Integrating Local Feature Detectors in the Interactive Visual Analysis of Flow Simulation Data

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Agenda

- Introduction
- Smooth vortex region detectors
- Case study: cooling jacket
Introduction

- Vortices difficult → many definitions → many detectors
- Common criteria give binary (yes/no) results for each cell
- Standard approach: compute iso surfaces of detector response
- Engineers interactively search for good iso-values → interaction using the value of the detector response
Idea

- Get access to the benefits of multiple detectors at the same time
- Allow additional attributes to be included in the vortex flow feature analysis
- Make strength of detector response available for analysis

Solution: integration of smooth reformulation of the detectors into an interactive framework

\[ \lambda_2 < -100 \]

- Helicity mapped to color
- Positive helicity and low pressure
- Temperature mapped to color
Smooth Detectors - Swirling Strength

- Jacobian $\mathbf{J}$ can be decomposed as

$$
\begin{bmatrix}
\mathbf{v}_r & \mathbf{v}_{cr} & \mathbf{v}_{ci}
\end{bmatrix}
= 
\begin{bmatrix}
\lambda_r & \lambda_{ci} & \lambda_{cr}
\end{bmatrix}
= 
\begin{bmatrix}
\mathbf{v}_r & \mathbf{v}_{cr} & \mathbf{v}_{ci}
\end{bmatrix}^{-1}
$$

- If $\lambda_{ci} > 0$ in a local curvilinear coordinate system the streamlines are determined by the eigenvalues
Swirling Strength

- **Binary** formulation: Vortex if we have a complex eigenvalue pair
- \( \lambda_{ci} \) determines speed of rotation
- **Smooth** formulation by linear scaling speed of rotation using min/max of \( \lambda_{ci} \):

\[
Fuzzy- \lambda_{ci} = \frac{\lambda_{ci} - \text{min}}{\text{max} - \text{min}}
\]
Smooth Detectors - Lambda 2

- Rate-of-strain tensor $S = 0.5(J + J^T)$ and rate-of-rotation tensor $\Omega = 0.5(J - J^T)$
- First Idea: Vortex where $||S|| < ||\Omega||$ (Hunt1988)
- Improvement: require $"||S|| < ||\Omega||"$ only in one eigenplane:
  - Compute eigenvalues of $S^2 + \Omega^2$
  - $S^2 + \Omega^2$ has three real eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$
  - If $\lambda_1 < 0$ then $"||S|| < ||\Omega||"$ in all directions
  - If $\lambda_1 > 0$ and $\lambda_2 < 0$ then $"||S|| < ||\Omega||"$ in one eigenplane
  - Binary: $\lambda_2 < 0$

- Smooth criterion:

$$\lambda_{2Fuzzy}(x) = \begin{cases} 0 & : \lambda_2(x) \geq 0 \\ 1 & : \lambda_1(x) \leq 0 \\ \text{scale}_D(-\lambda_2(x)) & : \text{otherwise} \end{cases}$$

simply linear scaling
Smooth Detectors - Local pressure extrema

- Neighborhood around cell N
- Scale values locally to get fuzzy-extremumness attribute

\[ \text{extremum}_{Fuzzy}(a(x)) = \begin{cases} 
0.5 & : \text{max} = \text{min} \\
\text{scale}_N(a(x)) & : \text{otherwise}
\end{cases} \]
Video

\[ \lambda_2 < 0 \]
Case Study: Cooling Jacket

- Cooling four cylinder engine
- Need temperature close to optimum (~ 363° K)
  - Good overall heat transport
  - Even distribution of flow to each cylinder
  - Avoid regions of stagnant flow
- Finding: vortical motion can both improve and hinder heat transport

[Dataset: ~1,5 mio cells (tetrahedra, prisms & hexahedra)]
Reduced Transport Due To Vortical Motion

- Select regions of near stagnant, hot flow for overview
- Unexpected large region in cylinder block!
- Restrict to medium to high levels of the $\lambda_2$ vortex detector
- Zoom shows vortex to cause heat build-up

→ Vortex reduces heat-transport
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Video

$\lambda_2$ vs. temperature
Gasket Vortices Improve Heat Transport

- Combustion heats top of cylinder most
- Inspection of surface reveals critical areas
- Intensive fluid transport away from surface necessary
- Gaskets cause vortical motion
- Combined visualization reveals: turbulence behind gasket is key

→ Vortex necessary for heat-transport
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Conclusions

- We have presented smooth formulations of vortex detectors that give insight into strength of the vortex
- Using multiple views the user can analyse the relation between vortex regions and other attributes
- User study on real-world data showed approach to be useful
- Engineers gave positive response to the ability to combine attributes and vortex detector response!
Thank you! Questions?

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