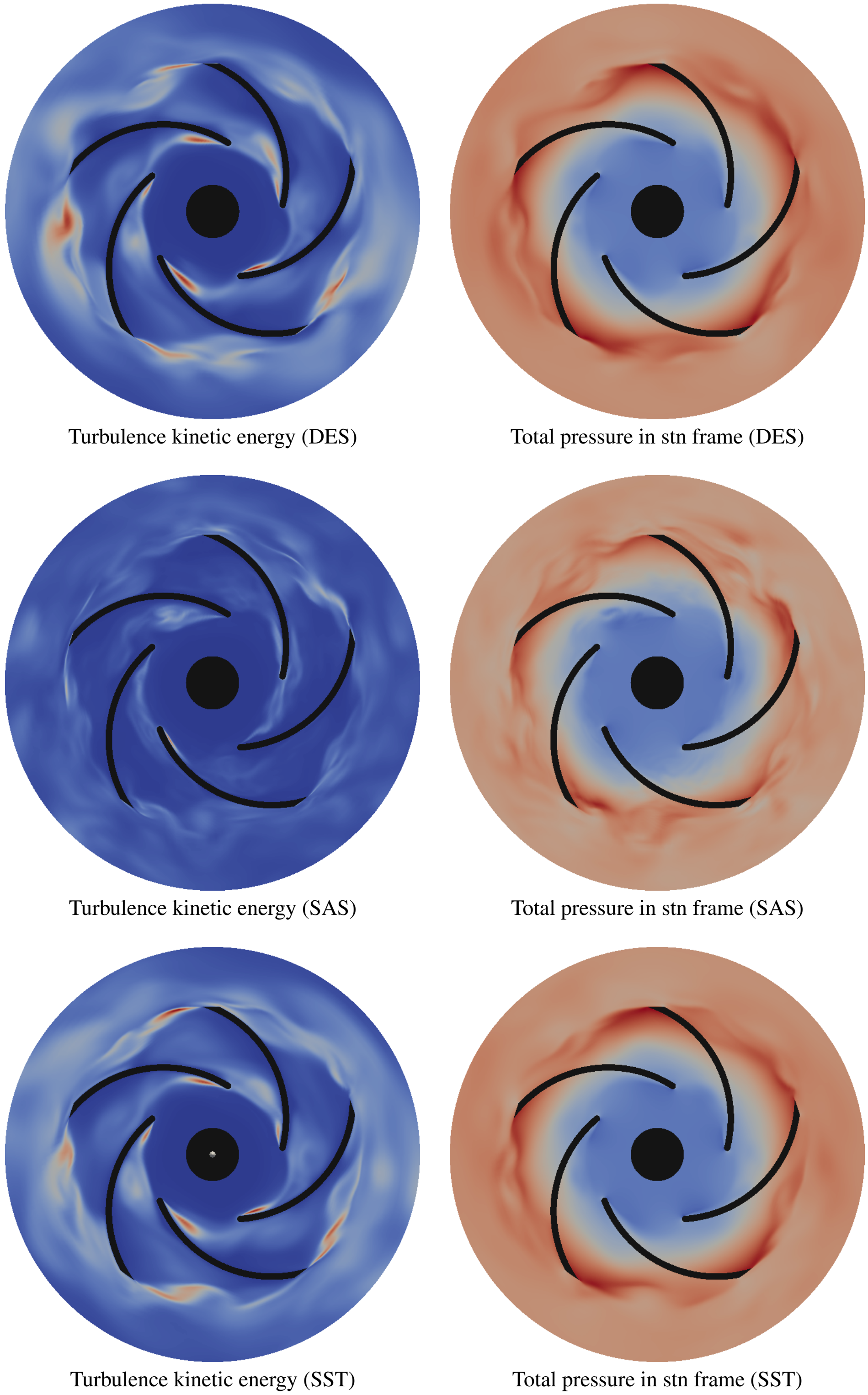
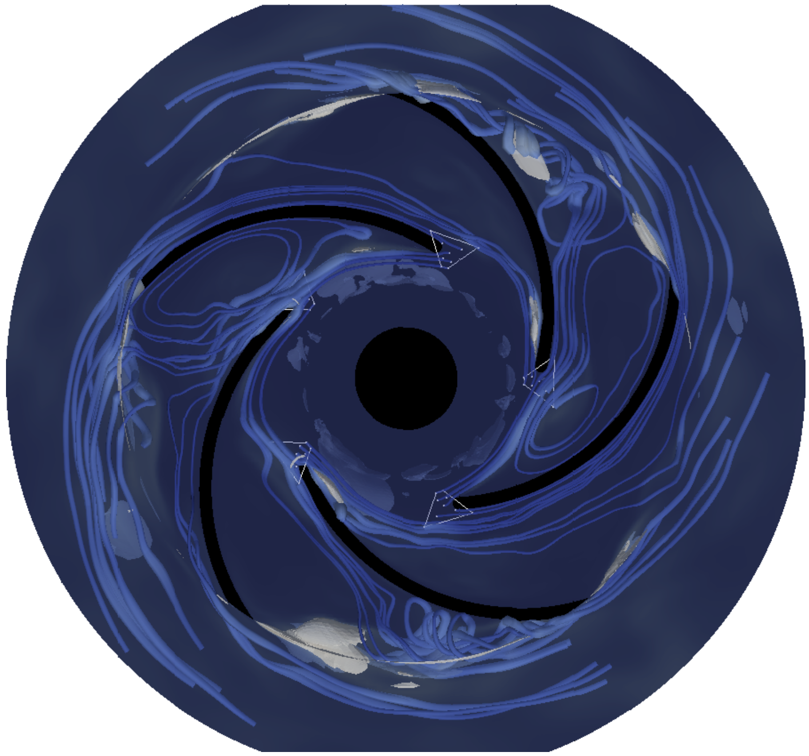
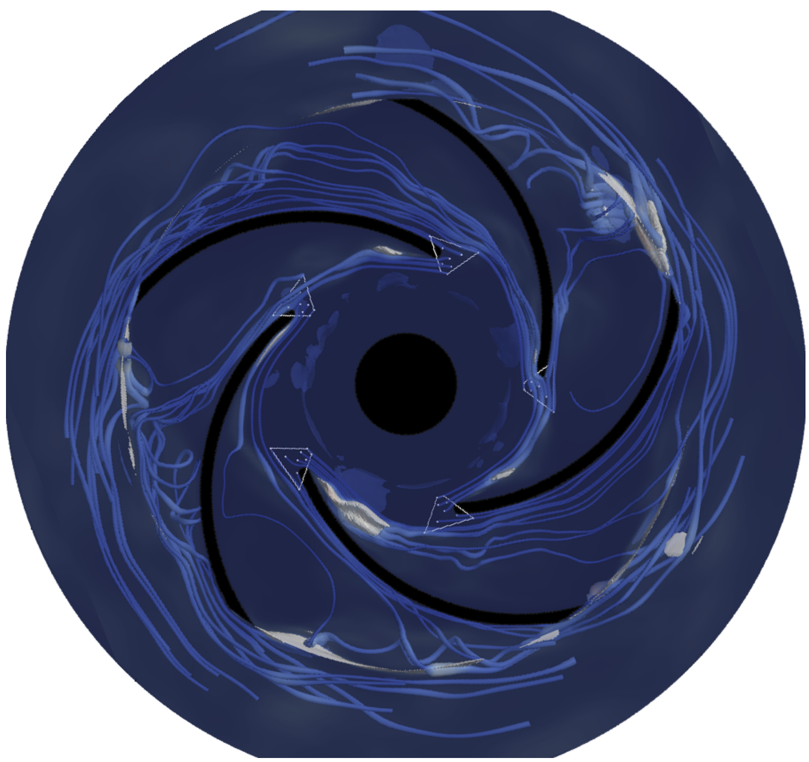


Figure 1: Comparison between the different provided turbulence models. A cut plane showing color-coded turbulence kinetic energy on the left-hand side and total pressure in stn frame on the right-hand side is provided for the time step $t = 0$ and for each turbulence model respectively. High values are coded in red color and low values in blue color. In the provided SAS data sets the velocity was very informative and we used it to study the general flow behavior. In contrast, we used the DES data for investigating the connections between turbulence and pressure distribution, which are clearly better resolved in these types of data sets. As stated in the description, the SST data is not well-suited for these simulations and was not used for our analyses.



$t = 40$



$t = 65$

Figure 2: Visualization of two different time steps of the SAS data. For each time step a set of nine streamtubes was seeded near each blade's top. The streamtubes were traced following the velocity field, where the tube's radius represents the local turbulence kinetic energy. In addition, isosurfaces (white) were extracted with respect to turbulence kinetic energy, representing regions with very high turbulence kinetic energy.

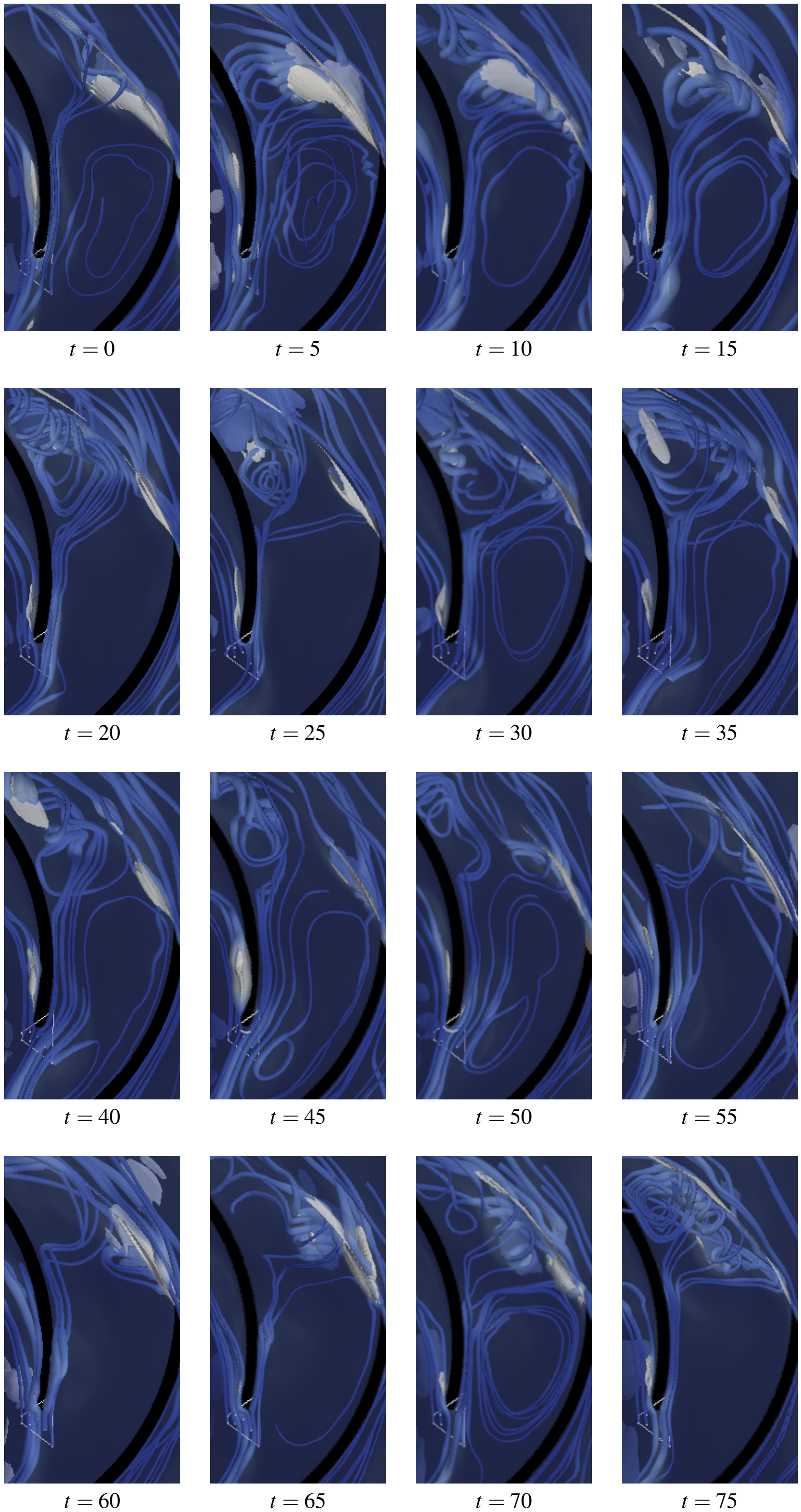
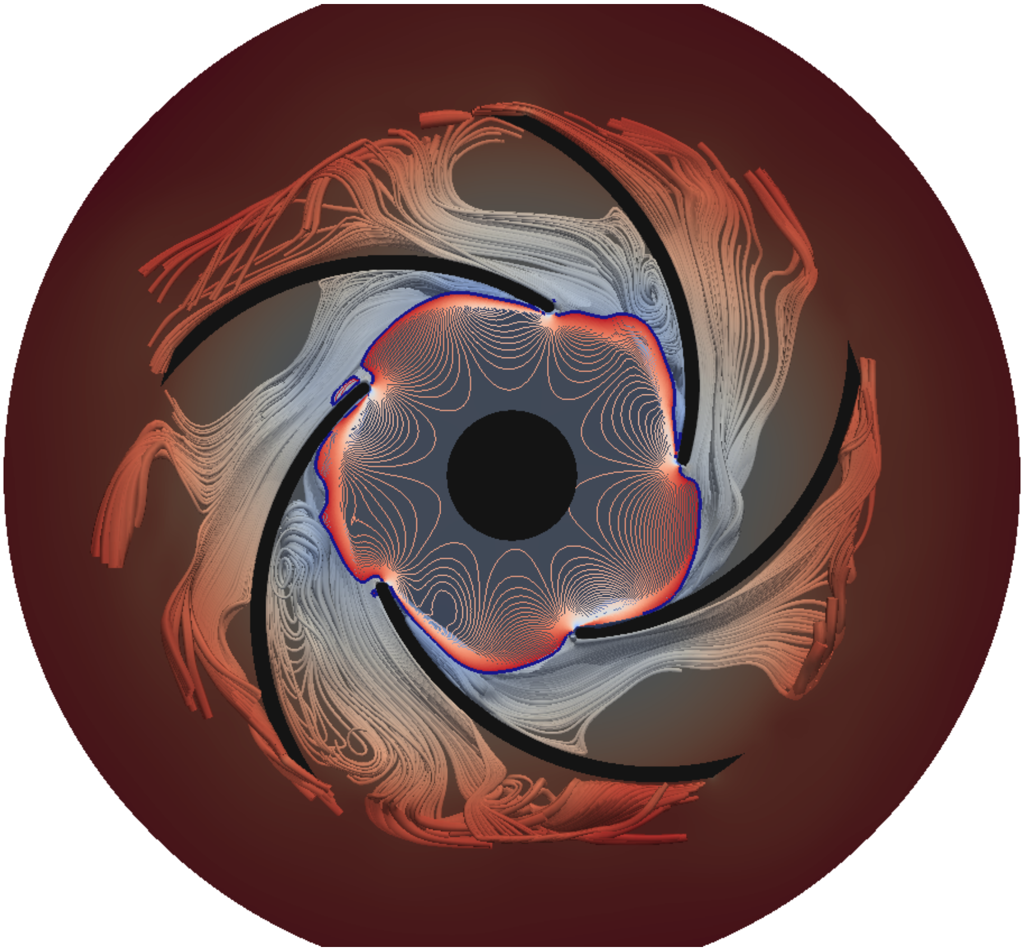
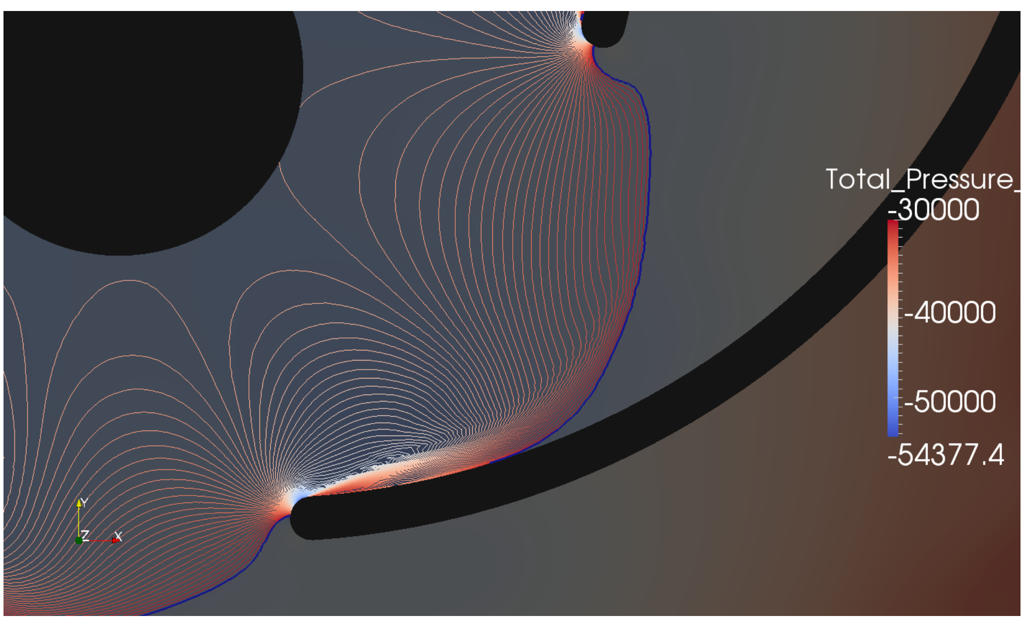


Figure 3: Close-up views of the space between two blades of the SAS data set for different time steps, representing a full rotation. As in Figure 2, streamtubes with respect to velocity and turbulence kinetic energy as well as isosurfaces segmenting regions with high turbulence kinetic energy were extracted.

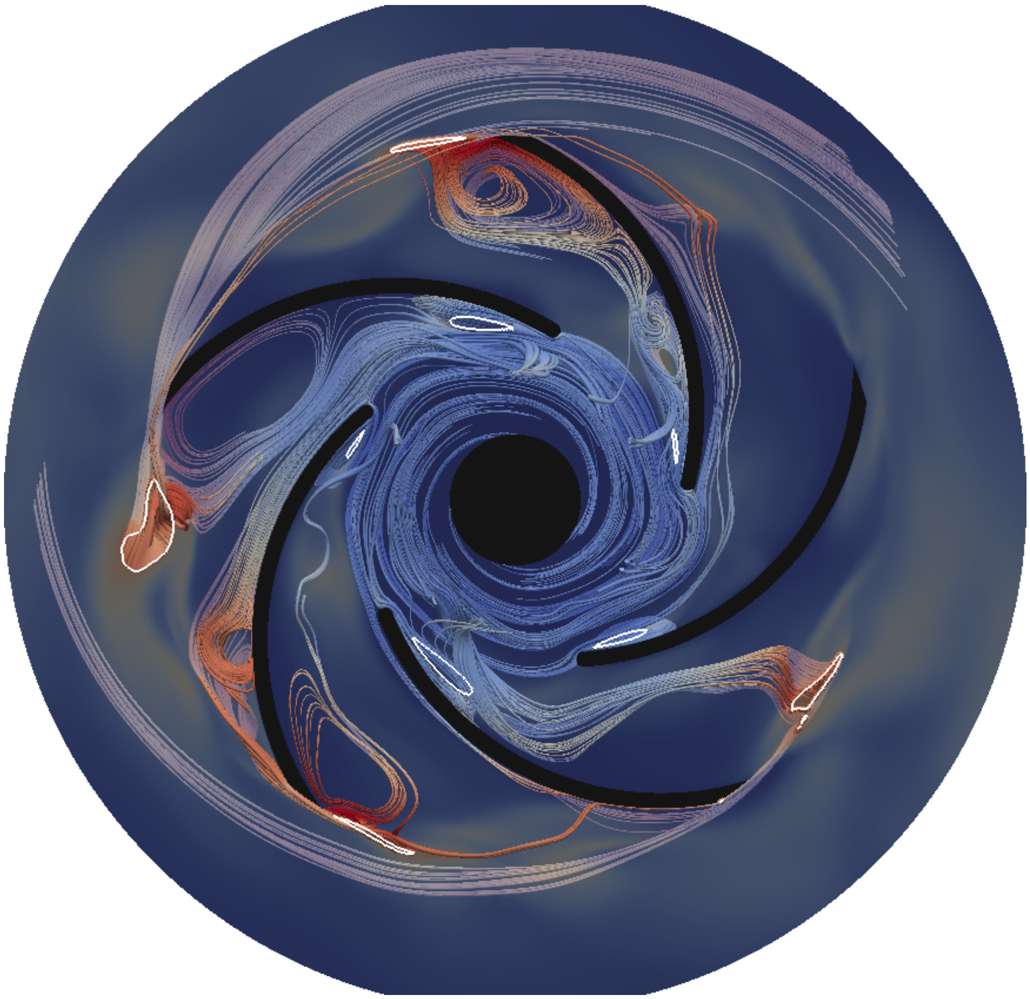


Overview



Detailed view

Figure 4: Visualization of the DES data set at $t = 0$. From the total pressure in stn frame an isoline close to the blades tops was extracted (blue) and a series of isolines with lower pressure, equidistant in feature space. The isoline close to the blades was used as seed for streamtubes, defined as in Figure 2. The domain disc as well as the streamtubes were color-coded with respect to total pressure in stn frame.



Overview

Detailed perspective view

Figure 5: Visualization of the DES data set at $t = 0$. From the total pressure in stn frame the regions of maximal (red) and minimal pressure (blue) were extracted and marked with white isolines. From these regions streamtubes were traced following the inverse relative velocity, showing the sources of flow ending into the extracted regions.