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Short Paper

A Stream Ribbon Seeding Strategy

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Abstract

Streamline seeding algorithms have a long and rich history dating back over two decades. And in recent years algorithms for stream surface placement have been developed. However, stream ribbons have been generally overlooked. We present, to our knowledge, the first stream ribbon seeding strategy. Stream ribbons are a tool for visualizing vector fields and are a common extension of streamlines with the added benefit of conveying a fluid's twisting motion along the direction of flow. Presented in this short paper is a novel strategy for seeding stream ribbons in vector fields. The strategy exploits the flow's local helicity, an important property of flow identified over 40 years ago, to guide ribbon seeding. Seed points are prioritised based on a derived helicity field. A selection of user options including adjusting ribbon width, separating distance, and ribbon length filtering are applied to support visualization and cater to the users interests. A filtering method is also presented whereby the number of stream ribbons can be reduced in order to highlight the most helical flow features. We demonstrate the technique on various flow fields and report feedback from a domain expert in fluid mechanics.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithm

1. Introduction and Motivation

Understanding the way in which objects interact with fluids is crucial in many industrial applications, therefore being able to visualize important features of a vector field is valuable. Streamlines offer an intuitive approach to visualizing the properties of flow, although they have limitations. Streamlines are less capable of conveying the twisting behaviour of the flow orthogonal to the direction of the flow.

Stream ribbons are an extension of stream lines, where an infinitely thin, fixed-width surface is attached to the streamline, enabling the orthogonal twisting of flow to be conveyed. This twisting motion is known as the helicity of the flow field. Helicity is the measure of knottedness and the tangle of a flow, an important property identified more than 40 years ago [Mof69]. This can be thought of as the tendency of a streamline to rotate or the amount of corkscrew motion along its length.

Streamlines have had a plethora of seeding strategies proposed over the last thirty years and a number of automatic seeding approaches already exist for stream surfaces [EML*11, ESRT13, BH15]. However, to our knowledge, no strategy yet exists specifically for stream ribbon seeding.

Stream Ribbons versus Stream Surfaces: A stream ribbon has properties in common with a stream surface, however unlike stream surfaces, the width of the stream ribbon is fixed. Stream ribbons are primarily used to highlight the helical features along the corresponding streamlines, whereas a stream surface is often used to represent the whole flow domain and partition the flow into different regions of flow behaviour. Stream surfaces may also be used to highlight features like vortices. However, stream ribbons are more common, especially in commercial packages such as Tecplot, because they are easier to implement than stream surfaces. Ribbons also create less occlusion compared to surfaces. In this paper, we focus specifically on stream ribbon seeding, a topic which, until now, is generally overlooked. The contributions of this short paper are:

- A novel seeding strategy for stream ribbons that exploits vector field helicity in order to guide placement of ribbons.
- User-adaptable seeding options and filtering techniques for the resulting stream ribbons.
- The first reactions and feedback from a domain expert in fluid mechanics.

2. Related Work

Streamline seeding algorithms have a rich history stretching over two decades. The survey paper by McLoughlin et al. cites 18 different streamline seeding algorithms [MLP*10].

Four survey papers can be used to highlight relevant work in flow field visualization [MLP*10,ELC*12a,PL09,BCP*12]. McLoughlin et al. summarize integration-based flow visualization methods in their survey paper [MLP*10]. Papers are classified first by the dimensionality of the visualization object: curves, surfaces or volumes. The second level classification used is the spatial dimensionality of the data followed by the temporal dimensionality. Seeding strategies provide a central theme and include 70 different papers. The paper accentuates solved challenges in geometric flow visualization and, in turn, highlights areas that are open to future research.

The surface-based flow visualization survey by Edmunds et al. [ELC*12a] discusses surface-based flow techniques and surface construction. Papers are initially classified into two main categories: construction and rendering. Surface construction techniques include 24 papers and rendering flow-based surfaces cites another 29. Surface construction techniques are further sub-divided into integral, implicit and topological while the rendering research is grouped into direct, geometric, and texture-based.

Peng and Laramee survey vector field visualization in 3D, and on 3D surfaces [PL09]. Papers are classified by the visualization technique; direct, geometric, texture-based, and feature based.

Illustrative techniques for flow visualization are examined in a survey by Brambilla et al. [BCP*12]. Illustrative techniques take inspiration from traditional hand crafted visualizations and address occlusion, cluttering and depth perception issues. Papers are classified based on a user-centric approach, according to what illustrative problems they address, such as perception, visibility, and feature focus.

The use of stream ribbons for visualizing flow was introduced by Volpe [Vol89]. He suggested using adjacent streamlines to form the surface of a ribbon. However if the streamlines exceed a specified separation tolerance, the ribbon is discarded. Schroeder et al. developed the stream polygon [SVL91]. A stream polygon is an n-sided polygon that is normal to a streamline, the deformation of which represents the shear and rotation of the flow. Multiple stream polygons can be placed along a streamline to convey the properties of the flow. Pagendarm and Walter describe the construction of a stream ribbon by using the angular velocity of a flow about the streamline [PW94]. The technique enables the construction of wide stream ribbons without the complexity of divergence seen when using multiple streamlines. This ribbon construction technique is used for the examples seen within this paper.

Automatic seeding algorithms have been applied to other stream objects, such as stream surfaces. Stream surfaces are surfaces constructed between streamlines to create a surface. Edmunds et al. present an automatic stream surface seeding algorithm [EML*11]. Surfaces are seeded at the domain boundary from isolines derived from a scalar field. The methods are further extended by Edmunds et al. [ELC*12b], enabling stream surfaces to be seeded based on inner regions of the flow domain. Edmunds et al. present an adapted vector field clustering algorithm to guide stream surface seeding [ELM*12]. Clusters are ordered hierarchically and a simplicity level parameter is used to identify clusters for seeding the surfaces. Seeding curves are computed from a derived field curvature.

A global stream surface selection method is proposed by Esturo et al. [ESRT13]. The method measures stream surface relevance by how well they align with the principle curvatures of the flow. This method is later improved to produce multiple surfaces by Schulze et al. [SEG*14]. Brambilla and Hauser developed another approach for seeding stream surfaces [BH15]. The algorithm seeds streamlines around a user selected point and measures their similarity, these seed point similarities are then used to create tensors for seeding stream surfaces.

Proposing a seeding strategy for stream ribbons differs from that of seeding stream surfaces. A seeding algorithm for ribbons focuses on conveying the local helicity of the flow—the primary strength of stream ribbons. Seeding strategies for surfaces are generally designed for other purposes such as partitioning the domain, highlighting vortices, and perhaps other features of the flow. To our knowledge this is the first algorithm specifically for ribbons.

3. Stream Ribbon Seeding

This section provides the definition of helicity and presents the seeding strategy and user-options developed for this prototype.

Description of Helicity: Helicity is the measure of the knottedness and how tangled a vector field is. This can be thought of as the tendency of a streamline to rotate or the amount of corkscrew motion along it's length. Helicity per unit volume or helicity density is defined as 1.

$$Helicity\ density = (\nabla \times v) \cdot v \tag{1}$$

Where v is the velocity field and $(\nabla \times v)$ is the vorticity field [Mof69]. The Jacobian matrix, ∇, denotes the velocity gradient of the vector field [LGSH06].

Derivation of Helicity Field: To calculate the helicity field of a flow field, the vorticity is first calculated. The equation for vorticity is:

$$\nabla \times v = \begin{bmatrix} \frac{dv_z}{dy} - \frac{dv_y}{dz} \\ \frac{dv_x}{dz} - \frac{dv_z}{dx} \\ \frac{dv_y}{dx} - \frac{dv_x}{dy} \end{bmatrix} \tag{2}$$

Where $\frac{dv_z}{dy}$ is the gradient of the z-component of the vector in the y-direction [Rot00]. Once the gradient of each data sample is calculated, the resultant vorticity vector is multiplied using dot product with the local velocity vector (Eq1) to derive the helicity for a given vector sample in the flow field. We direct the interested reader to Roth's work for further details [Rot00]. Alternatively, helicity can be computed at run time in order to save disk space, at the expense of computation time.

A Ribbon Seeding Strategy Given a scalar helicity field and it's associated flow field, vertices are ordered in descending value according to the helicity magnitude. Helicity is directional, an anti-clockwise motion is positive while a clockwise motion is a negative helicity value. Because the direction of helicity is not always important, the helicity magnitude is used. Ribbons can be seeded at any data sample position showing the highest helicity magnitude value. Stream ribbons are integrated forwards and backwards from this seed point. The user may continue adding stream ribbons at successively lower values starting from the maximum. This approach however can have limitations as often two adjacent data sample positions may have a similar helicity magnitude and so the ribbons created from the seed points may wrap around one another. This effect is more pronounced in simulations with more nodes.

To overcome this issue we propose to use a technique similar to that used by Jobard and Lefer in 2D flow fields [JL97], and used by Spencer et al. on 3D surfaces [SLCZ09]. These allow the seeding of streamlines, or in this case stream ribbons, a fixed distance (d_{sep}) from another streamline. Stream ribbons also terminate when they are too close to another stream ribbon (d_{test}). The separation distance between stream lines (d_{test}) can be controlled by the user. Stream ribbon seeding order is dictated by the helicity magnitude, as long as the next seeding point is a user-controlled minimum distance d_{test} away from previous stream ribbons. A ribbon (S) is constructed forward and backward from each seed point. Once all vertices within the flow domain are analysed as seed points, the algorithm is complete. The algorithm is summarized in pseudocode.

```
Input: $Q_p$: priority queue of domain samples
          in decreasing helicity magnitude
       $d_{test}$: Minimum seperation distance
       $l_{min}$: Minimum ribbon length
Output: $Q_s$: queue of ribbons to render
Local Variable: $p$: Current data point
                $S$: Current ribbon
seedRibbons($Q_p$, $d_{test}$, $l_{min}$)
WHILE $Q_p.!empty()$
  $p \leftarrow Q_p.removeMax()$
  WHILE $S$ !terminated
    IF ($p.isTerminated(d_{test}, Q_s)$)
      $S.terminate();$
      IF $|S| < l_{min}$
        Discard($S$);
      ELSE
        $Q_s.enQueue(S);$
    ELSE
      $S \leftarrow S + p$
    $p \leftarrow p.integrate().nextPoint();$
return $Q_s$;
```

```
Input: $p$: Current data point
       $d_{test}$: Minimum seperation distance
       $Q_s$: queue of ribbons
Output: boolean - true if point is valid
Local Variable: $S_{test}$: Test ribbon
       $p_{test}$: Test data point
isTerminated($d_{test}$, $Q_s$)
FOR EACH ribbon $S_{test}$ in $Q_s$
  FOR EACH point $p_{test}$ on ribbon $S_{test}$
    IF $p$ exceeds domain boundary
          return TRUE;
    IF $|p - p_{test}| < d_{test}$
          return TRUE;
return FALSE;
```

3.1. User-Adaptable Seeding Options

Filtering Based on Length $|S|$: A tendency for producing many short ribbons can sometimes be observed, these ribbons may offer less insight into flow patterns. To prevent this a minimum stream ribbon length, l_{min}, option is proposed as a user option. This rejects seeding points where the resulting stream ribbon length, $|S|$, does not meet the given minimal length l_{min}. See figure 1.

Domain Coverage: Ideally the stream ribbons reflect all features in the vector field, even where the helicity magnitude is low, in order to convey a full overview of behaviour. It may therefore be important to depict flow characteristics in all areas of the vector domain. This however can lead to cluttering and potential occlusion issues. Thus a balance needs to be found. Occlusion is a particular challenge with ribbons as they are essentially wide lines which occupy more visual space, leaving less space to view the centre of the volume.

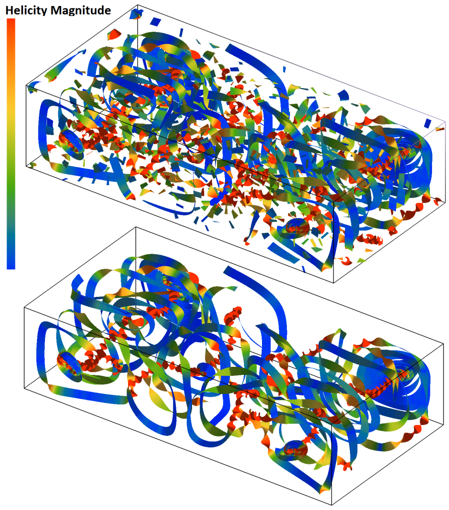

Figure 1: *Two Rayleigh-Bénard convection flows with ribbons seeded using our strategy. The first has the user option of a short l_{min} (5 integration steps) while the second has a long l_{min} (999 integration steps). Colour is mapped to helicity magnitude.*

To address cluttering, a filtering option is proposed that removes the last seeded ribbon, i.e. the ribbon seeded at the point with the lowest helicity magnitude, $|H|_{min}$. Further filtering removes the ribbon with the next smallest helicity magnitude and so on until all ribbons may be removed. See figure 2 (a & b).

Density: Another user option that addresses cluttering is the minimum separation distance d_{test}. By increasing d_{test}, the space between ribbons increases enabling space to view into the centre of the flow domain. See figure 2 (c & d).

Width: If ribbons are too wide there is greater potential for occlusion, but if too small the twisting behaviour is difficult to observe. The ribbon width, S_w, is therefore proposed as another user option. We also implemented some visual correctness verification options shown in the supplementary video.

4. Results

The success of the strategy can be judged upon whether a suitable representation of the flows and characteristic helicity are seen in the figures and by domain expert user feedback. In the three example flow sets used here, the helicity and flow features can be observed. In order to obtain the best representation of the flow however, it is advisable to tune the user options to each specific flow or user.

Figure 1 shows two images of a Rayleigh-Bénard convection flow with ribbons seeded by the strategy outlined in this paper. The flow is from a numerical simulation on a regular Cartesian grid of size $128 \times 32 \times 64$ [WSE05]. The top image has a very short minimum ribbon length, $l_{min} = 5$ integration steps, as set by the user. Many short ribbons can be seen within the flow domain that convey little information to describe the flow features. In contrast, the bottom image has a larger l_{min} of 999 integration steps, therefore only showing longer stream ribbons.

The ribbon seeding strategy is exemplified in figure 2 (a & b), an Arnold-Beltrami-Childress (ABC) flow, represented on a Cartesian

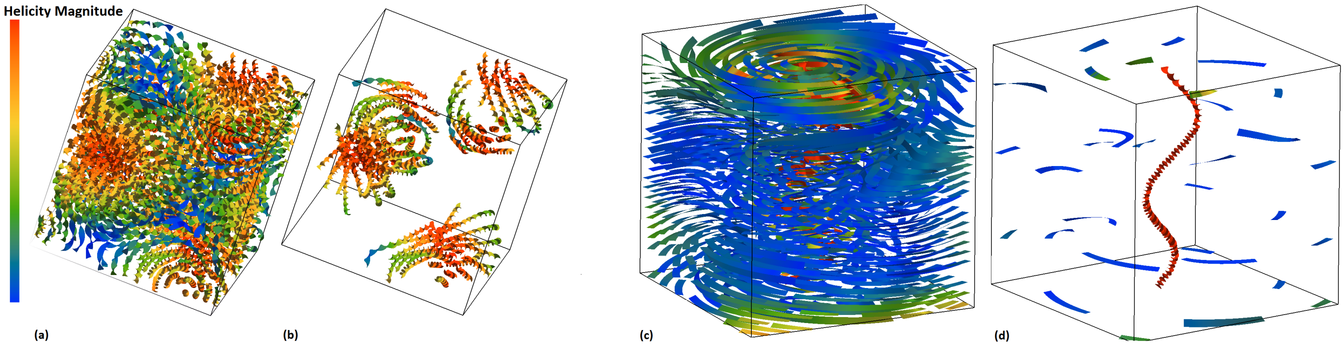

Figure 2: *Stream ribbons in a Arnold-Beltrami-Childress (ABC) flow (a & b) and a tornado simulation (c & d). Image (a) shows a dense ribbons seeding (dense coverage, 0% of ribbons removed), while image (b) shows the ribbons remaining after filtering the ribbons seeded at the lowest $|H|$ values (sparse coverage, 85% of ribbons removed). In image (c) the user has opted for d_{test} = 3% of domain length (very dense), in contrast to d_{test} = 23% of domain length in image (d) (sparse). Colour is mapped to $|H|$.*

grid of 128^3 [DFG*86]. Image (a) highlights all ribbons seeded within the flow domain, resulting in occlusion. The filtering option of removing the stream ribbons seeded from the least helical points is applied to produce image (b). This leaves only the most helical flow features.

Figure 2 (c & d) shows the ribbon seeding strategy applied to a numeric tornado simulation, both on a 128^3 Cartesian grid. These illustrates the difference between using a large ribbon separation distance, d_{test}, (c), and a large d_{test} in image (d).

Supplementary Video: The user adaptable seeding options are demonstrated in the accompanying video.

`https://vimeo.com/201876574`

Domain Expert Review: The following is feedback directly from a domain expert in fluid mechanics. He describes flow behaviour conveyed specifically by the algorithm presented here.

Thorough considerations for providing usability and flexibility are crucial when we develop a visualization tool. It is especially so for the tool that is designed to help explore the flow parameter (helicity density in the present case) in a variety of complex flows. The helicity density represents the vorticity stretching: it is a consequence of the conservation of angular momentum. The three examples presented here demonstrate our effort to achieve the usable functionality providing a variety of the options available to the users.

The visualization of the tornado simulation gives a clear indication of the presence of vortex core, while the surrounding flows are essentially irrotational. Unlike a visualization of the vorticity field by itself, the stream-ribbon visualization can explicitly show the behavior of vorticity "stretching" in the irrotational vortex field: this is a typical flow phenomenon presented in a textbook of fluid mechanics [Ach90].

Unlike the example of a tornado, the visualization of the ABC flow exhibits vortical flow "regions" for the periodical flows. Each stream ribbon shows variable vortex stretching and compression. In contrast the vortex core appeared in the tornado shows a single long string of vortex stretching.

The example of the Rayleigh-Bernard convection cell shows the mixture of the irrotational flow regions and the vortex stretching along the center of the cell as well as the region near the boundaries. Such behavior is due to the vorticity generation within the flow domain of the convection cells.

5. Conclusion

We present a novel stream ribbon seeding strategy that exploits the helicity of the vector fields to guide the placement of stream ribbons. User options facilitate feature discovery within the flow domain. A filtering option is also given for the resulting stream ribbons to enable a trade-off between visualizing the whole field and reducing the potential for occlusion.

Limitations & Future Work: When the least helical parts of a vector field are at the centre of a flow domain, the filtering technique would first remove the stream ribbons at the centre of the domain, making little contribution to the clutter problem for which the technique is implemented. Wide ribbons can also become distorted in very helical flows. The magnitude of the helicity is such that a wide ribbon surface intersects itself. Future work for this project includes creating a stream ribbon similarity index similar to the streamline similarity concept proposed by Chen et al. in [CCK07] and McLoughlin et al. in [MJL*13]. The aim is to represent the whole flow domain with the minimum possible number of stream ribbons to minimise the potential for occlusion. Adding illustrative rendering techniques such as halos to the ribbons would also contribute to the visual enhancement of the results.

The technique currently used to calculate the initial lateral orientation of a ribbon uses the normal between the velocity vector and a coordinate axis (z-axis). If the velocity is aligned with that axis, an alternative axis is used. An investigation into using different axes for deriving the initial normal, or using an alternative method is another avenue for future work.

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