Data Analysis in High Reynolds Number Turbulent Flows – Experimental Perspective

Mo Samimy and Nathan Webb

Gas Dynamics and Turbulence Laboratory

Aerospace Research Center

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- The work has been done by many graduate students and postdoctoral associates and only a few have been referenced in this presentation
  - Current: Nathan Webb, Ching-Wen Kuo, Jordan Cluts
  - Past: Jim Hileman, Martin Kearney-Fischer, and Mike Crawley

- Collaborations with colleagues at OSU, NASA, and AFRL, especially with Igor Adamovich, Datta Gaitonde, and Andrea Serrani have been instrumental for the work at GDTL/ARC

Outline of the Presentation

- Current experimental capabilities
- Complementary nature of computational and experimental work
- Traditional data analysis, its roots, and its pitfalls
- Examples of modern data analysis techniques
  - Spatio-temporal analysis
  - Structure identification
  - Modal decomposition
- Concluding remarks

Current Experimental Capabilities

- **Flow-field visualization and measurements**
  - Qualitative techniques such as schlieren imaging
  - Quantitative measurements such as PIV
- **Irrotational-field and far-field measurements**
  - Irrotational-field signature of flow (primarily large-scale structures)
  - Far-field (radiated noise)
- **Contact surface visualization and measurements**
  - Surface flow visualization (e.g. oil flow visualization)
  - Surface pressure measurements (traditional point-wise low- and high-temporal resolution pressure, PSP)
  - Surface shear stress measurements

Complementary Computational & Experimental Work

- **Occasional claims**
  - "soon wind tunnels will be unnecessary"
  - "soon we will measure 3-D, time-resolved kinematic and thermodynamic properties"
- **Well planned and coordinated experimental and computational work is the best approach and can provide a wealth of important information unavailable through either approach individually**
  - Coordination and collaboration must start at the experimental design stage
  - Both sides must leave their comfort zone, get engaged, and learn a little about the other's work

Traditional Data Analysis, Its Roots, and Pitfalls

- Pre 1970s discovery of large-scale structures (in high Re # flows), fluctuations in turbulent flows were considered to be **stochastic in nature**
- With this assumption, properties such as mean flow, Reynolds stresses, PDF of fluctuations, and spectral distribution should provide all the needed info on the nature of the flow – recall that we initially had **hot-wire**, then along came **LDV**
- Other parameters, such as skewness, flatness, spatial/temporal correlations, and coherence, provided additional information (though the last two required multiple measurement locations and/or time-resolved measurements)

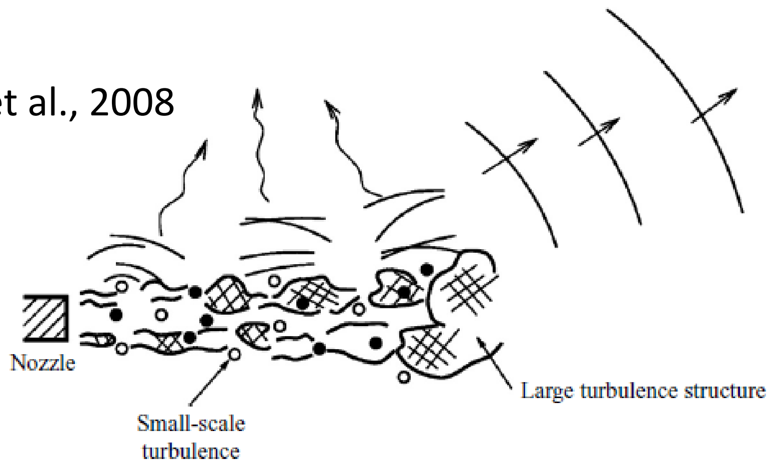
Large-Scale Structures and Their Dynamics

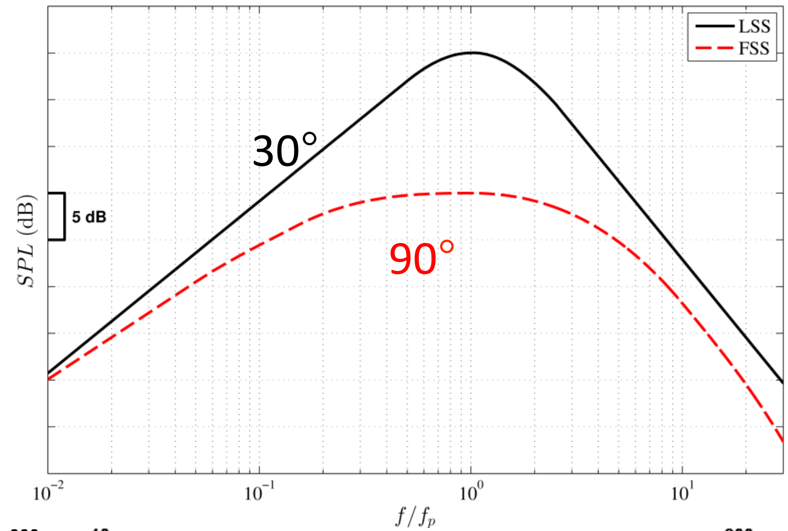
- Serendipitous discovery of large-scale structures in the 1970s changed the traditional view and highlighted the need for additional analysis and measurements
- These large-scale structures become "**less organized**" in high-speed and high Reynolds number flows and **understanding their dynamics becomes much more challenging**
- **Control of their dynamics**, for both altering their behavior and understanding their dynamics, is becoming possible and extremely important
- The lack of proper probing and understanding of their dynamics **could lead to incorrect/misleading conclusions** – the following slides provide an example of this

Contribution of Large-Scale Structures to Jet Noise and Near-field Unsteady Pressure

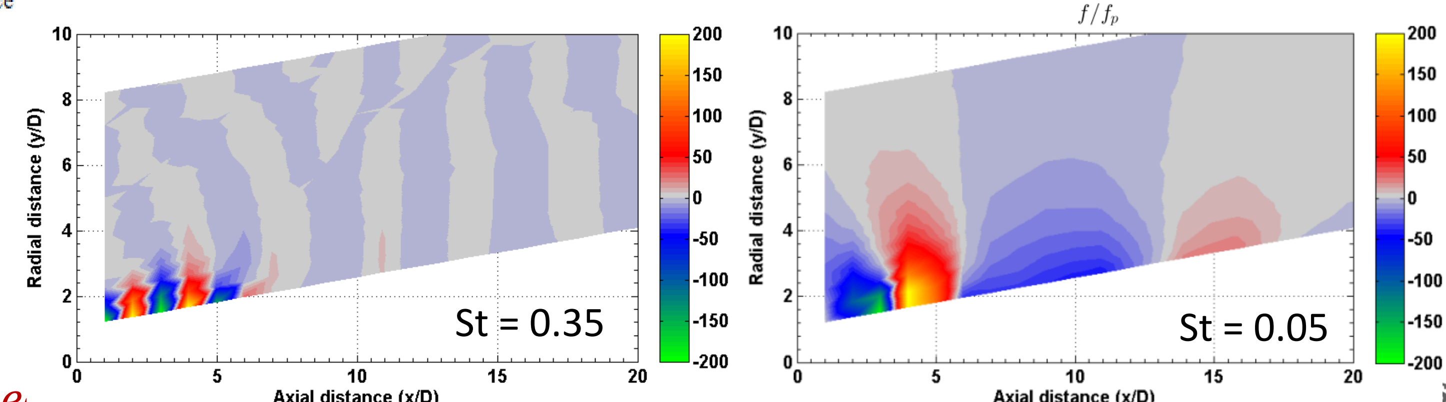
- Noise associated with large-scale flow structures radiates in peak-noise direction); and **the peak noise is 10 to 20 dB higher**
- **Irrotational-field signature** of large-scale structures is much more revealing

Tam et al., 2008



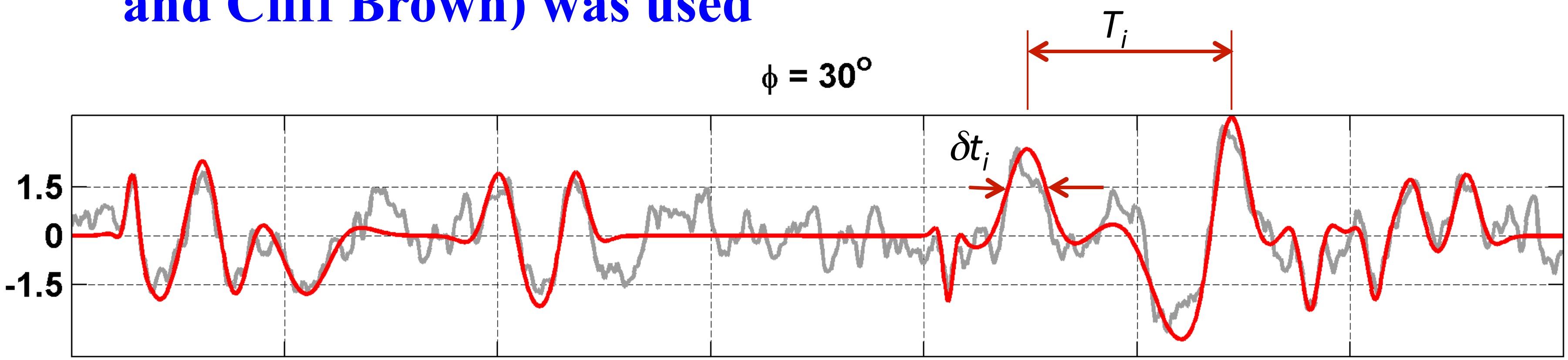


Kuo, et al, 2015



Contribution of Large-Scale Structures to Jet Noise

- Shallow-angle noise consists of **long-lived, intermittent peaks** that are well captured by a wavelet transformation
- Defined by: events width, δt_i (with mean of $\overline{\delta t}$), time between two events, T_i (with mean of $\overline{\Delta T}$), and event amplitude, A_i
- **An extensive data base from NASA Glenn (James Bridges and Cliff Brown) was used**



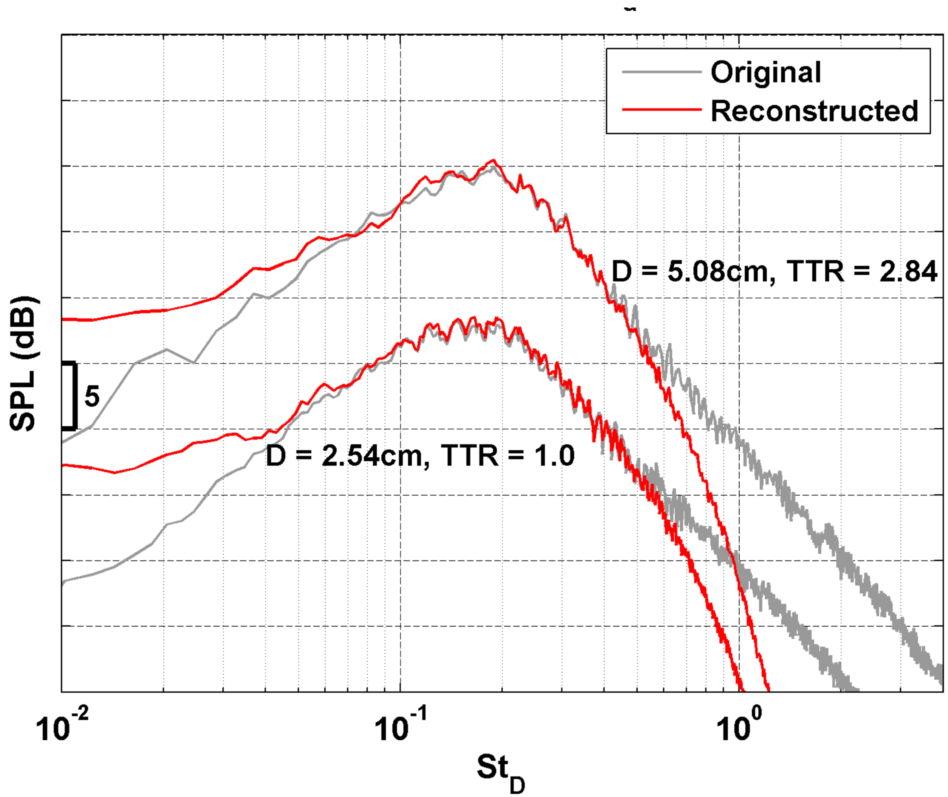
(Hileman et al., 2005)

$$\psi_i(t) = A_i\left(1-\frac{(t-T_i)^2}{\delta t_i^{\,2}\epsilon}\right)\exp\left[\frac{-(t-T_i)^2}{\delta t_i^{\,2}\epsilon}\right]$$

Kearney-Fisher et al., 2013

Contribution of Large-Scale Structures to Jet Noise

- Time-domain reconstruction using only modeled peak noise events is used to determine the spectrum
- **Spectra are well reconstructed for the peak noise portions of the low angles across a wide range of jet diameters, Mach numbers, and temperatures**



- **Reconstruction uses only 13% of data (omits 87% of the signal)**
- **This was a major piece of missing information on jet noise for nearly 50 years**

Kearney-Fisher et al., 2013

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  - Structure identification
  - Modal decomposition
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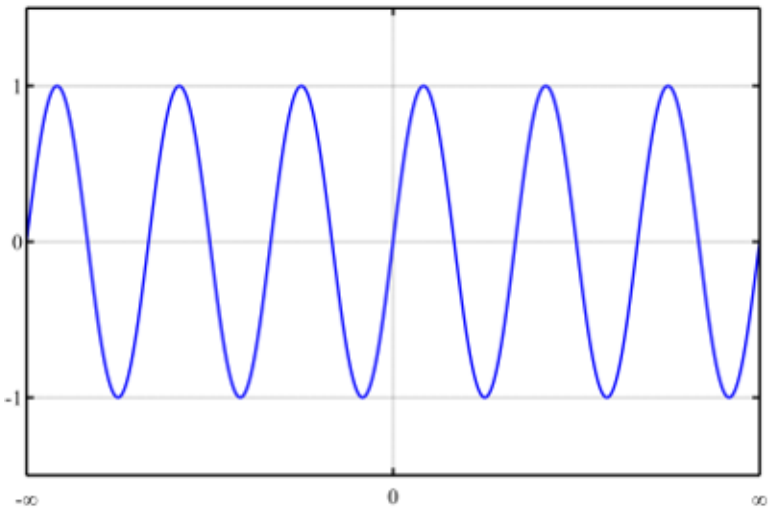
Spectral Analysis Shortcomings

- **Trigonometric basis functions** are simple to use, but this set of basis functions significantly limits the analysis because it:
  - **Is periodic for all time, thus removing all temporal information**
- Spatio-temporal analysis provides a better picture of the frequency content in the flow
  - Observe the first 5 Rossiter modes and their strength & persistence in time



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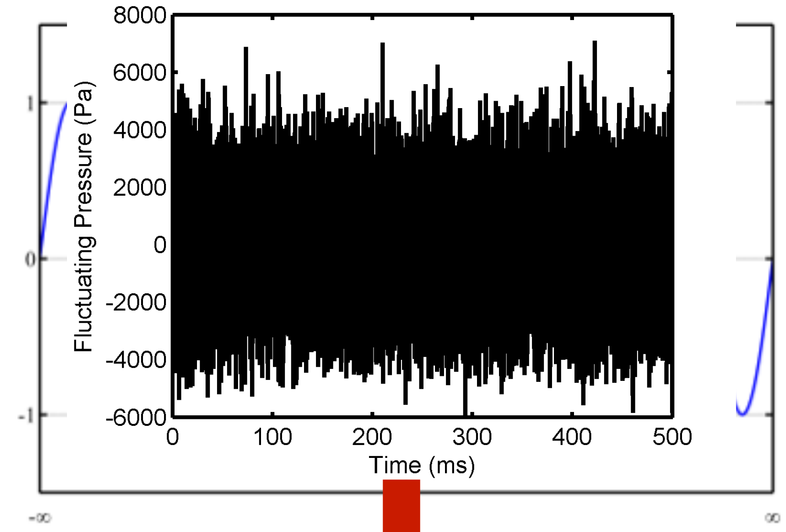

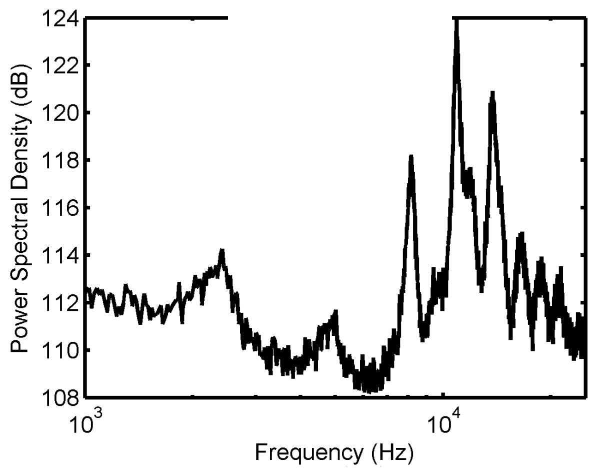

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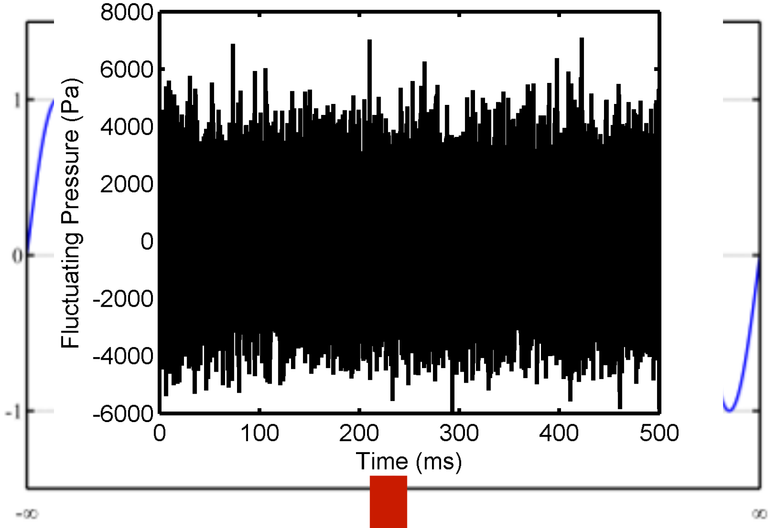
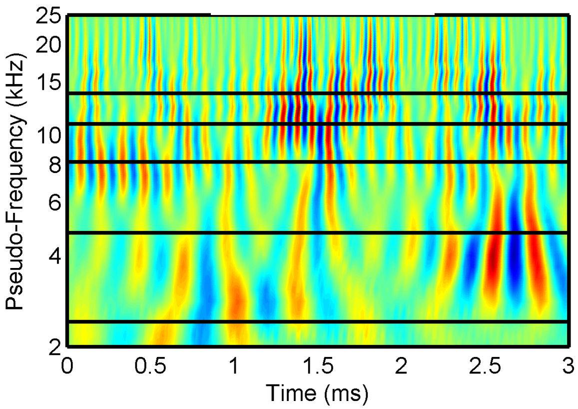
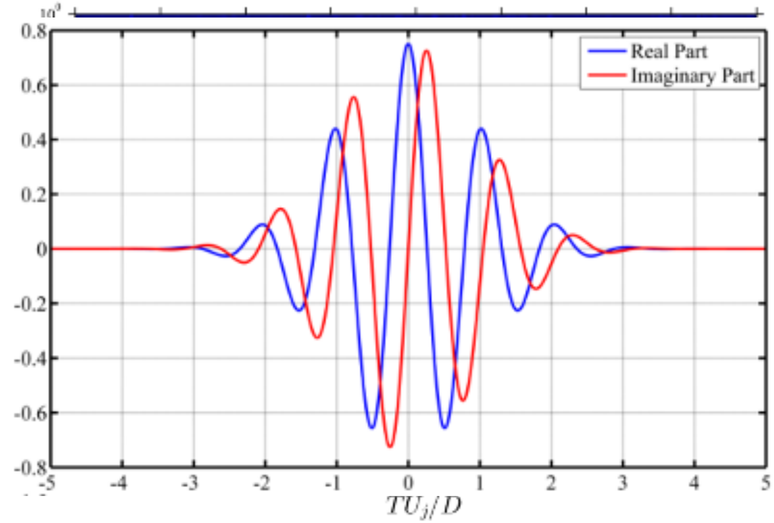




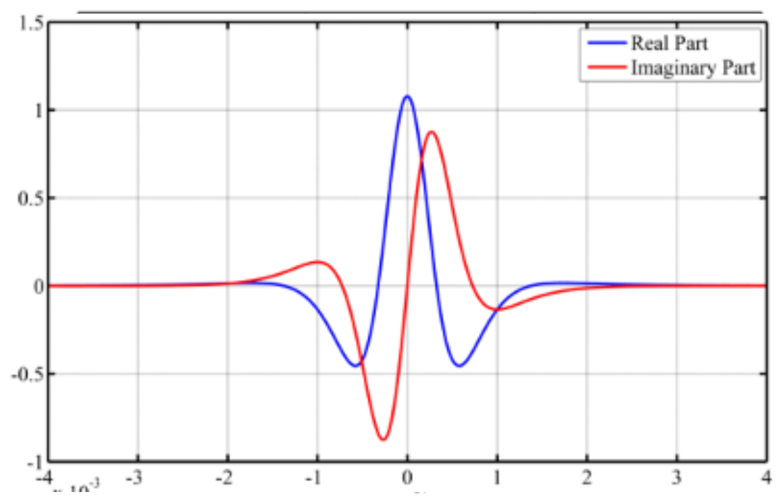
Spatio-Temporal Analysis

- Wavelet analysis
  - **Temporally bounded basis functions** provide temporally resolved transformations
  - Various mother wavelets allow different physical phenomena to be highlighted
- In complex flow fields (e.g. jet near field) which **contain important discreet events**, these properties can help to correctly interpret the results

Morlet Wavelet



Paul Wavelet



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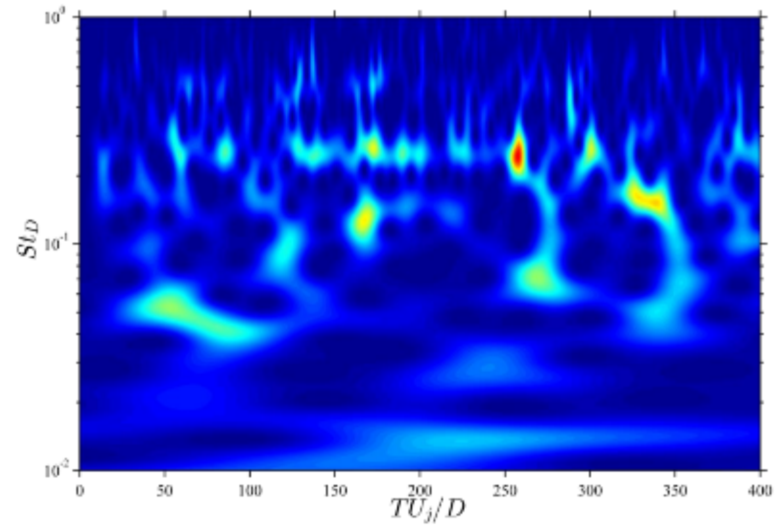

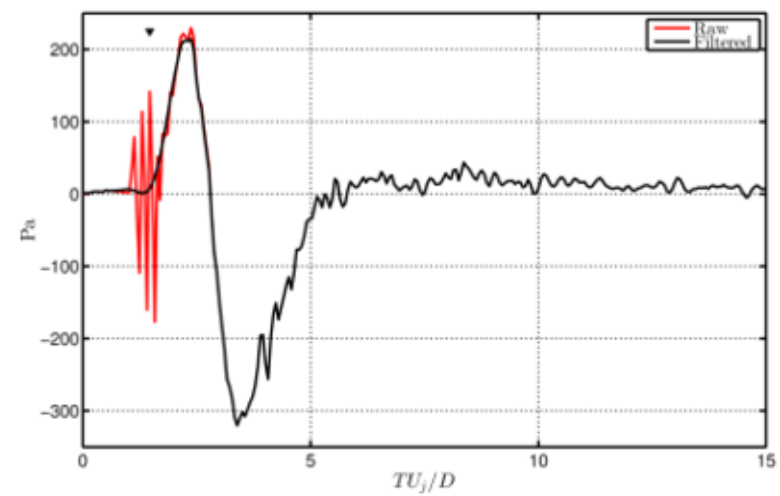

Spatio-Temporal Analysis Limitations

- Decompositions with a pre-defined set of basis functions **highlight data features with shape similar to the basis functions**
- This can yield misleading results in complex flow fields and **emphasizes the need to use multiple analysis techniques** on any data set

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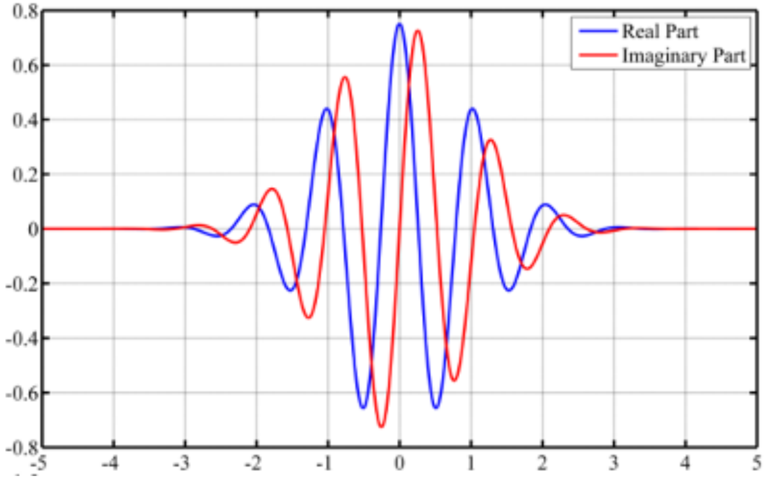
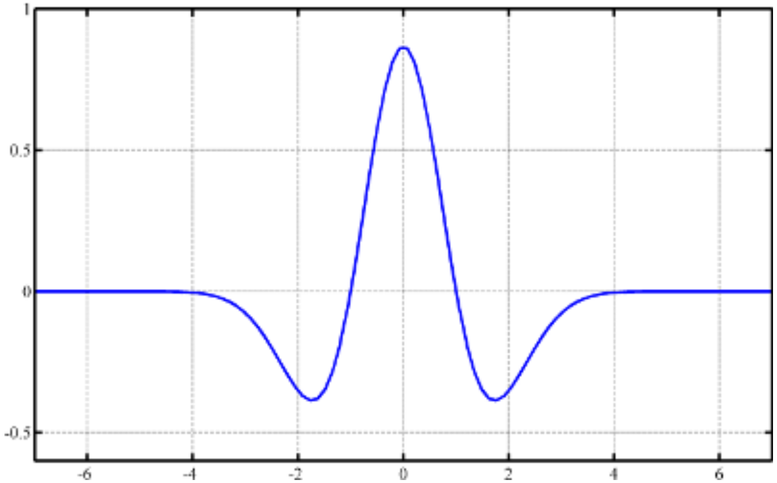


Mexican-Hat Wavelet



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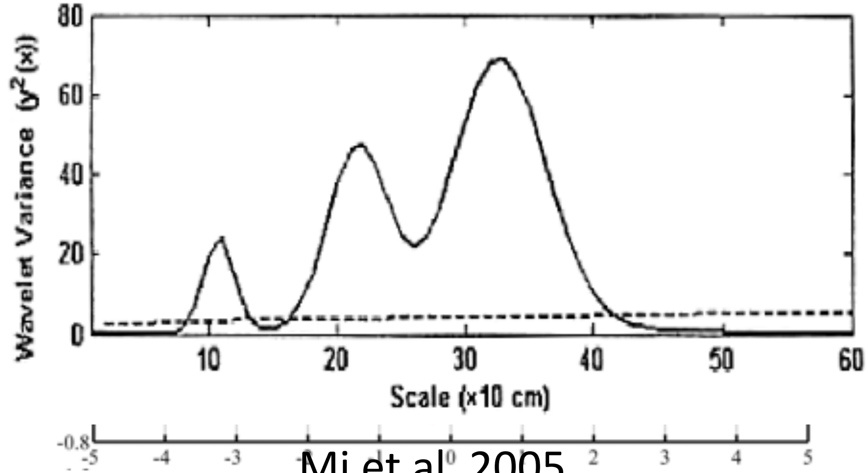
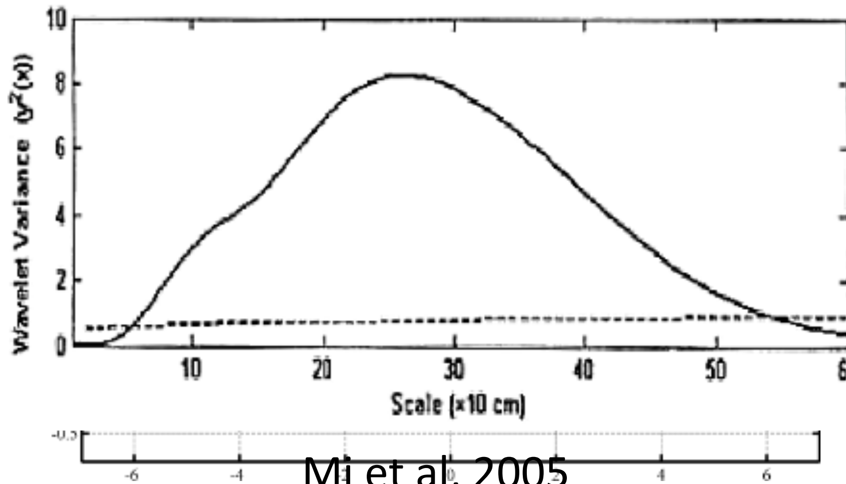
Morlet Wavelet Scalogram



Mi et al, 2005

Mexican-Hat Wavelet Scalogram



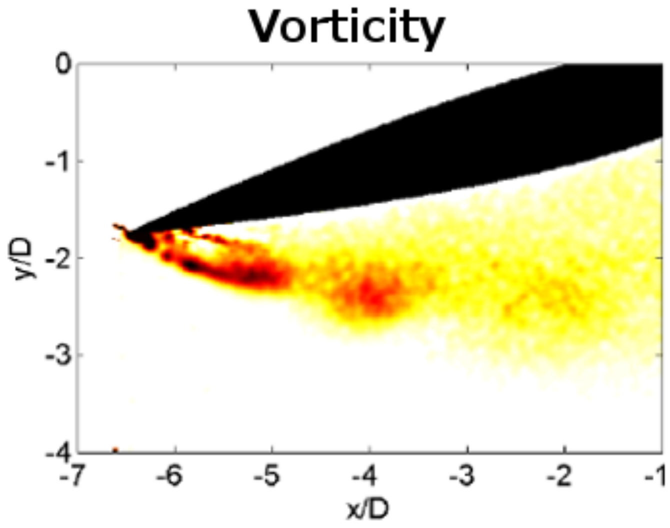
Mi et al, 2005

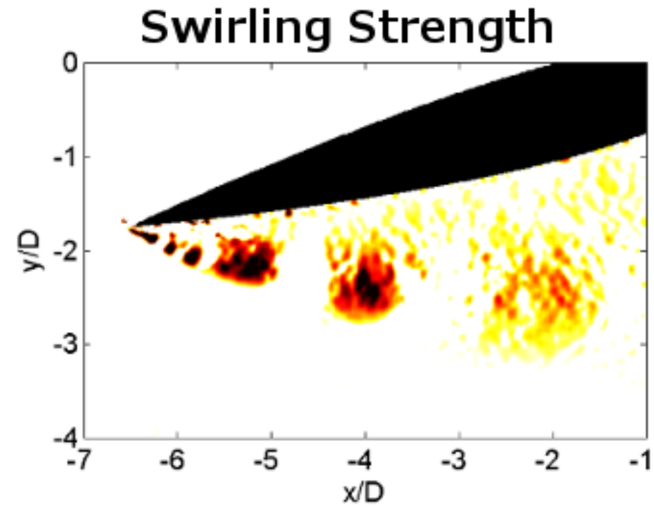
Structure Identification - Traditional Techniques

- **Structure dynamics** play a major role in determining the overall flow behavior
- **Vortex/structure identification** is therefore an important part of data analysis
- **Traditional methods such as vorticity** are easily confounded by shear, a commonplace feature in complex flows

Structure Identification - Modern Techniques

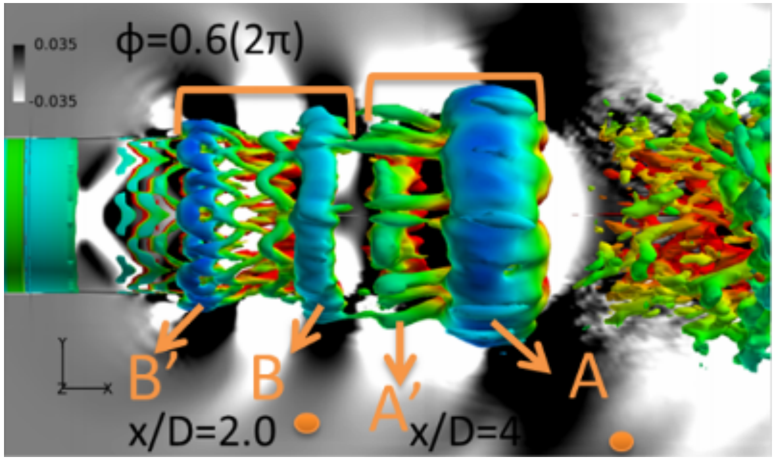
- **Critical Point Methods**
  - Δ-criterion/Swirling Strength
  - Q-criterion
  - λ_2-criterion
- These methods **seek to locate regions that are part of a vortex** – involve 1st principles based metrics more complex than vorticity

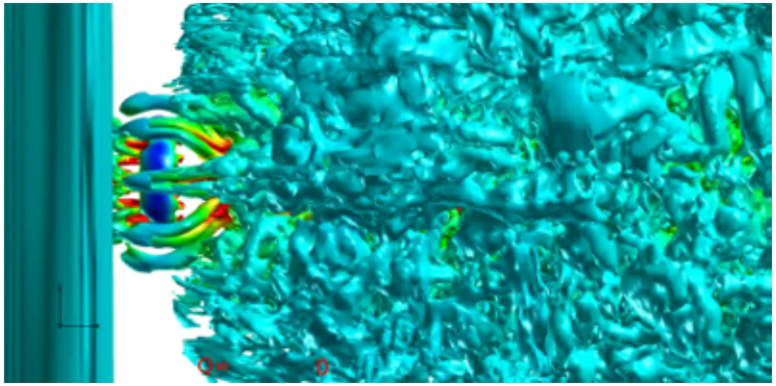




Structure Identification – Limitations

- The use of **spatial gradients of velocity** makes the critical point based techniques **susceptible to experimental noise**
- Most techniques provide a metric without a **physically apparent threshold for defining vortex size**: this leads to ambiguity

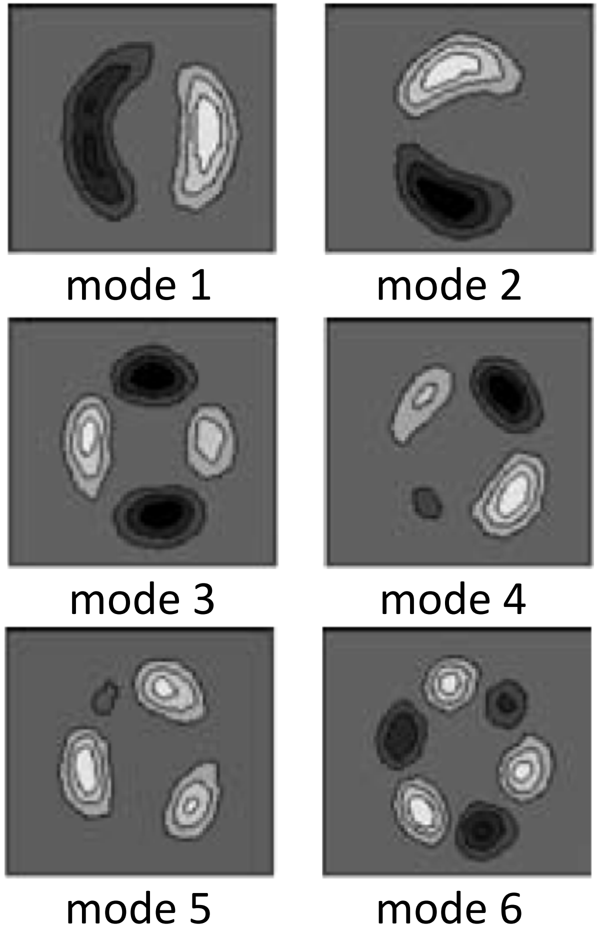




Speth and Gaitonde, 2014

Modal Decomposition – POD

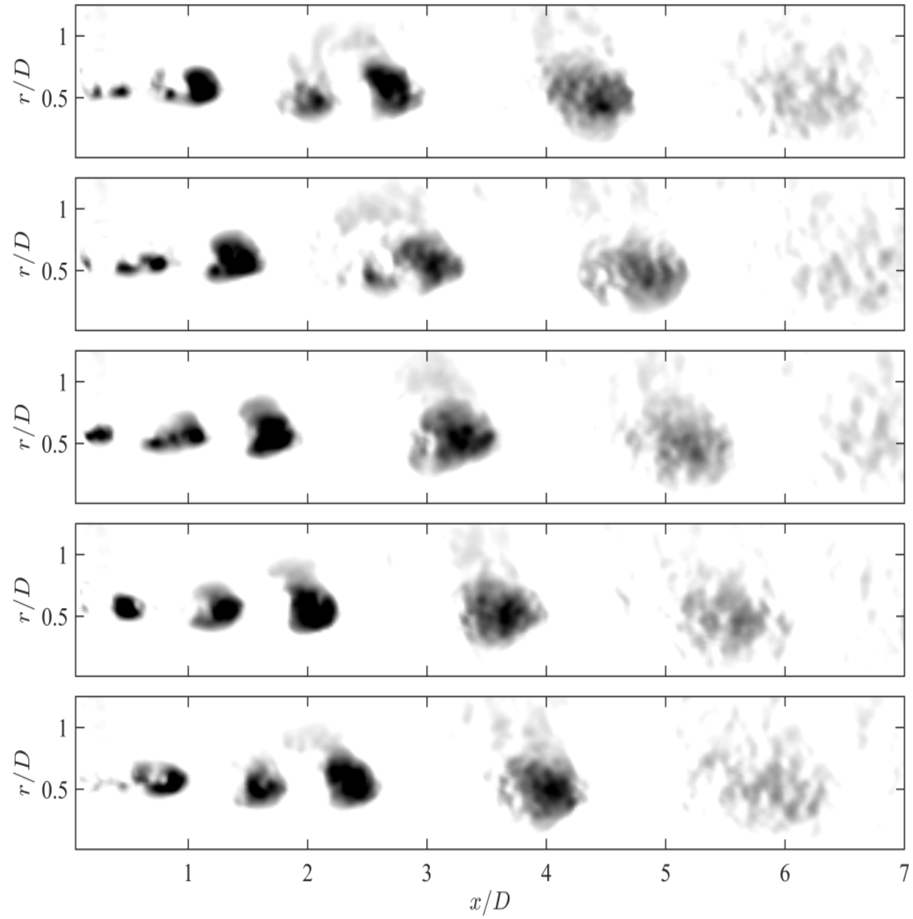
- Proper Orthogonal Decomposition (POD) is a **decomposition into orthogonal, energy based** data-specific basis functions
  - Basis function orthogonality makes POD good for **reduced-order modeling** (i.e. few modes are required for a good reconstruction) for feedback flow control
  - Energy based basis functions **do not necessarily correspond to physically relevant dynamics or phenomena**



Hileman et al., 2005
Mach 1.3 jet

Flow Structure Reconstruction – Multiple Techniques

- We have recently developed and used a new method to **reconstruct full-field, time-resolved data from**:
  - Full-field snapshots (PIV)
  - Time-resolved pressure measurements
  - Artificial neural networks
- Applied to a jet flow field (along with swirling strength) clearly shows flow **structures propagation, interaction, and pairing in the shear layer (a new discovery)**



Crawley et al., 2016

Concluding Remarks

- Experimental capabilities, data analysis, and the research community's understanding of the flow physics are continually improving
- It has become increasingly clear that:
  - There is no panacea in turbulent flow analysis – **no single tool or approach is sufficient**
  - Conventional data analysis techniques limit the information that can be gleaned from modern measurements and, in some cases, **could produce misleading trends/conclusions**
  - Modern data analysis and decomposition techniques are improving and becoming more useful in providing a better understanding of the flow physics
- **Increased collaboration between computational and experimental work could significantly improve our understanding and insight into flow physics and control**

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