Visual Analytics of Flow Features on Unstructured Grids

Category: System

1 Motivation

Computational fluid dynamics simulations are rapidly increasing in both capability and scale, leading to a massive increase in the amount of data that must be processed and analyzed. The maturation of technology has led science to a point where it is no longer sufficient to compute these simulations to prove that they can be done. Rather, science has led to a point where it is no longer sufficient to provide analysis tools that operate explicitly on unstructured grids, including Schlieren, shadowgraphy, silhouettes and contour rendering. Meanwhile, statistical and numerical computation on flow properties and features (e.g., density discontinuities, directional derivatives, Mach number, vorticity and helicity) enable global quantitative analysis of flow behavior. The user is engaged in an interactive visual analytics loop with a set of visualization and illustration motifs, such as feature-based transfer functions, contour rendering. Meanwhile, statistical and numerical computation on flow properties and features (e.g., density discontinuities, directional derivatives, Mach number, vorticity and helicity) enable global quantitative analysis of flow behavior. The user is engaged in an interactive visual analytics loop with a set of visualization and illustration motifs, such as feature-based transfer functions, statistical and numerical computation.

Index Terms—Flow Features, Visual Analytics, Illustrative Visualization, Multiple Shock Identification, Unstructured Grids

Abstract—Volume visualization and illustration techniques have proven to be effective in enhancing the depiction of scientific data. However, analysis is an essential component of visual exploration and discovery. Consequently, visualization and analysis are best performed within an integrated visual analytics environment. Moreover, the exploration and analysis tasks for complex, large-scale data need to support operations and exploration on features, their spatial and numerical properties, and not simply visualization of massive raw data. In this paper, we introduce a novel visual analytics system for representing, discovering, analyzing, and understanding flow features of multivariate, non-uniformly sampled datasets. Our system allows the user to visually explore and numerically analyze complex flow behaviors by means of a combination of feature-based transfer functions, statistical and numerical computation, and interactive illustration and photographic motifs. Spatial explorations on flow features are enabled by means of a set of structure enhancement techniques in the context of unstructured grids, including Schlieren photography, shadowgraphy, silhouettes and contour rendering. Meanwhile, statistical and numerical computation on flow properties and features (e.g., density discontinuities, directional derivatives, Mach number, vorticity and helicity) enable global quantitative analysis of flow behavior. The user is engaged in an interactive visual analytics loop with a set of visualization and illustration motifs, such as feature-based transfer functions, contour rendering. Meanwhile, statistical and numerical computation on flow properties and features (e.g., density discontinuities, directional derivatives, Mach number, vorticity and helicity) enable global quantitative analysis of flow behavior. The user is engaged in an interactive visual analytics loop with a set of visualization and illustration motifs, such as feature-based transfer functions, statistical and numerical computation.

1. Presentation of work

Presented in this paper is a visual flow analytics system that allows computational fluid dynamics researchers to discover, describe, investigate, and predict flow behaviors with integrated analysis and interactive visualization tools. Our integrated environment helps flow researchers answer questions that arise from the exploration of new concepts, theories, and calculations. This visual analytics framework is designed for flow feature exploration and analysis, and builds upon the latest visualization, illustration, and flow feature methods. This work provides the following contributions:

- An effective scheme for simultaneously performing interactive spatial, structural, and numerical analysis in an integrated environment
- A user interface that enables dual domain interactions and stresses feature analysis
- A set of visualization techniques that operate explicitly on unstructured grids, including Schlieren, shadowgraphy, silhouette and contour rendering
- A set of numerical and statistical analysis tools that provide the user insight into the defined features of the flow datasets

Figure 2 shows an overview of our visual flow analytics system. Our integrated framework reduces visual clutter while providing global statistics and visualizations with the ability to investigate localized features and interesting patterns. Our visual analytics framework is designed to enable the efficient identification, visualization, and numerical validation of critical flow characteristics such as shock waves and vortices.

We briefly summarize relevant work in Section 2 and present our visual analytics environment that combines illustrative motifs and feature exploration toolkits in Section 3. Section 4 and Section 5 explain flow feature calculation and our extended illustrative techniques for feature enhancement on unstructured grids. We further demonstrate the differentiation of shock wave using our system in Section 6. Discussions and conclusions are presented in Section 7 and Section 8.

2 Related Work

2.1 Visual Analytics Systems

The need to visually analyze scientific simulations drives the development of visual analytics systems. For example, workflow systems [3, 23] provide an effective visual reasoning module to gain feedback from the simulations and accelerate the workflow. Visualization systems [1, 8] provide general purpose visual analysis abilities on scientific data. The systems focusing on CFD data [2, 6] integrate multiple views to assist the data exploration. However, features are not
always detected due to the limitations of their rendering and analysis abilities.

Compared with previous systems that seek to combine analysis into the visual exploration environment, our system offers more flexibility in both the numerical analysis and feature enhancement. With our system, multi-dimensional transfer functions can be easily designed based on the informative characteristic of the underlying unstructured grids. In addition, our novel illustrative and photography inspired renderings for unstructured grid datasets help scientists to effectively visualize features.

2.2 Flow Visualization and Feature Detection

Researchers have developed many techniques for representing flow dynamics with expressive glyphs (e.g., arrow plots, streamlets, and streamlines [27]). These methods directly map the flow into a point-based visual representation and have proven to be very useful for investigating 2D and simple 3D flows. Particle traces (e.g., pathlines, streamlines, streaklines, and timelines [35, 36]) can be used to provide a sparse representation of flow dynamics. By representing the structures induced from particle tracing with a dense coverage, the instantaneous structure of the flow and its temporal evolution can be clearly visualized (e.g., LIC [28] and texture advection [18, 37, 40]).

Feature-based flow visualization computes an abstractive representation by filtering the data based on regions of interest. Common fluid flow features include vortices, shock waves, separation and attachment lines, recirculation zones, and boundary layers. These techniques can be classified by their approach: image processing, topological analysis and physical characterization of the flow [24]. Topology-based methods [27] are used to find interesting critical points [26]. Specific methods are used to find other flow features such as vortices [10, 12, 14, 25], shock waves [17, 20] and feature separation and attachment [13]. Shock waves and separation and attachment lines typically require specifically designed extraction techniques that are based on physical or properties of the flow. Hierarchical methods based on clustering have been used for vector simplification and to provide spatial information [35].

2.3 Volume Rendering and Illustration on Unstructured Grids

Previous work on visualizing unstructured grids can be roughly divided into two classes, ray casting and cell projection. By decomposing the projected shape of a tetrahedron into multiple triangles, the projected tetrahedra algorithm [29] is suitable for sparse datasets and easily accelerated with graphics hardware [16]. Straightforward GPU implementations of ray casting [22, 38] and cell projection [39] have achieved good speedup through parallelism. Other GPU-based approaches either reduce the rendering artifacts [16], or improve the performance by employing optimized data structures [4, 5]. Illustrative visualization techniques enhance the structural perception of datasets through the amplification of features and the addition of artistic effects. Typical volume illustration algorithms [7] work for regular volume data and are limited to moderate data sizes. Inspired by the art and photography used in experimental flow visualization, illustrative visualization of flow dynamics has attracted the attention of many researchers [11, 15, 31, 33]. Although the work in [32] extends volume illustration to irregular volume data, it does not incorporate many advanced flow features.

GPU-based Projected Tetrahedra (PT) rendering engine [30] enables two-dimensional transfer function design and rendering on tetrahedral grids. We extend this work with illustrative visualization techniques for flow feature enhancements.

3 Visual Analytics for Flow Features

Our system tightly integrates a dual domain, interactive visual analytics user interface with a number of components: 1) spatial and structural visualization, 2) illustrative exploration, and 3) statistical and numerical computations. The integrated use of a sequence of interactive motifs such as multivariate transfer functions, feature statistics, focus+context and cutaway viewing guides the user’s attentive focus while de-emphasizing distracting details. This section gives a description of each component of the visual analytics system and a demonstration of the system’s feature detection capabilities.

3.1 Dual Domain User Interface

We have developed a novel user interface (Figure 3) that adopts a dual domain interaction mode, allowing the user to simultaneously perform both statistical and visual exploration and validation. The left side of the user interface is designed to accomplish the visual exploration tasks using both two-dimensional and three-dimensional displays. The top left window provides basic two-dimensional explorations by means of cutaway viewing windows. Interactive three-dimensional spatial and structural explorations are shown in the bottom left window. Supported visualization modes include standard volume rendering, feature-oriented volume illustration, photography-inspired visualization and focus+context exploration.

Statistical exploration and validation are controlled and displayed in three subwindows and one panel on the right side of the user interface (Figure 3). Different flow properties including density, velocity, helicity, divergence and directional derivatives are plotted and manipulated in each window with associated numerical labels. Other computational values include the normal Mach number, pressure, and the distance of cells with a given value to the geometry. The histogram of each property or value is displayed allowing the user to select subregions of interest. This selected or filtered subregion is then visualized with different colors and opacities using the two-dimensional transfer function shown in the bottom right display window. The user can select values for the x and y axes and further refine the display by interactively manipulating the multivariate transfer function.

For scientists and engineers, our dual domain user interface provides substantial user flexibility and efficiency. Visual analysis, exploration and validation provide a global view while allowing the user to navigate and zoom on demand. The integration of both the interactively controlled visual display and the statistical views of the variables of interest provides the user with a complete analysis environment. This allows the scientist to better design and evaluate the numerical properties of the flow more thoroughly. Additionally, this allows the user to achieve more meaningful visual effects (Section 5) by leveraging the explored statistical and numerical information.

The entire interaction is coupled between the two domains in an easy-to-use and effective manner. The dual domain user interface provides the best combination of speed and accuracy. As the exploration
advances, the attention of the user is progressively directed to the most prominent regions or flow features that answer their questions. This enables the user to obtain accurate analysis results more efficiently. Note that numerical values can be validated in both domains at any time, and are used for further discovery and decision making.

Figure 3 illustrates the use of the visual analytics environment to analyze the Delta Wing dataset. To investigate vortices in the flow, the user first employs the two-dimensional cutaway widget showing the vorticity. This allows the user to get a localized view of the flow over the body and in the far field. From there, the user can choose to further investigate both the existence and location of the vortices and their causality. The constraint filtering windows allow the user to get a global view of the distributions of the norm of the density gradient and the cell distance to the body. This information is used to filter the data and feeds into the two-dimensional transfer function based on the vorticity and density. The user can then interactively design and refine this multivariate transfer function based on the visual output in the transfer function editing window. Statistical information regarding the transfer function defined cells is displayed in the statistical query window. A volume rendering of the formation of the vortex tube is shown in the three-dimensional visual exploration window at the bottom left.

### 3.2 Statistical and numerical analysis

Our system automatically derives new flow fields based on the loaded raw data fields. These fields include basic flow properties, vector fields and shock wave properties. The complete list of flow fields along with their derivation equations are shown in Table 1. The distribution for each property can be represented with a one-dimensional curve and drawn within the labeled physical coordinates, as demonstrated in the constraint filtering window in Figure 3. The correlation between the selected properties is illustrated in the bottom right window and is the basis for the design of the multivariate transfer function.

Statistical information regarding a single field can be easily obtained through our statistical query interface. The extremes, mean, standard deviation and other statistical properties (see Table 2 for a complete list) are computed upon user’s requests based on the data distribution of the cells that are selected by the designed transfer functions. The statistical query window showing the data distribution and statistical information is shown in Figure 3.

The statistics and numerical computations on the flow properties are used to detect features by converting each user-defined data range into a statistical filter and applying this filter as a two-dimensional transfer function. As a result, the selection of statistical and numerical analysis is immediately visualized in the visual exploration windows, greatly improving the exploration performance. Meanwhile, the statistical information can be queried, giving more insight into the data distribution. Moreover, if there are any abnormalities detected in the visualization results, the user can quickly investigate the problem by querying the available statistics and numerical computations.

<table>
<thead>
<tr>
<th>Data Field</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( g )</td>
</tr>
<tr>
<td>Velocity</td>
<td>( h(v) )</td>
</tr>
<tr>
<td>Energy</td>
<td>( e )</td>
</tr>
<tr>
<td>Pressure</td>
<td>( p )</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T )</td>
</tr>
<tr>
<td>Density Gradient</td>
<td>( V_g )</td>
</tr>
<tr>
<td>Density Gradient Magnitude</td>
<td>(</td>
</tr>
<tr>
<td>Laplacian</td>
<td>( \Delta g )</td>
</tr>
<tr>
<td>Normal Mach Number</td>
<td>( M )</td>
</tr>
<tr>
<td>First Directional Derivative</td>
<td>( \delta_1 g = \frac{1}{</td>
</tr>
<tr>
<td>Second Directional Derivative</td>
<td>( \delta_2 g = \frac{1}{</td>
</tr>
<tr>
<td>Weighted Density Gradient</td>
<td>(</td>
</tr>
<tr>
<td>Divergence</td>
<td>( \text{div}(h) )</td>
</tr>
<tr>
<td>Curl</td>
<td>( \text{curl}(h) )</td>
</tr>
<tr>
<td>Helicity</td>
<td>( H )</td>
</tr>
<tr>
<td>Distance to Body</td>
<td>( \text{dist}(-) )</td>
</tr>
</tbody>
</table>

We demonstrate the capability for feature separation with the ON-
Table 2. Statistical Properties for a single data field

<table>
<thead>
<tr>
<th>Property</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cells</td>
<td>$n$</td>
</tr>
<tr>
<td>Total Volume</td>
<td>$V$</td>
</tr>
<tr>
<td>Extreme</td>
<td>$\min \cdot, \max \cdot$</td>
</tr>
<tr>
<td>Mean</td>
<td>$\bar{g}$</td>
</tr>
<tr>
<td>Median</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$\sigma$</td>
</tr>
</tbody>
</table>

ERA M6 Wing dataset shown in Figure 4. Using traditional two-dimensional transfer functions, the flow features are difficult to differentiate visually (Figure 4 (a)). We refine the investigation by limiting the visualization to values that fall within a selected value range of cell distance to the M6 wing, yielding Figure 4 (b). We could also refine the result by limiting the Mach number to get Figure 4 (c). Finally, a shock wave is fully detected and visualized (Figure 4 (d)) by employing both the filters for the distance and the Mach number.

Fig. 4. Feature separation by employing a sequence of statistical filters to the ONERA M6 Wing dataset. (a) Standard transfer function based rendering; (b-d) Adding additional data filters clearly isolates the region of interest. The transfer functions are shown in the top left corner of each figure.

3.3 Illustrative and Photographic Motifs for Flow Feature Exploration

For efficient spatial navigation, we employ a focus+context interaction mode to direct the user’s attention to the most important regions. The user is allowed to move a sphere-based motif to locate and resize the focus region. Different illustration styles can be applied to the focus and context regions, as shown in Figure 5 (a).

Our system provides a cutaway viewing motif that allows the user to flexibly explore the data along an arbitrary cutting plane. By progressively changing the position of the cutting plane and displaying the values on that plane, the scientists can easily gain an overview of the flow features without any visual clutter. Figure 5 (b-d) shows the density and Mach number with the cutaway traversal mode. Note the color pattern difference between Figure 5 (c) and (d) that helps the scientists to understand the Mach number distribution as well as investigate the location of shock waves.

This mode allows the users to not only simulate photographic flow visualization techniques in the entire space, but also mimic their effects within any cutting plane, as shown in Figure 9 (a).

Fig. 5. Interactive motifs demonstrated with the Missile dataset. (a) Focus+context exploration; (b) A cutaway view of the density distribution; (c-d) Two cutaway views of the Mach number on different clipping planes. In (a), a geometric model for the aircraft is mixed in the scene. For (b-d), the cutting plane positions are illustrated as small snapshots.

4 Flow Feature Calculation

CFD simulations produce multiple variables at each node. However, these variables alone are not sufficient for feature discovery and need to be expanded. Our system derives new flow fields based on the raw variables. The complete list of fields is listed in Table 1 along with their mathematical equations. Moreover, per-vertex gradient and discrete vector fields are computed on user-selected fields for feature enhancement.

Fig. 6. Rendering the Blunt Fin data with (a) per-tetrahedra and (b) per-vertex gradient computation modes.
4.1 Per-Vertex Gradient Computation

In most previous work, a constant gradient for each tetrahedron is used for lighting [16, 38]. Although this scheme is fast, it yields unsatisfactory results similar to flat-shading in surface rendering that employs a constant normal for every triangle. To compute a per-vertex gradient, there are three categories of methods, namely, gradient average, Green-Gauss, and linear regression methods. Our system adopts the gradient average method to achieve the balance between the performance and quality. It computes the gradient of a vertex $v_i$ as the weighted average of the gradient of its neighboring tetrahedra: $\nabla g_i = \sum_{j \in N(v_i)} \omega_j \nabla g_j$, where $N_v(v_i)$ denotes the set of 1-ring neighboring tetrahedra of $v_i$ and $\omega_j$ denotes the weight. Figure 6 depicts the results from per-tetrahedra [16] and per-vertex gradient computations. Visually better results are achieved using per-vertex values than per-tetrahedra values.

4.2 Discrete Differential Operators on Tetrahedral Meshes

For a discrete vector field $\vec{h}(v)$ defined on $S$, we can compute its discrete divergence at vertex $v_i$ as $\text{div}(\vec{h}(v_i)) := \sum_{j \in N(v_i)} \nabla \phi_i \cdot G_j$, where $G_j$ is the volume of the tetrahedron $t_j$. Likewise, we can define the discrete curl operator: $\text{curl}(\vec{h}(v_i)) := \sum_{j \in N(v_i)} (\vec{h}(t_j) \times \nabla \phi_i) \cdot G_j$, where $\times$ denotes the vector cross operation [34]. Note that $\vec{h}$ can be either an arbitrary vector field defined on $S$ or $V_g$ that is derived from the discrete potential field $g$. In the latter case, we can further derive a discrete Laplacian operator for $g$: $\Delta g := \text{div}(\nabla g)$ and compute the helicity that represents the curl in the direction of the velocity field: $\text{curl}(\vec{h}) \cdot \vec{h}$.

These discrete differential operations are physically meaningful and benefit the visual analysis of the flow dynamics: the divergence operator sums the flux of the vector field through the one-ring neighborhood around a vertex, and the curl operator sums the vorticity of the component of the input vector field tangent to each face opposite to a vertex. We apply them to the input flow and construct a set of two-dimensional transfer functions by employing $|V_g|$, $\text{div}(\vec{h})$, $|\text{curl}(\vec{h})|$, $\Delta g$ as the second-dimensional parameters respectively, as shown in Figure 7.

5 Flow Feature Enhancement

The human visual system is great at the identification of oriented surface structures in uncluttered three-dimensional spaces, but is less adept at understanding data that fills space continuously. To succinctly identify and characterize structural information, we extend the illustration and photography inspired visualization of flows [33] to unstructured grids.

5.1 Illustration of Oriented Structures

Our system supports the following illustrative effects (Figure 8) for investigating the flow features with oriented structures:

Boundary Enhancement: We assume that the gradient changes linearly along a ray segment with length $l$. Given the gradient vectors $V_g, V_b$ and $\alpha, \beta$ at the entry and exit points, we modulate their opacities to be $\tau_l \vert V_g \vert^p$ and $\tau_b \vert V_b \vert^p$ where $p$ is the enhancement coefficient. The opacity of this ray segment becomes:

$$\alpha_l = 1 - \exp(-\frac{L^2}{2} (\tau_l \vert V_g \vert^p + \tau_b \vert V_b \vert^p))$$

It can be further extended to depict boundaries defined by other vector field operators described in Section 4.2, yielding different effects such as gradient magnitude isolines, curvature-based illustration and curl structure. For instance, we can enhance regions with strong divergence:

$$\alpha_l = 1 - \exp(-\frac{1}{2} (\tau_l \text{div}(\vec{h}))^p + \tau_b \text{div}(\vec{h}))$$

View-dependent Enhancement: Standard silhouette enhancement is fulfilled by incorporating the viewing vector $\vec{V}$ in the ray segment opacity computation:

$$\alpha_l = 1 - \exp(-\frac{1}{2} (\tau_l (1 - |V_g \cdot \vec{V}|)^p + \tau_b (1 - |V_b \cdot \vec{V}|)^p))$$

By replacing $V_g$ with other differential operators, different view-dependent effects can be achieved.

Contour Volume Effects: Similar to [33], we simulate the banding effects by modulating the opacity with a $\sin$ function:

$$\alpha_l = 1 - \exp(-\frac{1}{2} (|1 + \sin(\tau_l \cdot \vec{m})|^p + |1 + \sin(\tau_b \cdot \vec{m})|^p))$$

where $m$ is an adjustable phase constant.

5.2 Photography inspired techniques

Schlieren and shadowgraphy are two photographic flow techniques that use one-dimensional gradient variations to reduce the visual clutter of the flow. These techniques are incorporated into our system for unstructured grid feature enhancements using a similar algorithm to those that operate only on rectilinear grids [33]. We compute the displacement vector $\vec{e}$ and luminance map $L$ in a tetrahedron by accumulating the displacement’s projections on the xy-plane and the luminance distribution along the segment between the entry and exit points:

$$\vec{e} = 1 - \exp(-\frac{1}{2} \left(\frac{\partial g}{\partial x} \exp + \frac{\partial g}{\partial y} \exp\right))$$

$$L = 1 - \exp(-\frac{1}{2} \left(\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}\right) + \frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}))$$

Thereafter, two Schlieren effects with different cutoff methods can be simulated with:

Knife-angle: $I = s \left(\frac{1 + \vec{e} \cdot \vec{k}}{2}\right)$

Circular: $I = s \left|\vec{e}\right|$
density gradients at the vertices neighboring certain vertex where the normal Mach-number is close to 1.0 are in a shock region. The third method compares the weighted average of the norm of the density gradients at the vertices neighboring certain vertex \( v_i \), and the gradient norm of the density gradient in \( v_i \): \( ||\nabla_{v_i} g|| - \sum_{j \in N(v_i)} \omega_j ||\nabla_{v_j} g|| \). If the difference is positive, \( v_j \) is assumed to be in the vicinity of a shock. Despite their attractiveness, all these methods can only roughly identify shock regions, but do not provide a means of detecting the exact shock regions and differentiating multiple shocks.

With our visual analytics system, the detection and visualization of shock waves can be easily accomplished by integrating the normal Mach number, gradient norm or directional derivatives into the two-dimensional transfer function. The visualization of shock waves for two time steps of the Missile dataset are shown in Figure 10.

One distinctive feature of our system is that multiple shock waves can be further differentiated. Typically, the norm of the density gradient, the density or the distance to the body are used as the statistical properties used in the constraint filtering windows. The two variables used in the transfer function design window can be the norms of the first and second directional derivatives, or the normal Mach number. The user can choose two intervals from the two histograms and apply the resulting filters to the two-dimensional transfer function to differentiate multiple shock waves into primary and secondary shocks.

An example of detecting and differentiating multiple shocks on the Missile dataset is shown in Figure 11. When loading the data, the user can choose an initial view that is shown in the 2D cut-away view window of the system. In this figure, the user has chosen to display a Schlieren view to visually locate and highlight possible shock regions. The user can then choose data variables to further investigate the data distributions from their histogram plots. For the Missile dataset, density gradient norm and density are chosen. The user then applies a region selection by choosing a rectangular region on each of the data distributions. The selected values are reflected in the two-dimensional transfer function. The first and second directional derivatives are chosen to construct the multivariate transfer function, and the user refines the display by selecting values that have a second directional derivative near zero and a positive first directional derivative. The combination of these techniques and the coupling of interactive visualization allows the user to rapidly refine the visualization to show only the shock regions. The ability to use different region selections helps the user to see the differentiation of primary and secondary shocks in Figure 11.

![Image](image-url)

Fig. 8. Illustrating oriented structures of the Delta Wing dataset with: (a) a conventional transfer function; (b) the gradient based boundary enhancement; (c) the view-dependant gradient enhancement; (d) the view-dependant curl enhancement. A geometric model for the wing is rendered in grey in the scene.

6 Shock wave visualization and classification

Previously, shock waves have been visualized using thresholding of a variety of numerical calculations [9, 17, 19, 20, 21]. Ma, et al. [20] present three approaches. The first one computes the normal Mach-number \( M \) in the direction of the density gradient: \( M = \frac{\|\hat{h}\|}{a} \), where \( \hat{h} \) denotes the projection of the flow velocity onto the density gradient and \( a \) is the speed of sound. The points where the normal Mach-number equals 1.0 form the shock. The second method computes the zero-level iso-surface of the second directional derivative of the density \( g \) of the flow by \( \delta_2 g = \frac{\hat{h}}{\|\hat{h}\|} \cdot \nabla \left( \frac{L}{\|\hat{h}\|} g \right) \). The parts of the iso-surface where the normal Mach-number is close to 1.0 are in a shock region. The third method compares the weighted average of the norm of the density gradients at the vertices neighboring certain vertex \( v_i \) and the

![Image](image-url)

Fig. 9. Photography-inspired illustrations for the NASA X38 dataset. (a) A cutaway-enabled 2D schlieren rendering; (b) A Schlieren effect with 60 degree knife-edge cutoff; (c) A Schlieren effect with circular cutoff; (d) A shadowgraph effect.

Fig. 10. The shock waves for the Missile dataset at the 10th frame (a) and 173rd frame (b).

![Image](image-url)

Fig. 11. The ability to use different region selections helps the user to see the differentiation of primary and secondary shocks.
The results and comparisons for five datasets have been shown in the paper. Figure 3, 4, 10, and 11, respectively, demonstrate three applications for visualizing vortices, flow feature separation, and shock waves and their differentiation. Figure 12 displays the shock structures and the spinning motion around a finned missile as it traverses through space. The shock structure is clearly illustrated in Figure 12 (a). The missile is released at high velocity and the presence of the fins causes a spinning motion. As the missile begins to decelerate, secondary and tertiary shocks will form. Because of this relationship between spin and velocity, it is able to visually inspect the relationship between helicity and the shock structures over time. Figure 12 (b, c) display both the vorticity and helicity and allow us to compare the separated structures on a single time step.

8 CONCLUSION

With the dramatic increase in computational power available to the national simulation community, the capability and capacity for computing ever more complex fluid dynamics simulations is growing. This surge of growth has been both an extraordinary breakthrough for the computational scientists and a challenge for those analyzing the results. The tremendous growth in computational capability naturally gives rise to ever increasing data set sizes, and the traditional model of analyzing results from a single image or movie is now outdated. Integrated interactive visualization and analysis plays an essential role in exploring current and next generation flow simulations and closing this gap. Integrating data mining, data analysis, visualization and feature detection into a unified interface provides a very powerful tool for interactively discovering and verifying relevant information from these massive simulations. Relevant features can be extracted and classified, allowing the user to rapidly explore new models by understanding salient features in the flow.

This system was designed in collaboration with computational fluid dynamicists and is a result of balancing their visualization needs with analysis requirements. We have described our visual flow analytics system that enables spatial and numerical analysis through illustrative visualization and statistical techniques. This system allows a user to easily identify flow features while interactively obtaining informative feedback. We demonstrate the robustness and efficiency of our system with three challenging flow visualization tasks including flow feature separation, vortices, and shock wave detection and classification. We have also demonstrated our system’s novel ability to detect and differentiate between multiple shocks for further analysis, solving an important problem in flow analysis. We strongly believe that this system will significantly aid in the development of CFD simulations and in their subsequent analysis, particularly at very large scale. We have extended a set of existing structure enhancement techniques in the context of unstructured grids to better depict the flow features. In the future, we would like to investigate the dynamic behaviors of flow features within a sequence of datasets.

REFERENCES


