Tensor Visualization in Computational Turbulent Combustion: A Case Study

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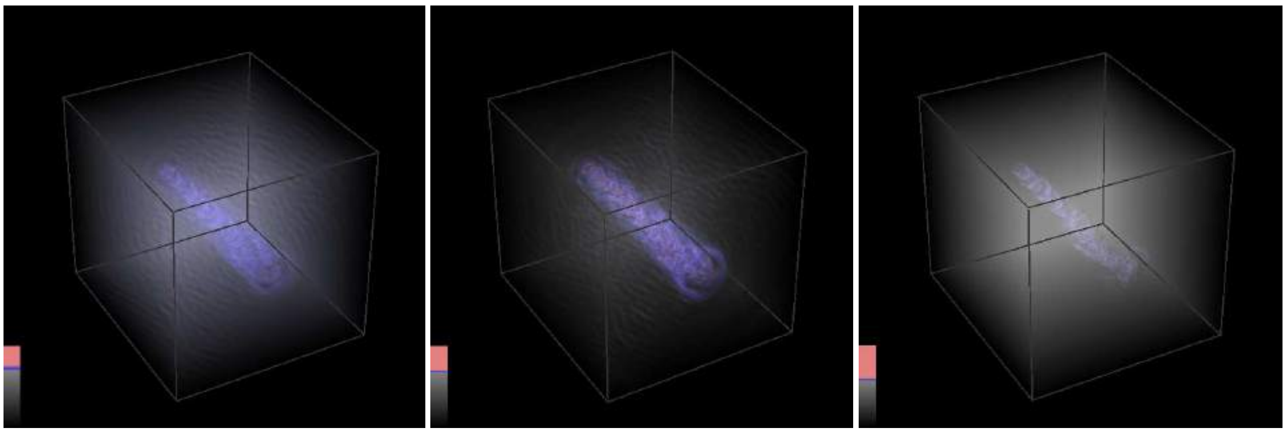

Figure 1: Volume rendering of *divergence* of the Sandia-D turbulent combustion dataset. Three timestamps are shown increasing in time from left to right. Note the rippling effect surrounding the central jet in the first timestamp; the effect disappears as the simulation goes further in time.

Abstract

Simulation and modeling of turbulent flow involve solving for and analyzing time-dependent and spatially dense tensor quantities, such as turbulent stress tensors. The interactive visual exploration of these tensor quantities can effectively steer the computational modeling of combustion systems. At the same time, visualizing such data poses significant challenges in terms of clutter, occlusion and navigation. We present an interactive framework which combines a detailed 3D inspection view based on volume rendering with glyph-based representations – used as 2D probes –, while leveraging interactive filtering and flow salience cues to clarify the structure of the tensor datasets. The result is a preliminary visual analysis tool to be utilized in debugging, benchmarking, and verification of models and solutions in turbulent combustion. We demonstrate this analysis tool on two example configurations and report feedback from combustion researchers, in particular with respect to the merits of the visualization techniques employed.

Keywords: Tensor Visualization, Application, Strain Tensor, Computational Turbulent Combustion.

1 Introduction

In turbulent reacting flow, providing closure models for stress and strain tensors is one of the most challenging problems as selecting such a model leads to different numerical methods for computational combustion. Visually identifying the characteristics of such tensor quantities in finer details can bring significant insights into the computational modeling process. The velocity strain tensor (S_{ij}) is defined as:

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (1)$$

where $\mathbf{u}$ is the fluid velocity and $i, j = 1,2,3$ represent the Cartesian components.

Visualization of tensors in turbulent combustion presents several key challenges. First, combustion datasets tend to be very dense leading to clutter and occlusion problems when visualizing them with existing tools such as ParaView [1]. Second, it is important to show researchers the 3D context of the flow and at the same time give them access to 2D visualization tools when exploring the data. Finally, care should be exercised when applying tensor visualization techniques from other fields (such as diffusion tensor imaging) to combustion data: many existing tensor representations do not have an intuitive equivalent in turbulent reacting flow.

In this work, we investigate the challenges associated with the exploratory visualization of tensor quantities in turbulent combustion simulations. In collaboration with combustion researchers, we then implement and evaluate an interactive framework for exploring turbulent combustion tensor data that addresses some of these challenges, in particular occlusion and clutter.

2 Methods

Several methods have been proposed for the visualization of tensor datasets. They include eigenvector color maps, glyphs, streamlines, volume rendering and volume deformation [2, 3, 4, 5]. Most of them are used to visually represent Diffusion Tensor Magnetic Resonance Imaging (DT-MRI) data, while some have been used in mechanical engineering to display different types of quantities, such as stress or fluid flow. To the best of our knowledge, this study is the first exploratory study of symmetric tensor visualization techniques in the context of turbulent combustion flow.

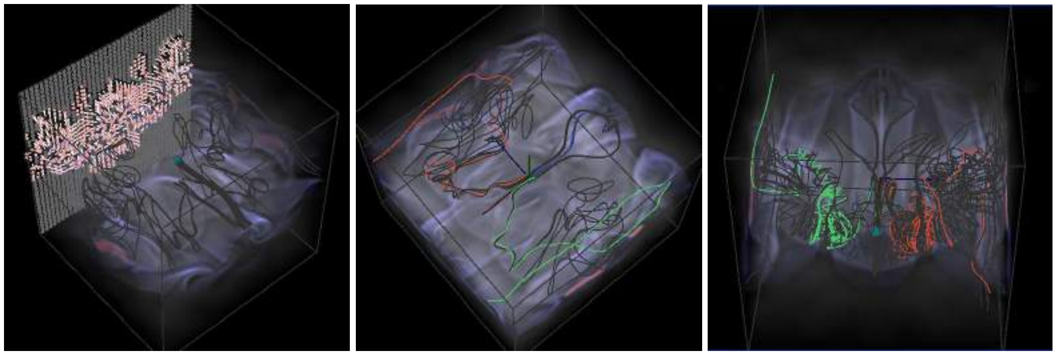

Figure 2: Combined tensor visualization techniques in computational turbulent combustion. The tool combines volume rendering (purple) with glyph-based representations (light gray and pink cutting planes), while leveraging interactive filtering of velocity streamlines (dark gray and color).

To address the challenges outlined in Section 1, we propose an interactive visualization framework combining glyph-based representations — used as a 2D-projection exploratory tool — with real-time volume rendering — used as a 3D-context visual anchor, and with velocity streamlines — serving as flow salience cues. To further address the problem of clutter and occlusions we implement interactive filtering techniques, allowing the user to focus on specific regions of interest of the tensor field.

Datasets. We have employed results of two simulations in this study. The temporal mixing layer is a configuration where two streams of fuel and oxidizer flow over and against each other in a grid of size 193x194x193. The Sandia-D dataset is a jet configuration with a fuel jet at the center surrounded coaxially by a slower speed hot pilot flame in a grid of size 160x160x200.

Glyph Representation. We use 3D glyphs to show the velocity field and the principle eigenvector field of the stress tensor. To reduce clutter, the glyph representations are mapped to axis-oriented cutting planes and the number of glyphs was subsampled by displaying only every fifth element along each direction(empirically determined). An unidirectional vector(null vector for the velocity field; equal eigenvalues for the tensor field) is represented by a gray sphere.

Volume Rendering and Streamlines. We integrated volume rendering with the glyph representation for the tensor field visualization. For volume rendering we used *divergence* which can be calculated as the trace of the strain tensor in Eq. 1. The divergence reveals the 3D structure of the tensor field and effectively shows how the density of the fluid changes in different regions. Figure 2 shows three images of divergence for the temporal mixing layer flow. To further emphasize the flow-context of the tensor data, the volume rendering was augmented with velocity streamlines (Fig. 2) — a technique borrowed from flow visualization.

Interactive Filtering. A user can manipulate the scene through mouse and keyboard interaction. During rotation or zooming, we use low-resolution volume rendering to maintain interactivity. The user can focus on a sub-region of the flow by highlighting and comparing streamlines of interest. By default, all streamlines are muted gray, while mouse interaction allows the user to highlight and contrast two or more representative streamlines (Fig. 2, right).

3 Results and Discussion

We evaluate our tool on the two datasets described in Section 2, with particular emphasis on the relative merits of the visualization techniques employed. Questions posed during analysis are of the form, what artifacts does the modeling introduce during the simulation? How do these artifacts evolve over time? What are the regions and magnitude of error? Two of the authors are combustion researchers and provided the following feedback. For the mixing layer dataset, volume rendering and the streamlines made the "mushroom" pattern at the mid-zone immediately visible and helped distinguish it well from the zero-divergence outer zones (Fig. 2). The researchers noted that the tangled, asymmetric streamlines in the mid-plane illustrate well the turbulent behavior where opposing streams of fuel and oxidizer meet. The analysis of the Sandia-D dataset provided a surprise, thus showcasing the advantages of the tool as a means of debugging numerical simulations; in Fig. 1 please note the rippling artifacts surrounding the central jet. This non-physical ripple effect could be attributed to numerical artifacts of the employed discretization scheme in the simulation, and is pronounced only in the incompressible regions, as clearly pronounced in the volume rendered tensor field.

With respect to the various components of the visualization scheme, the volume rendering combined with the interactive streamlines generated the most excitement. Glyph based representations were considered the least helpful, as they were prone to significant occlusion and clutter. Overall, the researchers found the system as an exploratory tool "very good" and "cool" and a definite improvement over tools such as ParaView, in particular with respect to interaction and flexibility.

4 Conclusion

In this paper, we examined the challenges associated with tensor-field visualization in the context of turbulent combustion calculations, then we proposed and evaluated a tool that combines several visualization techniques. Our approach leverages interactive filtering and flow salience cues to clarify the structure of the tensor datasets, while effectively addressing the problems of occlusion and clutter. Side-by-side views of multiple timesteps facilitate the analysis of time-space relationships. Feedback from combustion researchers indicates that the tool (in particular, volume rendering of divergence and the interactive streamlines) has useful application in the exploration of turbulent combustion simulations, and emphasizes the urgent need of the field for custom visual analysis tools.

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