# Effective Texture Models for Three Dimensional Flow Visualization

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## Abstract

Visualizing three dimensional flow with geometry primitives is challenging due to inevitable clutter and occlusion. Our approach to tackling this problem is to utilize semi-transparent geometry as well as animation. Using semi-transparency, however, can make the visualization blurry and vague. We investigate perceptual limits and find specific guidelines on using semi-transparency for three dimensional flow visualization. We base our results on the user study that we conducted. The users were shown multiple semi-transparent overlapping layers of flow and were asked how many different flow directions they were able to discern. We utilized textured lines as geometric primitives; two general texture models were used to control opacity and create animation. We found that the number of high scoring textures is small compared to the total number of textures within our models. To test our findings, we utilized the high scoring textures to create visualizations of a variety of datasets.

## 1 Introduction

Flows are ubiquitous in visualization applications. Ocean currents, the flow of gas in a turbine or wind over an airplane wing, blood flow in the human body - these are all cases where adequate flow visualization is a necessity. Over decades, a variety of methods have been developed to visualize flow in two or three dimensions. Flow over a plane is usually referred to as 2D. Methods that are applied to cases when flow is close to a 3D surface are often referred as 2.5D. Methods that deal with cases of overlapping 2D flow are often also denoted as 2.5D. Visualizing of 2D flow is usually considered an easier task compared to the three dimensional case. For three dimensions, problems of clutter and occlusion make flow visualization a challenge.

One way to reduce occlusion is to utilize semi-transparency. Semi-transparency provides partial visibility of flow features that otherwise would be fully occluded. An example is shown in Figure 1. However, as we keep decreasing the opacity of the overlapping primitives to reduce occlusion further and reveal more flow features, visualization becomes progressively more blurry and vague and eventually becomes completely incomprehensible. Thus, it is important to investigate perceptual limits when semi-transparency is used. This would allow us to create flow visualizations that reveal the largest possible number of flow features while not introducing too much blur and clutter.

We propose a user study that allows us to investigate limits of occlusion perception when visualizing flow with semi-transparent geometry primitives. The effectiveness of such visualization depends on how well one perceives overlapping flow directions at different depths. For the user study, we propose experimental models for streamline textures.We introduce two streamline texture models, which allow us to generate a vast set of textures. We create an effect of flow motion by moving the textures along the streamlines. We use a set of overlapping 2D layers of flow as an experimental dataset. This model was selected for two reasons. First, we assume that textures that do not work well for 2.5D flow visualization, won't perform well for three dimensional flow. Second, we observe the following: for any sufficiently small neighborhood in screen space, we can assume that the projection of three dimensional flow to this neighborhood consists of a number of overlapping linear flows at different depths. The only exception are vicinities of critical points. However, as we are dealing with a discretized domain, for a local neighborhood with a size of several pixels, we get one flow direction at this location at a given depth. Thus, our experimental dataset is an adequate model for the purposes of our study, which is primarily focused on occlusion. We explore the parameter space of streamline texture models and discard those textures that do not create effective visualizations. We select a set of candidate textures for our user study. The results of the user study provide us with qualitative and quantitative guidelines on using semitransparency for flow visualization to mitigate occlusion.

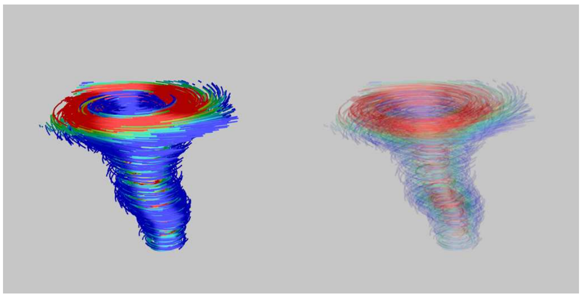

Figure 1: *Tornado* dataset rendered with opaque (left) and partially transparent (right) streamlines. Streamlines are velocity-colored, from blue (low) to red (the highest velocity). Using semitransparent streamlines reveals the inner structure of the dataset. On the other hand, visualization becomes more cluttered and blurry.

## 2 Related Work

Flow visualization is a large and very well developed area of scientific visualization that still attracts much attention. A wide variety of approaches has been developed to visualize flows in 2D, 2.5D, and 3D. Approaches to visualize vector fields can be categorized into dense (texture-based), feature-based, direct, and geometry-based techniques. A number of very good reviews of the field are available [Hauser et al. 2002][Laramee et al. 2004][McLoughlin et al. 2010].

A number of methods to mitigate the problem of occlusion for three dimensional flow visualization have been proposed over the years. View dependent methods [Marchesin et al. 2010][Lee et al. 2011] remove streamlines that occlude important regions for a given viewpoint. View independent algorithms seed streamlines in areas of higher importance [Chen et al. 2007; Xu et al. 2010; Verma et al. 2000]. However, when any of the above methods are used, certain flow features may still not be represented.

Researchers in scientific visualization have long been using principles of human perception to achieve best results, but recently

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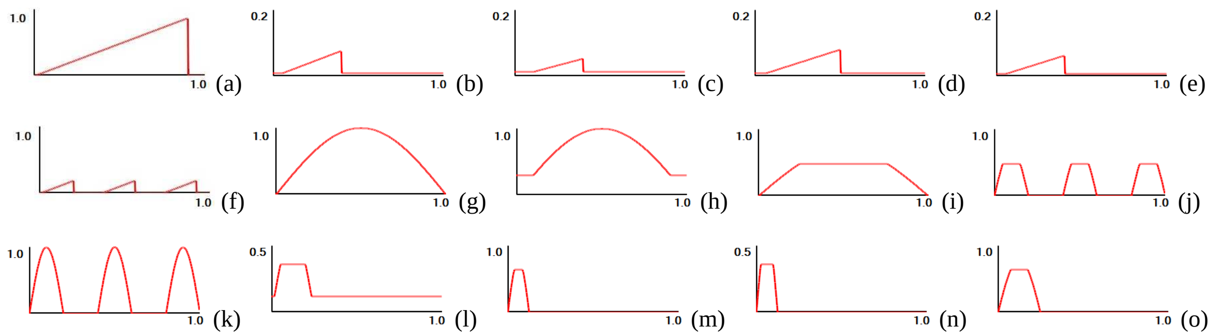



Figure 2: Examples of texture patterns for flow lines. Horizontal axis corresponds to texture coordinate and vertical axis corresponds to opacity. Figures (a)-(f) show patterns generated with Model 1 ($T_{sawtooth}$), and figures (g)-(o) show patterns generated with Model 2 ($T_{sin}$). Figures (b)-(e) show the highest scoring $T_{sawtooth}$ textures from Experiment 1, and figures (l)-(o) show the highest scoring $T_{sin}$ textures from Experiment 2.

perception has started to receive even more attention [Bartz et al. 2008]. The role of color is covered in many books, for example [Wong 1996][Itten 1961][Ware 1999], and numerous articles. Recently, the role of motion when creating scientific visualizations was discussed by Huber and Healy in [Huber and Healey 2005]. Weiskopf [Weiskopf 2004] investigated how color influences perception of motion in animated visualizations, including flow visualization, and provided a set of design guidelines for visualization applications. Importance of utilizing perceptual principles and theory of human vision for flow visualization is stated by Ware in [Ware 2008].

Researchers working in a field of vision have studied different aspects of human perception of motion for a long time which resulted in a wealth of important findings. Their work, however, primarily focuses on revealing how the human visual system works and on creating models of human visual system perception [Wandell 1995][Cochin et al. 1998][Treue et al. 1991].

Visualizing multiple layers of materials is an important topic in computer graphics and scientific visualization. In many cases there is a need to overlay materials in the same view, for example, in a medical visualization different soft tissues should be visible above the bone. The use of textures to enhance perception of semi-transparent layers has been covered by Interrante *et al.* in [Interrante et al. 1995] and by Interrante in [Interrante 1996], and more perceptual aspects of visualization of textured layers were covered by Bair *et al.* [Bair and House 2007][Bair et al. 2005] and House *et al.*[House et al. 2005]. Kinetic visualization by Lum *et al.* [Lum et al. 2002] employs particle system to provide motion cues that improve shape perception of visualized objects. Visualization of two overlapping layers of flow is discussed by Urness et al. [Urness et al. 2006].

There are a number of papers that evaluate different aspects of flow visualization via user studies. Forsberg *et al.* [Forsberg et al. 2009] performed user studies in which test subjects were asked to perform some common tasks in flow visualization, such as locating and finding the type of a critical point and tracing a particle. Weigle and Banks [Weigle and Banks 2008] compared the use of perspective and global illumination for flow visualization, when dense tubes are utilized.

# 3 Experimental Setup

The goal of our work is to determine the limits of human perception when three dimensional flow is visualized with partially occluded animated semi-transparent geometry primitives and to find a set of guidelines for this visualization approach. To achieve our goal, we create a user study. For this purpose, we introduce streamline and dataset experimental models. Experimental dataset is a set of constant flow directions at different depths, overlapping each other, with streamlines being represented as lines with certain texture patterns and opacities applied to them. This allows us to investigate the following questions. What is the maximum number of partially occluded flow directions discerned by the user? What opacities and textures should be used in visualizations to maximize the number of discernible depths of flow? What animation speed should be selected?

The parameter space of the experiments is huge. There are millions of different combinations of colors, opacities, and texture patterns, each combination defining a particular visualization. With multiple user studies we have identified those parameter configurations that allow discerning a maximum number of partially occluded flow directions. We provide a detailed description of our experiments in the following sections.

## 3.1 Experimental Model

### 3.1.1 Streamline Models

We represent a streamline as a line with a specific width and length. The simplest way to apply semi-transparency to a streamline is to set a uniform opacity value for the whole streamline. However, it doesn't provide the best results. Utilizing some kind of a time-dependent texture pattern is beneficial. For example, by moving the texture along the flow primitive we can create an effect of flow motion [Gelder and Wilhelms 1992]. We introduce two general models for the distribution of transparency over a flow primitive.

**Texture Model 1** First, we explore a set of "sawtooth" textures. Examples of this function with different parameters are shown in Figure 2 (a-f). The model is defined as:

$$\psi(x,t) = \pi x + \sigma t \tag{1}$$

$$\kappa = atan(\frac{a_{max} - a_{min}}{A\pi}) \quad (2)$$

$$T(x,t) = \begin{cases} scale\ clamp(\kappa\psi(x,t), a_{min}, a_{max}) & \text{if } \psi(x,t) < C \\ scale & \text{otherwise} \end{cases} \quad (3)$$

$T(x,t)$ represents the texture opacity, where $x$ is a texture coordinate that changes from 0 to 1 - from the start to the end of the streamline. The clamp function returns $a_{min}$ value if its first parameter is less than $a_{min}$ and returns $a_{max}$ value if first parameter is larger than $a_{max}$. Combining *clamp* and $\kappa$ functions allows us to create a variety of texture patterns to control the opacity. Multiplying the expression by *scale* allows us to vary the overall streamline opacity. The $\sigma t$ term relates to the animation of the flow: $t$ is time and $\sigma$ specifies the speed of the animation. If we set $\sigma$ to zero, we enforce non-animated flow pattern. Parameter $C$ controls the width of the "tooth" of the texture. Other parameters for a particular streamline (not included in the above formula) are the line width $w$, line length $l$ and color $c$. Only textures along the flow direction are studied. Equation 3 represents a single sawtooth, and to generate multiple 'teeth' we combine $\lambda$ number of teeth together, as in Figure 2(f). [1]

**Texture Model 2** We also explore the model based on transcendental functions and defined as:

$$\phi(x,t) = sin(\lambda\psi(x,t)) \quad (4)$$

$$T(x,t) = \begin{cases} scale\ clamp(\phi(x,t), a_{min}, a_{max}) & \text{if } \psi(x,t) < C \\ scale & \text{otherwise} \end{cases} \quad (5)$$

In Model 2, $\lambda$ specifies the frequency of *sin* function, and parameter $C$ allows us to create *sin* textures with individual "spikes", as shown in Figure 2 l), m), n).

These two models allow a wide range of textures and are easily controlled for our experiments. The two models do not represent all possible texture patterns, but we feel they are sufficiently rich for our study. We do not believe that introducing a different style of texture would provide substantially different results. We refer to the textures introduced in this section as $T_{sawtooth}$ and $T_{sin}$ in the rest of the paper.

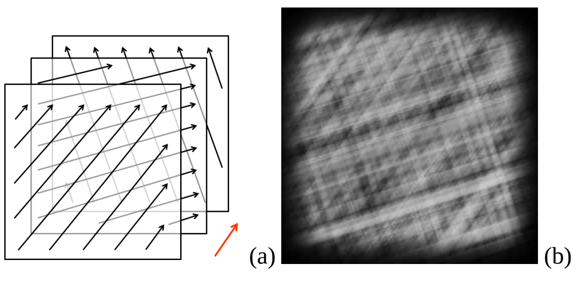


Figure 3: (a) Schematic depiction of the dataset: layers with different flow directions are viewed on top of each other. The red arrow shows the view direction. (b) Experimental dataset visualization: three flow directions visualized. Dark borders are used to highlight the fact that this is not a full-size visualization, but only a part of it. Please notice that we use dark borders for other visualizations in this paper with the same purpose.

[1] We experimented with other functions to generate sawtooth patterns, such as $T(x,t) = Aclamp((x\lambda/\pi + \sigma t) - \lfloor(x\lambda/\pi + \sigma t)\rfloor, a_{min}, a_{max})$, but decided to use Equation 3 as it gives us more flexibility.

#### 3.1.2 Dataset Model

The models introduced above define a single flow geometry primitive. However, visualization depends also on the total number of streamlines and how they are distributed in space. We construct a set of test datasets based on the following observations. For any 3D flow dataset, the viewer sees streamlines projected to a viewing plane. As the vector field representation is discrete, for a specific location (small neighborhood with a size of several pixels) on the viewing plane, there is only one flow direction at a specific depth. Projections of these flow directions to planes parallel to a viewing plane form a "stack" of overlapping flows. The quality of visualization which utilizes semi-transparency depends on how well one can discern these overlapping, partially occluded flow directions at different depths. Thus, for our user study we introduce a test dataset that consists of $n$ overlapping flow layers with homogeneous flow. For each layer, we generate a large candidate set of streamlines. We select a subset based on a metric from this large set. For the experiments described below we used a random subset of streamlines from the candidate set. An example of the experimental dataset is shown in Figure 3.

### 3.2 Parameter Space Exploration

The parameters for streamline models and dataset model define a *13*-dimensional space. The dimensions are:

- $a_{max}$, $a_{min}$, $\lambda$, $C$, *scale*, $A$ (for Model 2), streamline color, streamline width $w$, and streamline length $l$
- steamline density, number of overlapping layers of flow, angle difference between flow directions, animation speed

Thoroughly exploring *13*-dimensional parameter space with a user study is not feasible in any reasonable time. Instead, we have performed a variety of experiments with a limited number of users. We have identified the areas of the parameter space that should be explored and the areas that could be discarded from exploration. In the following subsections we cover in detail how we narrowed down the paramter space and determined ideal parameters of our experimental model.

**Streamline Models Parameters** Our initial sampling included using at least 10 different values for each of the streamline model parameters. We found that the number of 'spikes' or 'teeth' for a texture should be 2, 4 or 8. The images with streamlines that have higher number of 'spikes' are perceived as excessively noisy due to large number of high frequencies in the image. Thus the larger values of $\lambda$ were not used. The parameter $C$ should not be sampled too densely as well. It is almost impossible to recognize the difference between values for $C$ being less or equal to 0.3. In all further experiments we have utilized at most four values of $C$. We substituted the *scale* parameter with $a_{max}$ term for $T_{sin}$ texture and with $a_{max}a_{min}$ term for $T_{sawtooth}$ texture as our experiments showed that premultiplying with these terms achieves a goal of having a scale factor perfectly. The parameter $a_{min}$ is kept low as high values of this parameter result in high opacity of streamlines and visualizations with such streamlines usually don't have more than few layers visible.

**Streamline Density, Streamline Width, and Length** We alter the number of streamlines and streamline width and length to find the level of coverage for a layer. The reason for this is that our

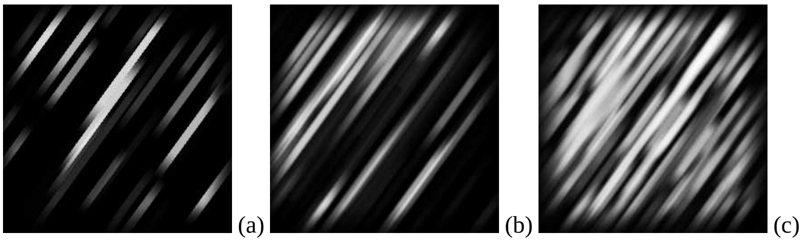


Figure 4: Low (a), medium (b) and high (c) streamline densities for a flow layer.

goal is to create a set of guidelines when the domain is densely covered. We have ensured that there is always a streamline in a given local neighborhood, which leads to a dense coverage overall. We have also ensured that the width of a line on the screen should be at least several pixels, and the line length is much larger than line width. The width of streamlines was fixed for all further experiments. The length was set to be 'infinite', i.e. the streamlines are fully spanning the viewing area. Example visualizations of a flow layer with different streamline densities are shown in Figure 4.

**Animation Speed** We have experimented with a variety of animation speeds. One observation is that perceived animation speed depends not only on the $\sigma t$ term, but also on the other texture parameters in the models that we utilize. For the experiments, we fixed the animation speed in screen space. Faster animation speeds result in visualizations which are harder to perceive, as the visualization becomes temporally incoherent which is often perceived as flickering. On the other hand, slower animation speed and thus slower motion is hard to perceive as well.

**Streamline Colors** For the user study, we have used grayscale for the colors of the animated streamlines. Luminance contrast plays the key role in motion perception [Ramachandran and Gregory 1978].Though color plays a role in the perception of flow velocity magnitude [Weiskopf 2004], in our user study the goal is to differentiate flow directions, rather than flow velocities. Also, we primarily focus on occlusion, which depends on texture opacity and not on texture color. Thus, we use grayscale without any loss of generality. Each streamline was assigned a random grayscale value.

**Dataset Parameters** We have experimented with a variety of number of flow layers in the test dataset. We have found that it is very hard for the user to discern more than 7 or 8 directions, hence we limit our test datasets to 10 flow layers. Each layer has only one particular flow direction. We have used several values as minimal angle difference between flow directions. We ended up fixing the minimal angle difference to be at least 10 degrees. This allows us to focus on discerning significantly different directions. Each of the flow directions is randomly assigned to a particular layer.

**Layer Opacity (Ink)** Some of the streamline textures have such low or high opacities, that in the resulting visualizations it is impossible to discern more than a few flow layers. We use the concept of layer *ink*, that is equal to the total amount of opacity of a layer, as a metric. For a given layer, opacity values for the pixels in the screen are averaged over the animation time period. Then we sum up all the values and divide the sum by the total number of pixels. We find this metric to be useful in describing a particular experiment. Our preliminary experiments allowed us to define a range of ink values when visualizing different streamline models. We present these numbers in Table 1.

Table 1: Parameter ranges before and after parameter space reduction, discussed in section 3.2. The center column shows the ranges that were originally explored while the right column shows the ranges used for the user study.

| Parameter Name | Original | After reduction |
|---|---|---|
| Streamline width | 10 (from 1 to 10) | 1 (fixed width) |
| Animation speed | 5 (slow to fast) | 1 (fixed speed) |
| Streamline colors | $11^3$ | 11 |
| Streamline density | 10 (low to high) | 1 (fixed density) |
| Layer Opacity (Ink) | 0.0 to 1.0 | 0.001 to 0.2 |
| Number of layers | 5 (from 5 to 10) | 1 (fixed at 10) |
| Angle between flow directions | 5 (different angles) | 1 (fixed - at least 10 degrees) |
| $C$ | 10 | 4 |
| $a_{min}$ | 10 | 7 |
| $a_{max}$ | 11 | 11 (not changed) |
| $\lambda$ | 10 | 4 |

# 4 Experiments

After parameter space reduction, we have created two experiments that we describe in detail in the current section. Each test subject was presented with a set of animated flow visualizations. For every visualization in this set the test subject was asked to record the number of flow directions which he or she could discern. There was no maximum time enforced for displaying a particular visualization, the test subjects could spend any amount of time on any visualization. The time spent for decision making, however, was recorded.

## 4.1 Experiment 1

For Experiment 1, "sawtooth" texture patterns were used. Based on the observations from the experiments discussed in Section 3.2, we have selected one hundred texture patterns. Texture parameters used were from a set [0.01, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5] for $a_{min}$, and from a set [0, 0.1, 0.2, ..., 1.0] for A and $a_{max}$, while $C$ was from a set [0.67, 1.57, 2, 3.14]. Ink (layer opacity) using these texture parameters ranged from 0.001 to 0.06. The number of streamlines (density), streamline width and streamline height were all kept unmodified. The resolution for all experiments was a 512 by 512 image. All experiments were conducted looking top-down at the layers. The number of layers was set to 10. Each layer had only one specific flow direction. Flow directions differed by 18 degrees. Each flow direction was assigned to a random flow layer. This random order was not altered when switching between different texture patterns. All streamlines in the dataset (in each layer)

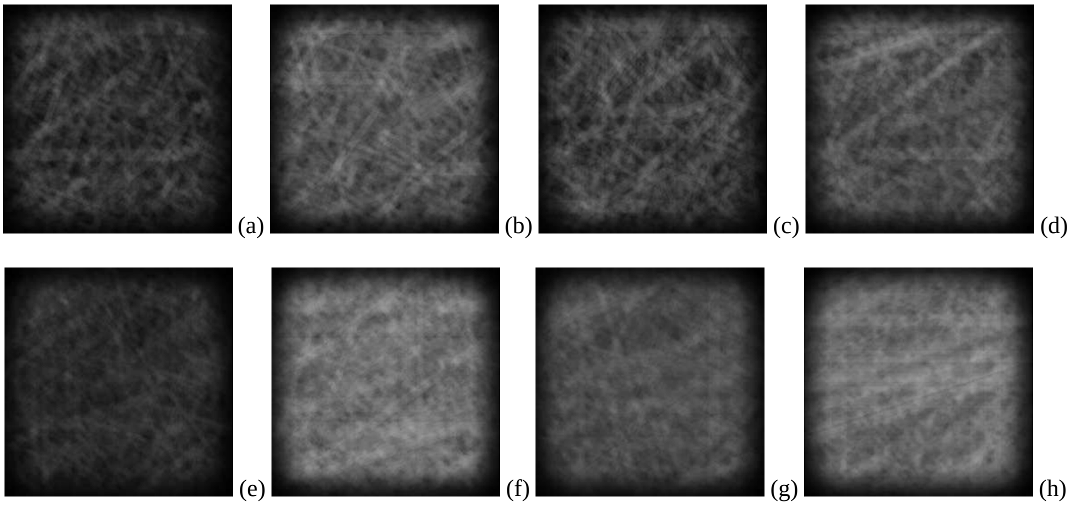


Figure 5: Single frames of animated visualizations used in Experiment 1. Top row: example visualizations with some of the highest scoring textures from Experiment 1. Bottom row: example visualizations with some of the lowest scoring textures from Experiment 1. Bottom row, left (e): too little opacity makes directions hard to discern. Bottom row, (f), (g), (h): high opacity of the front layers results in poor visibility of the further layers. Please notice that without animation, single frames of low scoring visualizations may look more preferable than the highest scoring ones.

used the same texture pattern. The colors for every streamline was selected randomly from a [0, 1] interval (black to white). The background was kept black.

Eleven test subjects have participated in the user study. All had normal or corrected to normal vision. All were graduate students majoring in Computer Science, 10 males and 1 female. Three were familiar with flow visualization. Each of the test subjects was shown 100 visualizations. For every visualization the number of discernible directions was recorded.

The numbers from the user study form a 2D matrix of results $R$, with rows corresponding to textures and columns corresponding to test subjects. If we use $i$ as a row index and $j$ as a column index, then $R(i,j)$ is the number of directions for visualization with texture $i$, discerned by a test subject $j$. For each texture $i$, we average the number of discerned directions over all test subjects. This allows us to find textures performing better on average and minimize importance of outliers. We present maximum, minimum, and mean texture scores and times in Table 2(a).

Table 2: (a) Maximum, minimum, and mean texture scores and times (in seconds) for Experiment 1. The score for each texture was calculated by averaging the number of discerned directions for the texture over all test subjects. (b) Details of the highest and the lowest scoring textures for Experiment 1.

| | |
|---|---|
| Max number of directions discernible | 6.3 |
| Min number of directions discernible | 2.0 |
| Mean number of directions discernible | 5.0 |
| Max time | 63s |
| Min time | 8s |
| Mean time | 18s |

(a)

| Highest scoring textures (average score $\geq$ 5.9) | Lowest scoring textures (average score $\leq$ 4) |
|---|---|
| Number: 10 out of 100 | Number: 10 out of 100 |
| Average ink: 0.038 | |
| Maximum ink: 0.051 | Low scoring high opacity textures average ink 0.054 |
| Minimum ink: 0.025 | Low scoring low opacity textures average ink 0.012 |

(b)

There is an interesting observation about the results of Experiment 1. While the best scoring textures look relatively similar and have similar opacity distributions, the lowest scoring textures fall into one of the two categories: the ones with too high or too low ink. We show ink values for these textures in Table 2(b). Figure 5 shows example visualizations with some of the highest and the lowest scoring textures.

## 4.2 Experiment 2

For Experiment 2, the setup was the same as for Experiment 1, except for a different streamline texture pattern and adding 0.0 to a set of $a_{min}$ values. "Sin wave" texture patterns were utilized. A candidate set of 100 textures was selected. As in Experiment 1, the same eleven test subjects have participated in Experiment 2.

Table 3: (a) Maximum, minimum, and mean texture scores and times (in seconds) for Experiment 2. The score for each texture was calculated by averaging the number of discerned directions for the texture over all test subjects. (b) Details of the highest and the lowest scoring textures for Experiment 2.

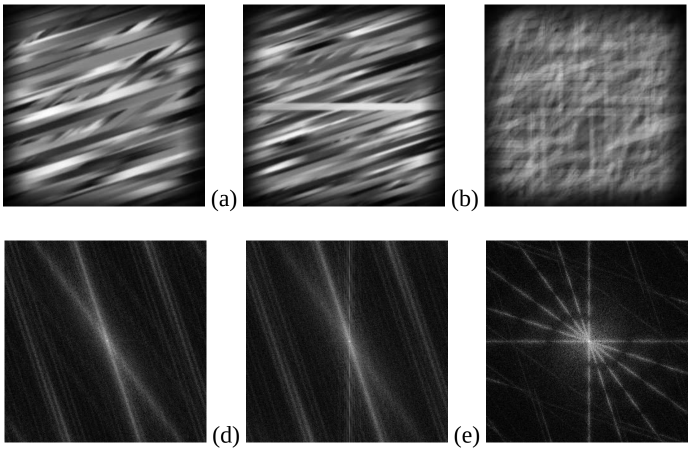
| | |
|---|---|
| Max number of directions discernible | 5.7 |
| Min number of directions discernible | 3.7 |
| Mean number of directions discernible | 4.7 |
| Max time | 70s |
| Min time | 11s |
| Mean time | 19s |

(a)

| Highest scoring textures (average score $\geq$ 5.4) | Lowest scoring textures (average score $\leq$ 4.1) |
|---|---|
| Number: 12 out of 100 | Number: 12 out of 100 |
| Average ink: 0.083 | |
| Maximum ink: 0.154 | Low scoring high opacity textures average ink 0.165 |
| Minimum ink: 0.027 | Low scoring low opacity textures average ink 0.017 |

(b)

We present the results of Experiment 2 in Tables 3(a) and (b). As with Experiment 1, there are two sets of the highest and the



(a) (b) (c) (d) (e) (f)

Figure 6: Top row shows example visualizations and bottom row shows their corresponding 2D Fourier transforms. Left: two visible flow directions result in two lines in Fourier space. However, as the further flow direction visibility is low due to occlusion, its 'stripe' in frequency domain is blurred and less sharp than that of the front layer. Center: Even a single well visible horizontal streamline results in a new direction in the frequency domain (notice a vertical line in Fourier space). Right: a total of six directions are visualized and all six directions in the top visualization are discernible. Corresponding directions in the frequency domain are visible.

lowest scoring textures, respectively. We present the exact parameters of the highest-scoring textures, along with the scores and standard deviations for both experiments online at www.cse.ohio-state.edu/research/graphics/. Figures 2 (b)-(e) show the highest scoring $T_{sawtooth}$ textures from Experiment 1, and figures 2 (l)-(o) show the highest scoring $T_{sin}$ textures from Experiment 2.

## 4.3 Analysis in Frequency Space

To get a better understanding of why certain visualizations in our user studies have larger number of discernible directions than the others, we found it useful to look at the visualizations in the frequency domain. Figure 6 shows three example visualizations and their corresponding 2D Fourier transforms. The top left image shows visualization with only two flow directions discernible. Two flow directions correspond to two directions in the Fourier space. The opacities of the streamlines are high, occluding the other flow directions, which results in blurred and vague corresponding stripes in the frequency domain. The center image adds a single horizontal streamline and thus flow direction which adds a vertical stripe to the frequency domain. The right image has six different flow directions. All of them are discernible and are represented in Fourier space by corresponding stripes. Overall, clear, discernible direction in image space results in a sharp, clear stripe in frequency domain. Barely discernible directions, on the other hand, result in more vague and blurry stripes in frequency domain.

## 4.4 Visualization Guidelines

Based on the results from the experiments with a limited number of users, as well as results from Experiments 1 and 2, we formulated the following guidelines for visualizing semitransparent flow. Guidelines for opacities and number of discernible flow directions follow directly from Tables 2 and 3, while the rest of the guidelines summarize our observations discussed in Section 3.2.

**Opacity**

- Opacity of a small neighborhood at a particular depth should not be less than approximately 0.03, and should not exceed approximately 0.15.

**Number of flow directions**

- It is difficult to perceive more than 7 overlapping flow directions at different depths. As a guideline, when designing a visualization, one can not expect users to discern more than 7 depths of flow.

**Ink distribution**

- Using animated opacity along a streamline provides both better flow visualization and reduced occlusion.
- While opacity along the streamline can be distributed in a variety of ways, it should cover at least 50 percent of the streamline.
- The difference between minimum and maximum opacities for a streamline should be at least 10 percent. Otherwise, the result would be an 'almost solid' streamline with hard to discern flow motion.

**Animation**

- Using animation to reveal flow features with motion is crucial. When the speed is too slow, animation does not help in revealing flow features. High animation speed results in incoherency and perceived flickering of the visualization.
- Streamline texture models create a periodic pattern. The animation speed should be selected in a way that the texture does not move for more than a half of a function period in two successive frames. This implies that texture models with larger frequencies (the larger number of 'spikes') should be animated with a slower speed than the ones with the lower frequencies.

We would like to stress the following. Despite the fact that the results confirm our common sense that too little opacity or too much opacity are equally bad and that the opacity on the individual streamline should occupy more than just a small fraction of the streamline, randomly picking a texture that 'seems right' may not generate effective visualizations.

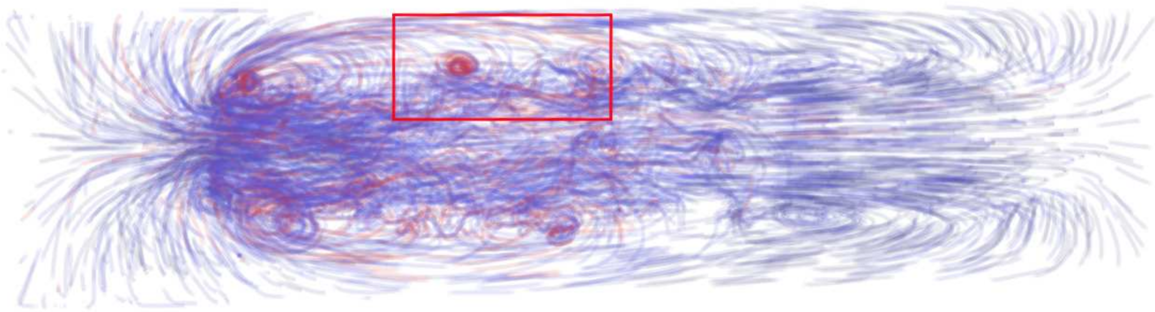


Figure 7: A single frame of animated Plume dataset visualization. We used semi-transparent streamlines with one of the highest scoring $T_{sin}$ textures to create it. Highlighted is a part of Plume dataset that is later used in visualizations in Figure 8.

## 5 Evaluation and Comparison

To evaluate the results of our user study, we created visualizations of the *Plume* dataset. In Figures 7 and 8 we show different visualizations of *Plume*. All visualizations use the same color scheme based on streamline curvature. Streamlines with higher curvature are colored red and streamlines with lower curvature are colored blue. Figure 7 shows one frame of the animated visualization of *Plume* with one of the highest scoring $T_{sin}$ textures. With semi-transparent streamlines, complex inner flow features are visible. The animated visualization is included as an accompanying video with the paper [2].

In Figure 8, we provide a comparison of visualizations of a part of *Plume* dataset that is highlighted in Figure 7. Utilizing opaque streamlines with halos, as shown in Figure 8(a) introduces occlusion which makes it hard to reveal complex inner flow structures. For example, circular structure with red streamlines, which is clearly visible in Figures 8(b) and (c), is fully occluded and not discernible in Figure 8(a). Figure 8 (b) shows one frame of animated visualization that uses one of the highest scoring $T_{sin}$ textures. Figure 8 (c) uses semi-transparent streamlines with uniform opacity distribution. Total opacity for a streamline is the same as for streamlines shown in Figure 8(b). Both images with semi-transparency ((b) and (c)) reveal the complex flow features well. However, there is an important difference. While streamlines with uniformly distributed opacity provide smoothness and coherency, animated streamlines with non-uniform opacities greatly enhance perception of the flow. In the accompanying video[2] we show side-by-side comparison of flow visualizations that use animated and non-animated flow, with single frames shown in Figures 8 (b) and (c), respectively.

## 6 Conclusion and Future Work

In this paper, we have described the details of a user study that explored how semitransparency can be applied to three dimensional flow visualization. Experimental setup was the following. Dense textured lines were used to visualize flow. We have introduced streamline texture models and used overlapping layers of flow with different directions as experimental datasets. We explored the experimental parameter space and performed a user study to find the parameters that allow the user to discern a maximal number of flow directions. Based on these results, we formulated a set of visualization guidelines.

There are multiple research directions that we would like to pursue in the future. We would like to extend the current study to answer the following question. Given that a number of occluded flow directions in the dataset is larger than a user can perceive at once, how do we select which flow directions to show the user at a given spatial location? We would like to analyze and cluster the top performing parameters. This should give us insights on how the top performing parameters are distributed in *n*-dimensional space. Picking the best texture from each cluster, we can then explore the effectiveness of using different textures for each layer. Another interesting problem is quantizing arbitrary flow directions in a dataset to, say, 10 predefined ones. Thus, for a given view, the user doesn't have to perceive more than 10 flow directions simultaneously. Of course, the question on the quality and error bounds of the visualization arises in such scenario. We also plan to extend our study to LIC with multiple overlapping flow layers.

[2]The videos are available at www.cse.ohio-state.edu/research/graphics/

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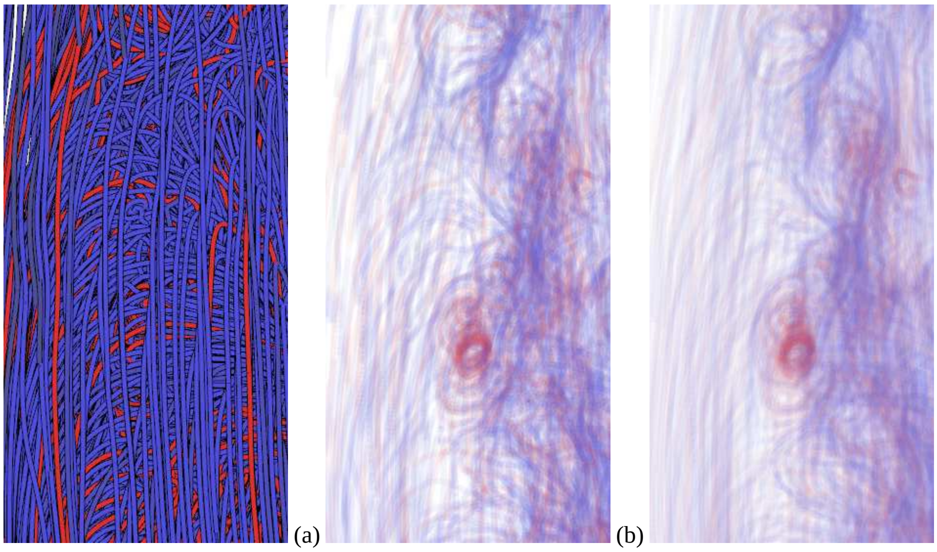

Figure 8: Visualizations of a part of Plume dataset. (a) Plume visualized with opaque streamlnes with halos. (b) One frame of animated visualization of Plume with one of the highest scoring $T_{sin}$ textures. (c) Plume visualization that uses semi-transparent streamlines with uniform opacity distribution.


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