Engineering, Operations & Technology
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How can efficient time intervals be established for numerical simulations

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Overview

- Unsteady flow simulations have become more common as computing power has grown
  - Detached Eddy Simulations (DES) have been used in offset diffusers, aero-acoustics, high lift configurations, aero-optics, etc.
  - DES has provided many success stories, but the best-practices are still evolving for its usage.
  - Expense of DES can limit usage on programs
- Many users still struggle with obtaining and extracting useful data from unsteady computations
  - Degree of required user expertise rapidly grows with the fidelity of the simulations
  - Unsteady simulations can generate terabytes of data which requires careful scripting to automate user intervention
  - The effects of grid and temporal resolution are poorly understood for many problems as programs do not desire to pay for such studies before receiving data
  - Efficient and massively parallel computing requires CFD code modifications for modern hardware architecture

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Issues

- **How many time steps does one need to collect?**
- **How large of a time step can a user afford?**
  - Boeing has used dual time methods to greatly accelerate the clock time required to obtain statistics.
  - Allows time steps to be set based on physics of problem
- **Do any particular DES approaches have any advantage in terms of efficient time intervals?**
- **Does grid resolution impact the time interval needed to obtain statistics?**
- **Can low dissipation or higher order numerics offer help in reducing the burden of grid requirements?**
- **Are there other approaches to reduce the amount of data required?**

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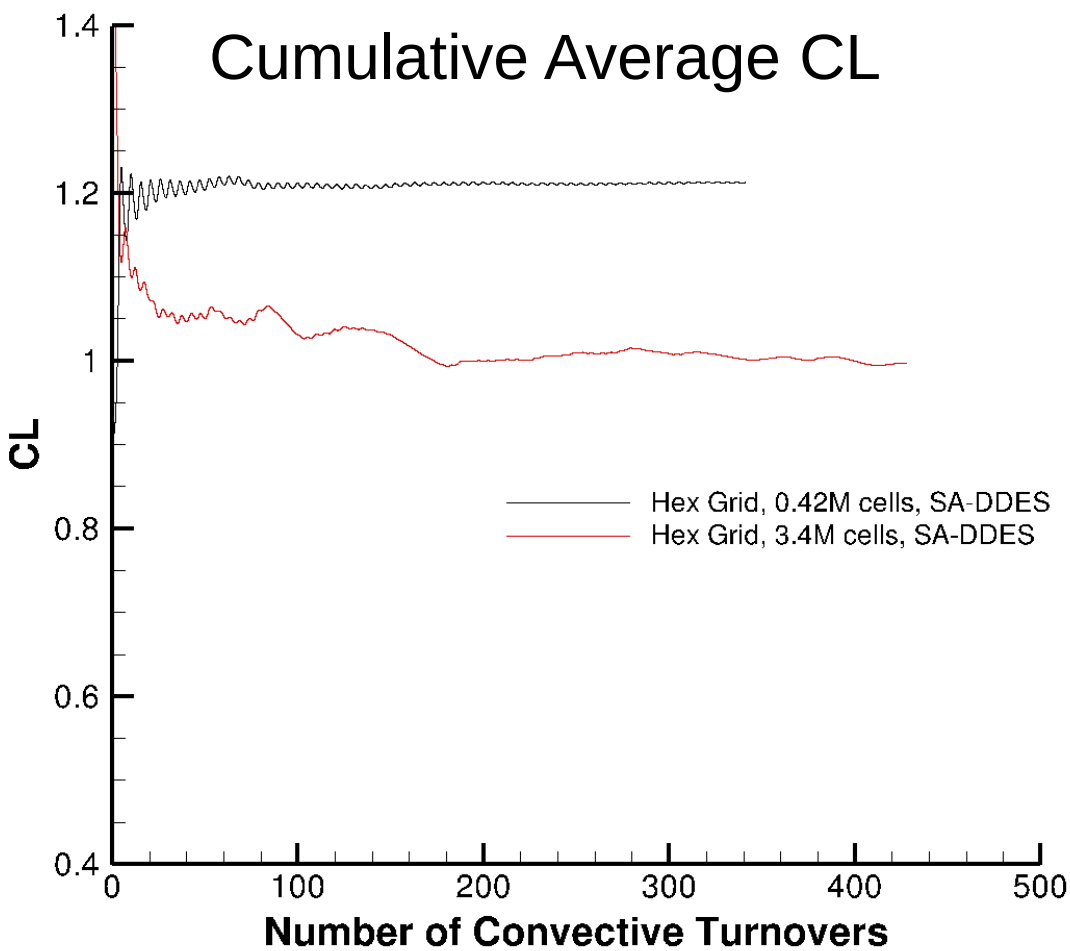
Massively Separated Flows – Impact of grid resolution, topology, and model selection



- **NACA 0021 at 60° AoA, Re=2.7E5**
- **The plot illustrates cumulative average of CL as a function of convective turnover time**
- **Coarser grids require less integration time as less physics are resolved and the solution is more URANS-like**
- **Refined grids can require 500+ turnover times for accurate data**
- **Turbulence model (SA-DDES, SST-DDES, and SST-SAS) does not appreciably impact the required integration time**
- **Grid topology also not a major factor in required integration time**
- **Note: This is AFTER the initial transients have been convected out of the domain, which can easily require hundreds of turnover**

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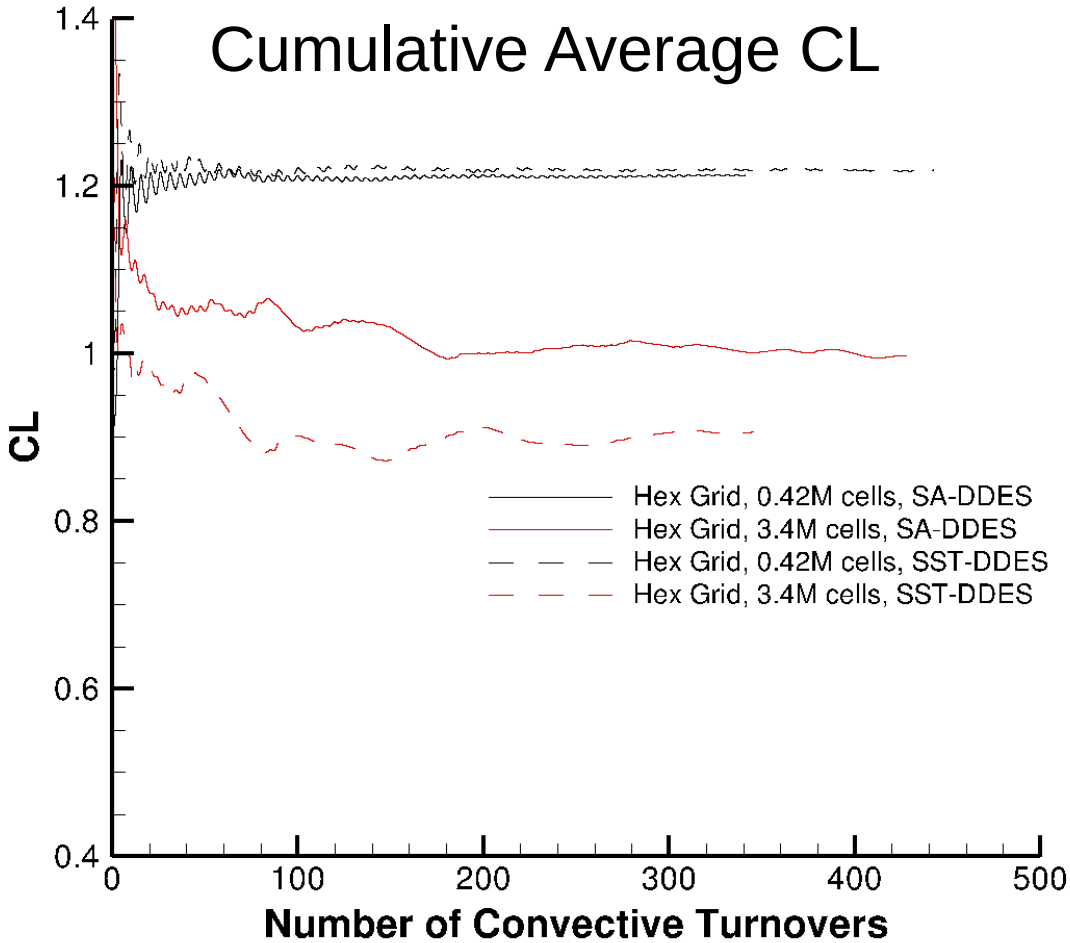

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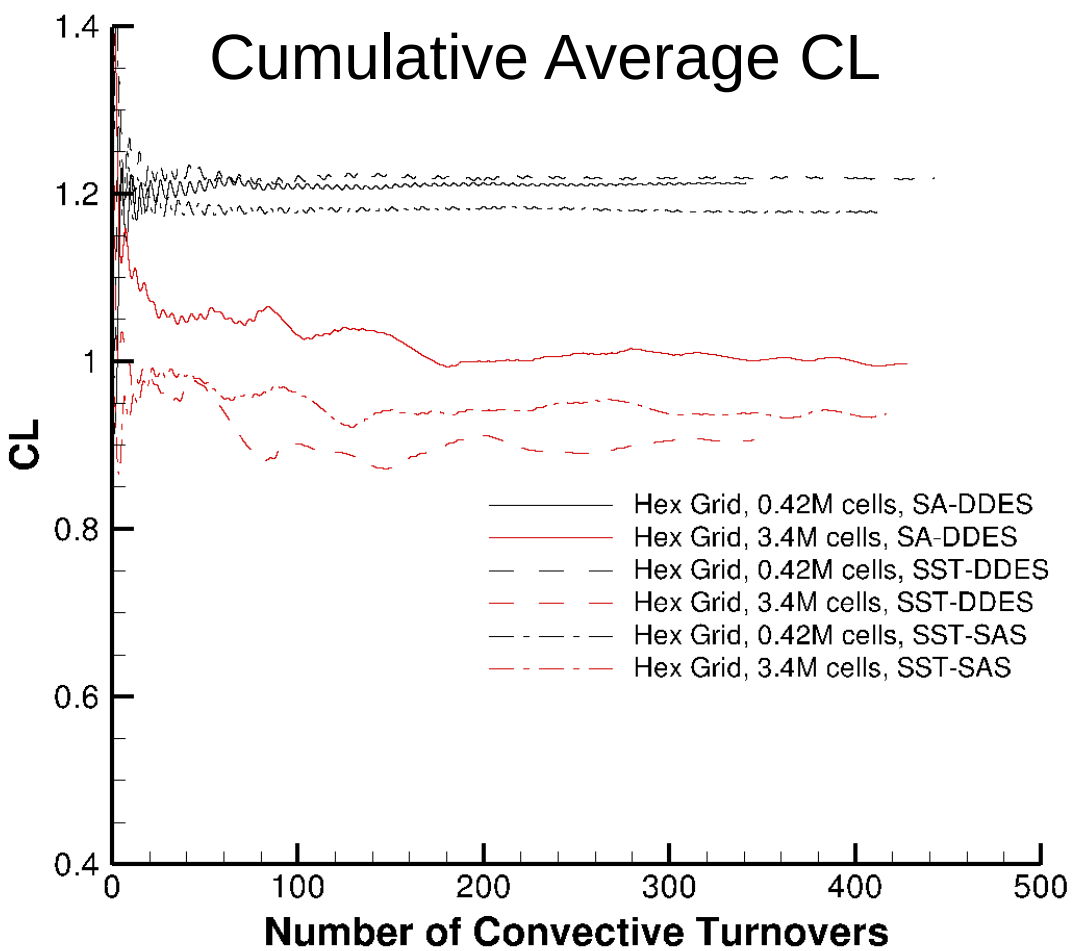

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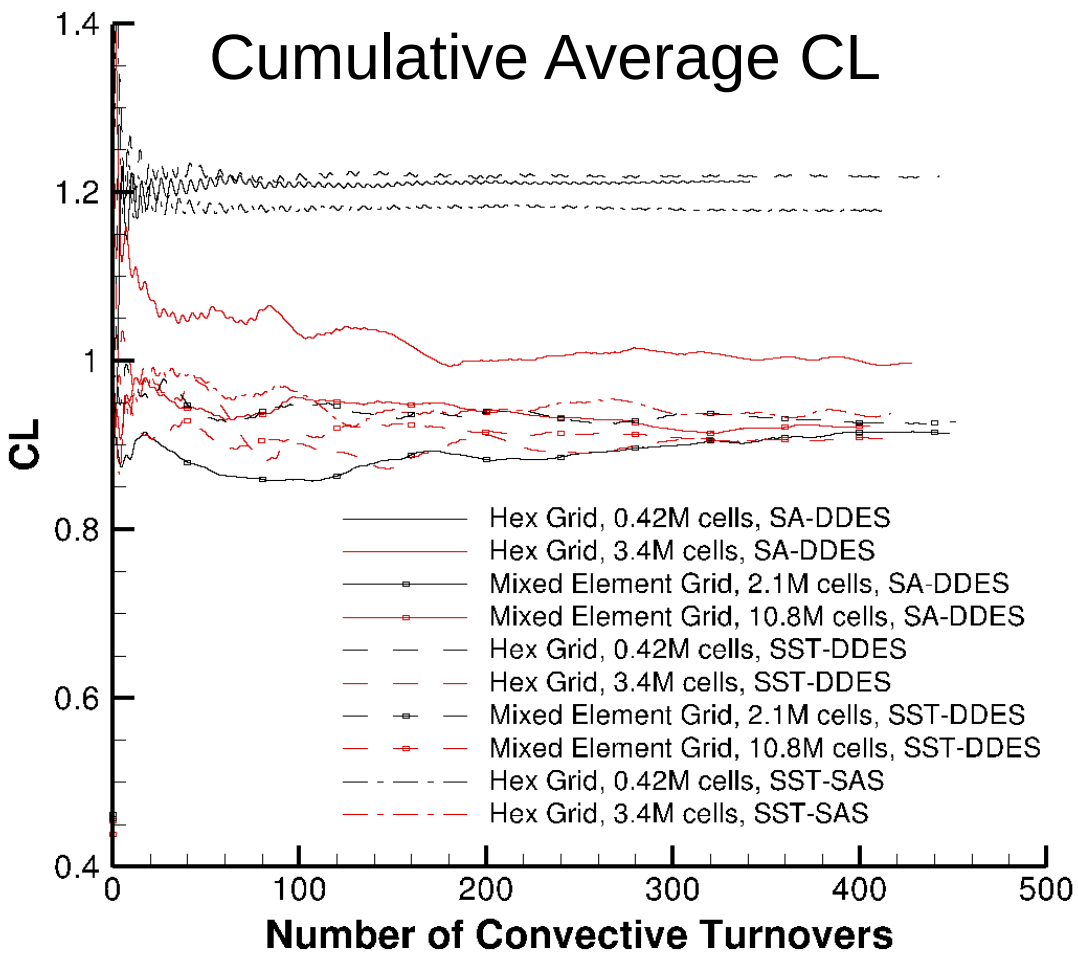

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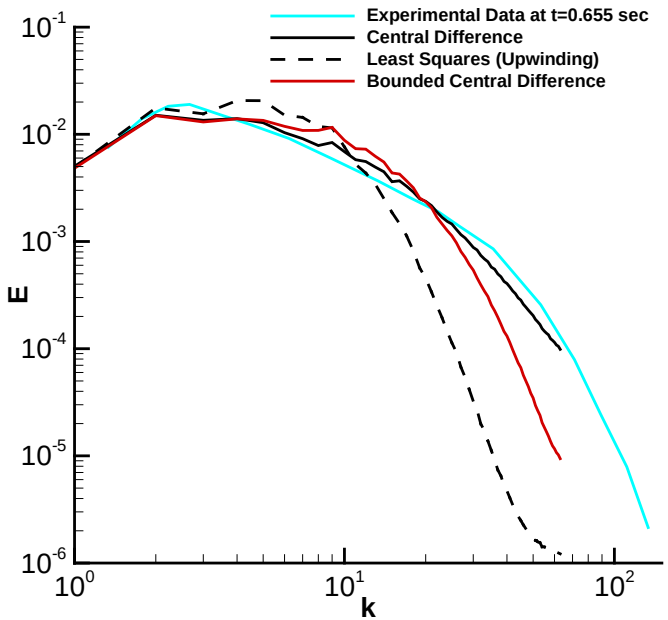
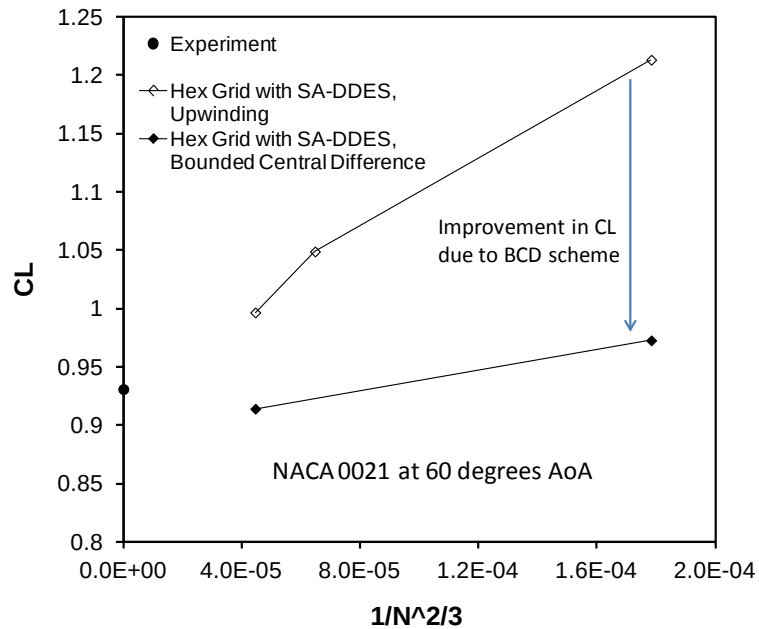
Impact of low dissipation schemes



- **Decaying isotropic turbulence allows various schemes to be directly compared**
- **Low dissipation schemes can improve high frequency resolution**
- **This may allow a user to use a coarser grid with Bounded Central Difference (BCD) than with upwind schemes and obtain similar results. This will allow a user to obtain similar results in a shorter time on similar hardware.**

- **Separated flows can also benefit from low dissipation numerics**
- **NACA 0021 at 60° AoA results show that BCD can greatly improve predictions of CL across a range of grid resolutions**
- **This can allow users to obtain similar/better results on a smaller grid than they use with upwinding**



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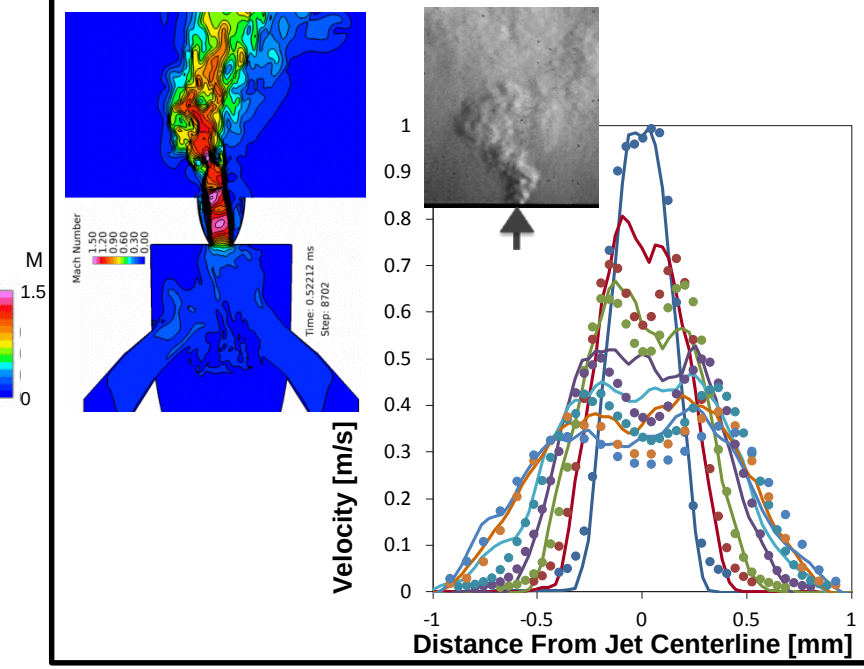
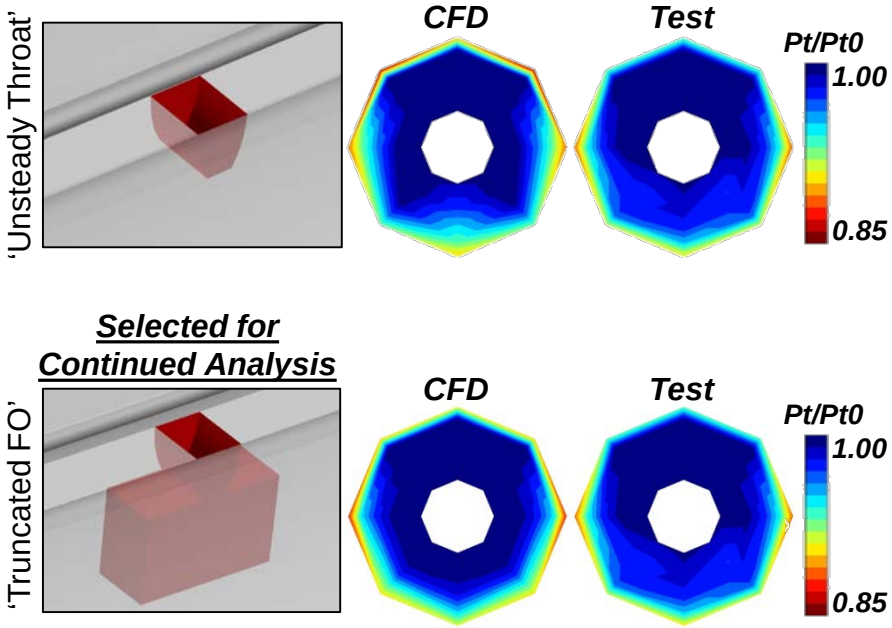
Boeing Time-Accurate Analysis with Flow Control

Characterization of Isolated FO:

Time-accurate LES | Schlieren Imaging



SD-1 Validation with FOs ON:



- **The behavior of an isolated fluidic oscillator was characterized using a high resolution time-accurate simulation**
  - Predicted jet frequency and plume behavior (spreading, peak splitting, decay rate, etc.) were verified using experimental data from a bench test performed by Georgia Tech
  - An unsteady boundary condition was developed to avoid modeling of each fluidic oscillator, reducing the grid size and turn-around time.

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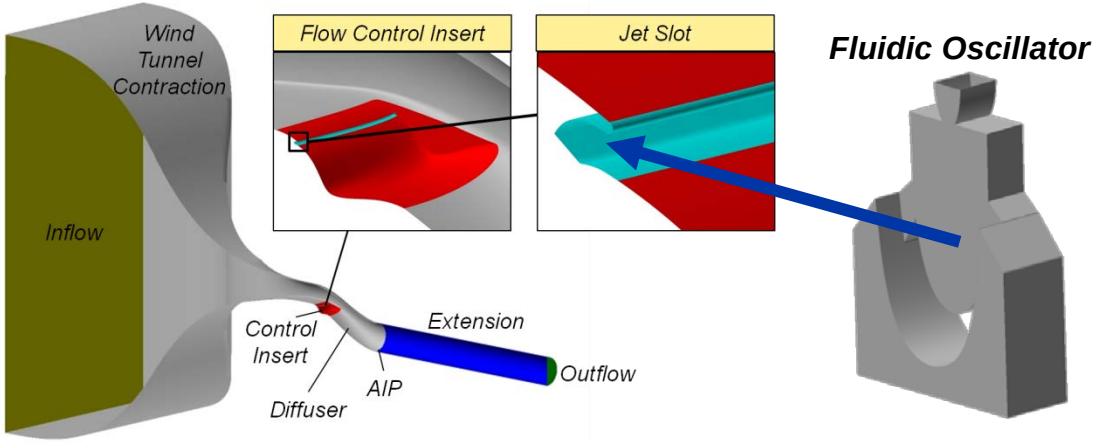
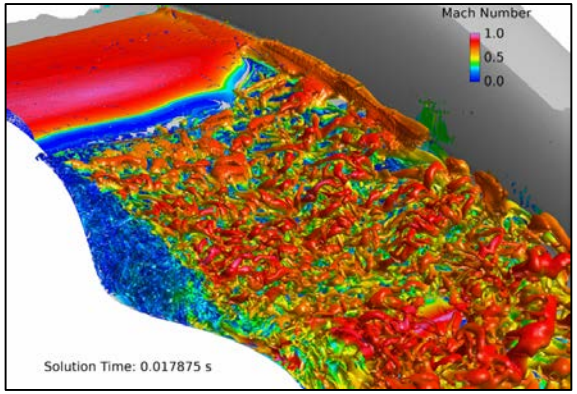
Time step limitations in “real” configurations – S-ducts with flow control

- **The characteristic time associated with the fluidic oscillator, based on nozzle diameter and core jet velocity, is approximately 8 microseconds**

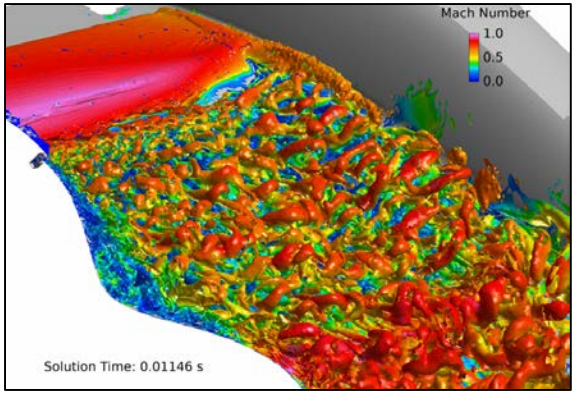


- **The characteristic time associated with the diffuser, based on AIP diameter and core velocity, is approximately 526 microseconds**

Oscillators Off



Oscillators On



AFC necessitates two orders of magnitude reduction in the simulation time step

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Dynamic Distortion Prediction

- Engines are designed to operate within a range of dynamic flow distortion

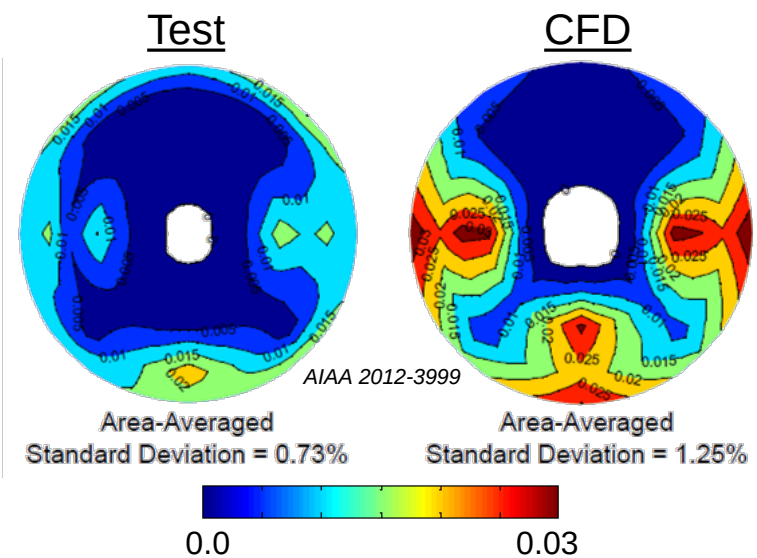
- Exceeding the limits will result in adverse effects on engine operability, and could lead to loss of aircraft

- It is very challenging to accurately predict the unsteady behavior of a wide range of scales while ensuring statistical stationary of the 40-probe data

- High quality experimental dataset are needed to improve and validate CFD technology

- Increased confidence in CFD will not only enable a reduction in the time spent testing in wind tunnels, but could also lead its use for certification

AIP Turbulence



Boeing views this as a critical enabling technology requiring further investment

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Full/Sub-scale Dynamic Distortion Relationship

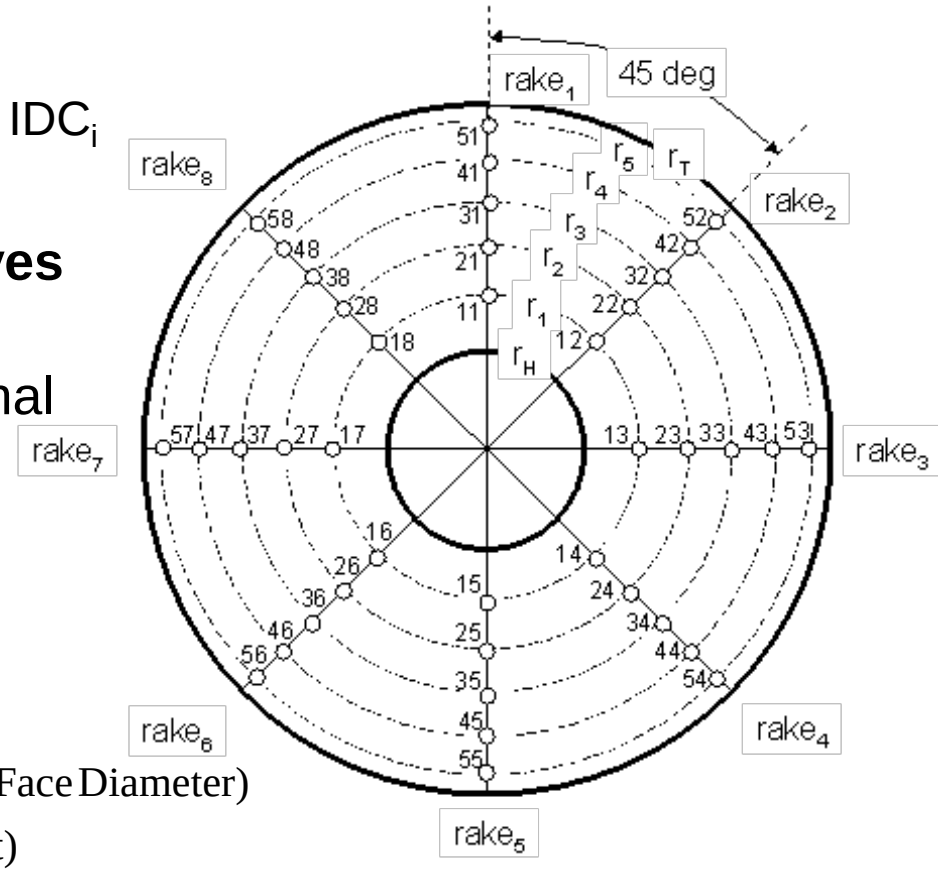
- **Distortion descriptors calculated based on SAE ARP1420B**
  - Descriptors defined on ring basis
    - Circumferential Distortion Intensity – IDC_i
    - Radial Distortion Intensity – IDR_i
- **Max peak value of IDC or IDR drives inlet/engine compatibility**
  - Key similarity parameter is Strouhal Number:

$$\left.\frac{\tau\sqrt{T_t}}{L}\right|_{FullScale} = \left.\frac{\tau\sqrt{T_t}}{L}\right|_{ModelScale}$$

where: τ = Sample Time

L = Characteristic Length (Engine Face Diameter)

T_t = Total Temperature (~ constant)



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Full/Sub-scale Dynamic Distortion Relationship (cont'd)

- Relationship between full scale and model scale becomes:

$$\tau_{ms} = \frac{D_{ms}}{D_{fs}} \tau_{fs}$$

where: ms = Model Scale

fs = Full Scale

- **Max peak value of IDC or IDR Nominally occurs within ~30 secs on full-scale basis**
  - For a 40 in diameter fan and a 5 in AIP 40-probe rake:

$$\tau_{ms} = \frac{D_{ms}}{D_{fs}} \tau_{fs} = \frac{5}{40} 30 = 3.75 \sec$$

Almost 4 seconds of CFD Data Needed to Simulate Testing

An Extreme Challenge For Present-Day CFD Capabilities !!

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Non-deterministic Methods

- **Certification / Qualification by analysis**
  - Cost of developing new aircraft continues to increase
  - We are expected, and must deliver, higher performance more affordably
  - Need a longer term vision for technology development and deployment
    - Geometry preparation, grid generation/adaptation, turbulence model, uncertainty quantifications
  - Source of CFD error not well understood at corners of envelope (turbulence model, grid resolution, numerics, etc.)
    - Non-deterministic approaches are essential to quantify CFD results

CFD will not be primary source of data for design, optimization, and certification-by-analysis unless the uncertainty of results is quantified

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Conclusions and Recommendations

- **Full flight envelop analysis requires routine use of unsteady simulations on large scale**
- **Uncertainty quantification is an essential element of design, optimization, and certifications/qualifications**
  - Use of CFD in mix with wind-tunnel and flight-test data
- **Flight-testing and Certifications/qualifications by analysis**
  - Expensive but provides insight to challenges & issues
  - Cheaper than flight testing
- **Efficient/accurate unsteady turbulence model**
  - Consensus on turbulence model, best practices, …
- **Unsteady simulation cycle-time must be reduced by one to two orders of magnitude to impact development cycle**
- **Highly parallel (10^5 to 10^6 cores) and efficient:**
  - Algorithms (higher-order, compact stencil, low dissipation scheme, FV-hex mesh)
  - CFD code/process architecture
  - Mesh adaptation

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Path Forward

- **Create a consortium of experts from academia, government labs, and industry**
  - Massively parallel
  - Algorithms / turbulence models
  - Adaptation
  - High-quality test data
  - Identify the use cases (i.e. benchmark cases)

- **The gap between the US and Europe in unsteady flow technology has grown over the past decade**
  - Significant investment is required
  - Tight collaboration between the technology developer and end-users (i.e. within a consortium)

An organization, adequate resources, and collaboration team is a must for success

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