Efficient Hybrid Methods for Computational Aeroacoustics in Complex Environments

Philip J. Morris and Yongle Du

Department of Aerospace Engineering

Penn State University

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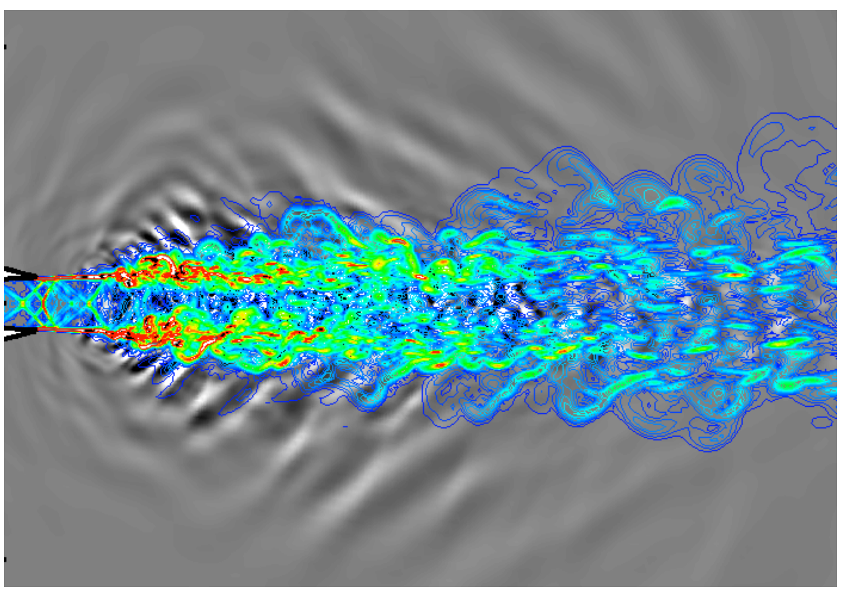
Outline

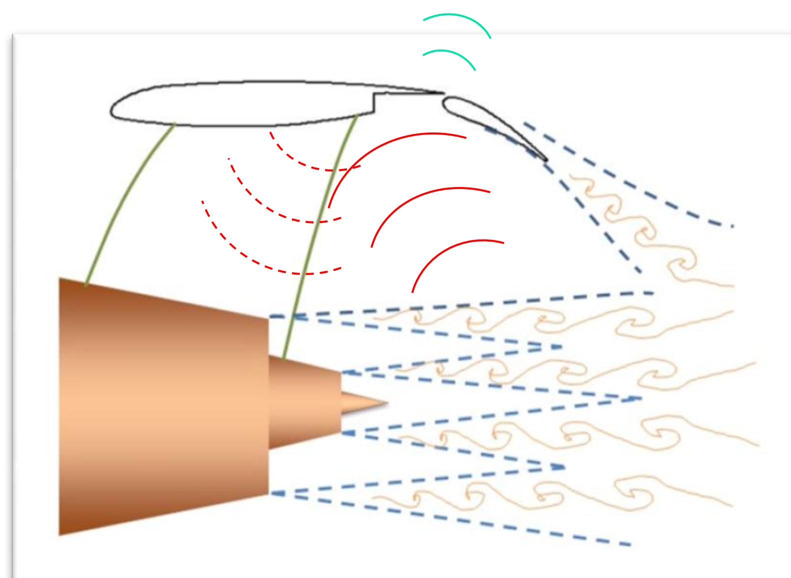
- Challenges of CAA simulations in complex environments
- Compact Disturbance Equations (CDE) for coupled CFD/CAA simulations
- Example applications
  - Waves in a jet
  - Trailing edge noise
  - Jet noise
  - Acoustic scattering
- Conclusions

Installed Jet Noise

- Very limited near-field flow region (CFD)
  - Viscous dissipation, non-linearity, shocks
  - very fine turbulent eddies – especially in interior of the nozzle
- Large far-field noise propagation region (CAA)
  - Inviscid, nearly linear
  - Relatively large time and length scales



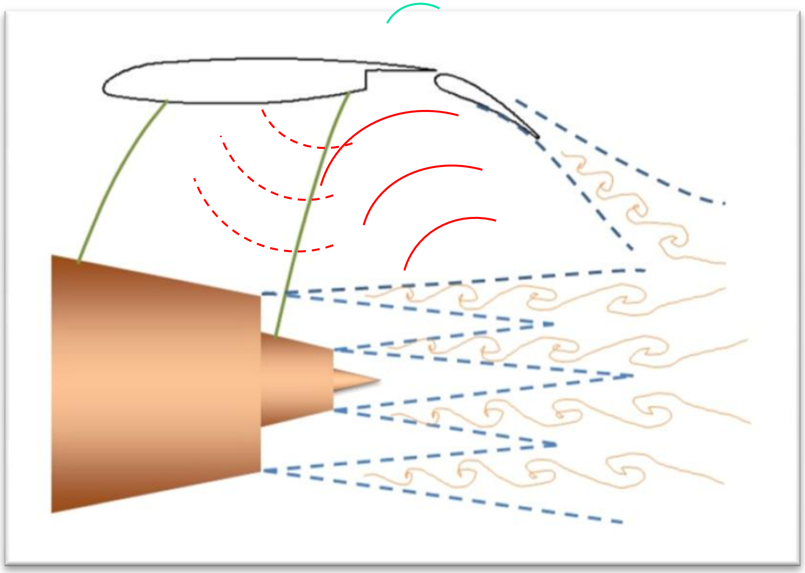
Uninstalled jet noise



Installed jet noise

Complex Flow Physics

- Different flow physics
  - Strong non-linear fluctuations in the source region
  - Weak acoustic fluctuations outside the mixing layer
  - Simultaneous simulation required
- Non-linearity causes numerical difficulties
  - Non-reflecting BCs, dispersion/dissipation errors



Installed jet noise

Linearized Equations

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- Splitting: mean flows + disturbances

Mean | Disturbance

$$\mathbf{U} = \bar{\mathbf{U}} + \mathbf{U}' = \left[\begin{array}{ccccc} \bar{\rho} & \bar{p} & \tilde{u} & \tilde{v} & \tilde{w} \end{array} \right]^T + \left[\begin{array}{ccccc} \rho' & p' & u'' & v'' & w'' \end{array} \right]^T$$

- Linearized N-S equations

$$\frac{\partial \mathbf{u}'}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{u}' + \mathbf{u}' \cdot \nabla \mathbf{U} = -\nabla p + \nu \nabla^2 \mathbf{u}' + \mathbf{f}$$

$$\nabla \cdot \mathbf{u}' = 0$$

  - Parabolic Stability Equation (PSE)

$$u = \hat{u}(x, y) e^{-i\omega t + i\theta(x) + i\beta z}$$

Herbert, 1994

Gudmundsson and Colonius, 2011

  - Convective instability modes in jets

Linearized equations

- Linearized Euler Equation

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho'\\(\rho u)'\\(\rho v)'\\(\rho E)'\end{pmatrix}+\frac{\partial}{\partial x}\begin{pmatrix}(\rho u)'\\\rho_0 u_0 u'+(\rho u)'u_0+p'\\\rho_0 v_0 u'+(\rho v)'u_0\\\rho_0 H_0 u'+(\rho H)'u_0\end{pmatrix}+$$

$$\frac{\partial}{\partial y}\begin{pmatrix}(\rho v)'\\\rho_0 u_0 v'+(\rho u)'v_0\\\rho_0 v_0 v'+(\rho v)'v_0+p'\\\rho_0 H_0 v'+(\rho H)'v_0\end{pmatrix}=0$$

  - Pros: Ideal for noise propagation simulation:
    - Better accuracy and non-reflecting BC treatment, less cost
  - Cons: Noise sources absent
    - Coupled with the near-field LES of a separate computation
    - Flow exchanged at fixed interfaces/overlapping regions

Q: A single equation & computation
for flow/acoustic simulations in segregated domains ?

CFD/CAA: Coupled or Decoupled?

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- Decoupled:
  - Near-field LES + Acoustic analogy (FWH, Kirchhoff …)
  - Challenging for installed jets
    - requires a very large domain to include installed geometries
- Loosely coupled:
  - Separate near-field LES + far-field LEE
  - Feasible for installed jets
  - Data communication?
- Fully coupled:
  - DNS (Direct Noise Simulation)
  - Not affordable for complex installed jets

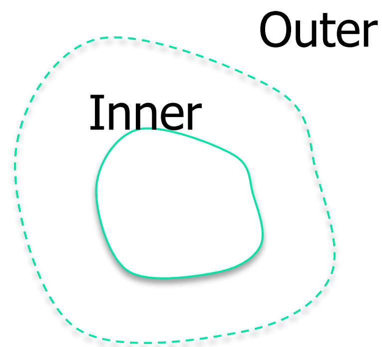
<u>Our goal:</u>
Closely coupled CFD/CAA in a single computation

Coupled CFD/CAA?

- Data communication?

Domain splitting

Hemeda and Elhadidi, 2014. AIAA J.



Loosely coupled via source terms

Bogey et al., 2002, AIAA J.
Ewert et al., AIAA 2014-3053.

$$L(q', q_0) = S$$

Source term extracted from a separate LES computation or stochastic sound sources

Closely coupled with a soft interface/zone (The present study)

A Previous Related Approach

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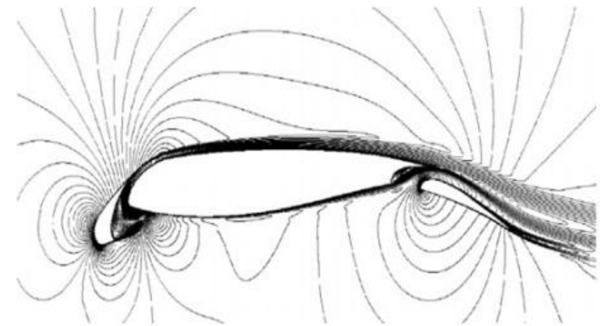
- Non-Linear Disturbance Equations (NLDE)
  - Flow splitting: mean + disturbances
  - Rearrangement of the exact N-S equations
    - LHS: disturbances
    - RHS: mean flow only
  - Pros:
    - Smaller domain
    - Better BC treatments
  - Cons:
    - Complex formulation

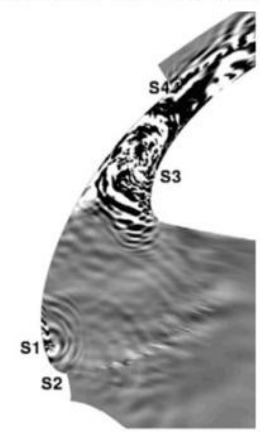
Morris *et al.*. 1997



(a) Mach number contours of the RANS calculation

Slat noise
Labourasse and Sagaut, 2004

(b) NLDE subdomain



(c) Isovalues of $\nabla \cdot u$

Compact Disturbance Equations

- A compact decomposition
  - Previously: decomposition of the primitive variables

Mean/Base Disturbance

$$\mathbf{U} = \bar{\mathbf{U}} + \mathbf{U}' = \begin{bmatrix} \bar{\rho} & \bar{p} & \tilde{u} & \tilde{v} & \tilde{w} \end{bmatrix}^T + \begin{bmatrix} \rho' & p' & u'' & v'' & w'' \end{bmatrix}^T$$

  - Now: compact decomposition

⇩

Mean/Base Disturbance

$$\mathbf{Q} = \bar{\mathbf{Q}} + \mathbf{Q}' = \begin{bmatrix} \bar{\rho} & \bar{\rho}\tilde{e} & \bar{\rho}\tilde{u} & \bar{\rho}\tilde{v} & \bar{\rho}\tilde{w} \end{bmatrix}^T + \begin{bmatrix} \rho' & (\rho e)' & (\rho u)' & (\rho v)' & (\rho w)' \end{bmatrix}^T$$

No assumptions are made about U and U'
Mean/Base flow can be arbitrary

Coupled Navier-Stokes/LEE

- Compact decomposition
  - A scaling factor α to switch on/off nonlinear terms

Momentum

$$\rho u_i = \bar{\rho}\tilde{u}_i + \left(\rho u_i\right)'$$

$$= \bar{\rho}\tilde{u}_i + \underline{\bar{\rho}u_i'' + \rho'}\tilde{u}_i + \alpha\rho' u_i''$$

Base Linear Non-linear

Momentum flux

$$\rho u_i u_j = \bar{\rho}\tilde{u}_i\tilde{u}_j + \left(\rho u_i u_j\right)'$$

$$= \bar{\rho}\tilde{u}_i\tilde{u}_j + \underline{\tilde{u}_j\left(\rho u_i\right)' + u_j''\left(\bar{\rho}\tilde{u}_i\right)} + \alpha\boxed{\left(\rho u_i\right)' u_j''}$$

Base Linear Non-linear

Combined Navier-Stokes/LEE

- Momentum disturbance

$$(\rho u_i)' = \bar{\rho} u_i'' + \rho' \tilde{u}_i + \alpha \rho' u_i''.$$

Linear

$$\frac{\partial (\rho u_i)'}{\partial u_i''} = \bar{\rho}$$

Non-linear

$$\frac{\partial (\rho u_i)'}{\partial u_i''} = \bar{\rho} + \alpha \rho'$$

- Momentum flux disturbance

$$(\rho u_i u_j)' = \tilde{u}_j (\rho u_i)' + u_j'' (\bar{\rho} \tilde{u}_i) + \alpha \boxed{(\rho u_i)' u_j''}$$

Linear

$$\frac{\partial (\rho u_i u_j)'}{\partial u_i''} = \bar{\rho} \tilde{u}_j$$

Non-linear

$$\frac{\partial (\rho u_i u_j)'}{\partial u_i''} = (\bar{\rho} + \alpha \rho')\left(\tilde{u}_j + \alpha u_j''\right)$$

- Flux Jacobian Matrix

Linear

$$\frac{\partial Q'}{\partial U'} = \frac{\partial \bar{Q}}{\partial \bar{U}}$$

$$\frac{\partial F_j'}{\partial U'} = \frac{\partial \bar{F}_j}{\partial \bar{U}}$$

Non-linear

$$\frac{\partial Q'}{\partial U'} = \frac{\partial Q}{\partial U}$$

$$\frac{\partial F_j'}{\partial U'} = \frac{\partial F_j}{\partial U}$$

Flux Jacobian matrix

$$\frac{\partial \mathbf{F}_j'}{\partial \mathbf{Q}'} = \frac{\partial \mathbf{F}_j' / \partial \mathbf{U}'}{\partial \mathbf{Q}' / \partial \mathbf{U}'}$$

Mathematical Properties

- Flux Jacobian Matrix

Flux Jacobian matrix

$$\frac{\partial \mathbf{F}_j'}{\partial \mathbf{Q}'} = \frac{\partial \mathbf{F}_j' / \partial \mathbf{U}'}{\partial \mathbf{Q}' / \partial \mathbf{U}'}$$

- Eigenvalues and eigenvectors for:
  - Stability analysis
  - Characteristic decomposition for boundary and interface conditions
  - Numerical methods:
    - Explicit artificial dissipation
    - Limiters in Roe-type splitting in FD/FV methods
    - and more

Compact Disturbance Equations (CDE)

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- Exact rearrangement of the Navier-Stokes equation

Linear terms

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho' \\ (\rho e)' \\ (\rho u)' \\ (\rho v)' \\ (\rho w)'\end{bmatrix} + \frac{\partial}{\partial x_j}\tilde{u}_j\begin{bmatrix}\rho' \\ (\rho e)' + p' \\ (\rho u)' \\ (\rho v)' \\ (\rho w)'\end{bmatrix} + \frac{\partial}{\partial x_j}u''\begin{bmatrix}\bar{\rho} \\ \bar{\rho}\tilde{e} + \bar{p} \\ \bar{\rho}\tilde{u} \\ \bar{\rho}\tilde{v} \\ \bar{\rho}\tilde{w}\end{bmatrix} + \frac{\partial}{\partial x_j}\begin{bmatrix}0 \\ 0 \\ p'_{xj} \\ p'_{yj} \\ p'_{zj}\end{bmatrix}$$

$$+\alpha\frac{\partial}{\partial x_j}\boxed{u_j''\begin{bmatrix}\rho' \\ (\rho e)' + p' \\ (\rho u)' \\ (\rho v)' \\ (\rho w)'\end{bmatrix}} - \frac{\partial}{\partial x_j}\begin{bmatrix}0 \\ -q'_j + \tilde{u}_i\tau'_{ij} + u_i''\bar{\tau}_{ij} \\ \tau'_{xj} \\ \tau'_{yj} \\ \tau'_{zj}\end{bmatrix} - \alpha\frac{\partial}{\partial x_j}\begin{bmatrix}0 \\ u_i''\tau'_{ij} \\ 0 \\ 0 \\ 0\end{bmatrix} = \underbrace{\frac{\partial\bar{\mathbf{Q}}}{\partial t} + R(\mathbf{Q})}_{\text{Base flow}}$$

Non-linear terms

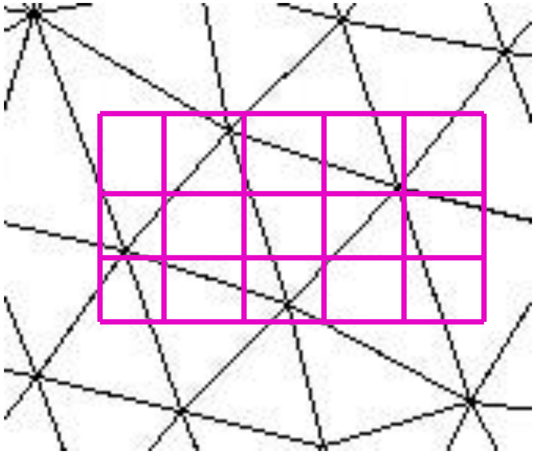
Linear viscous disturbances

Non-linear viscous disturbances

Base

Benefits and Implementation

- Reduced computational cost
  - Relatively inexpensive RANS base simulation for complex configurations
    - Can use unstructured meshes
    - Can use third-party solvers
  - LES in a reduced simpler domain, optimal grid distribution and BCs
    - Reconstruct flux disturbances only
    - Minor changes with turbulence models
- Hybrid RANS/LES



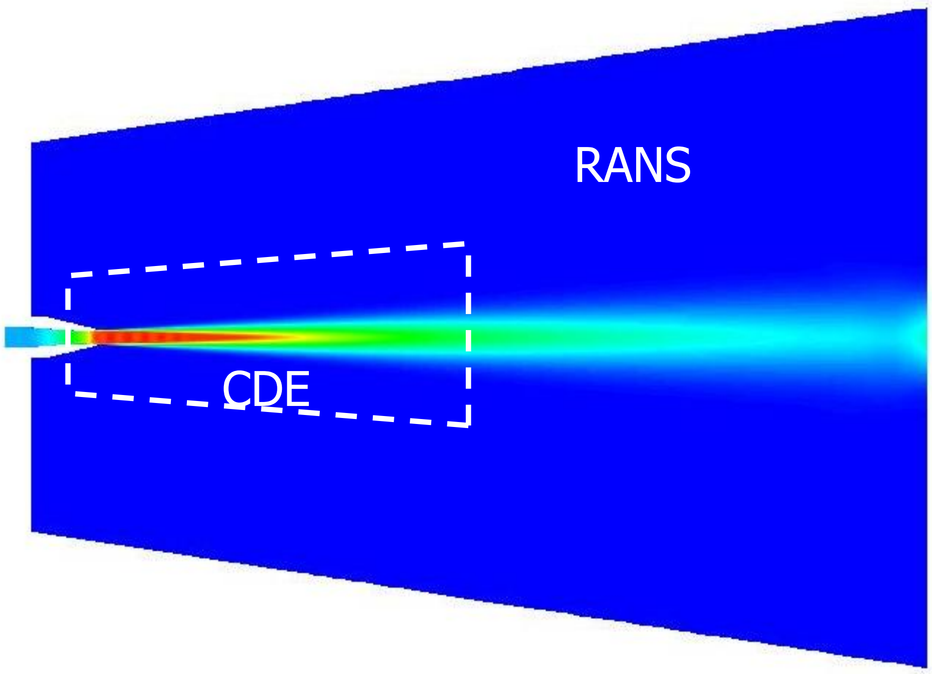
Interpolation

CDE Equation Options

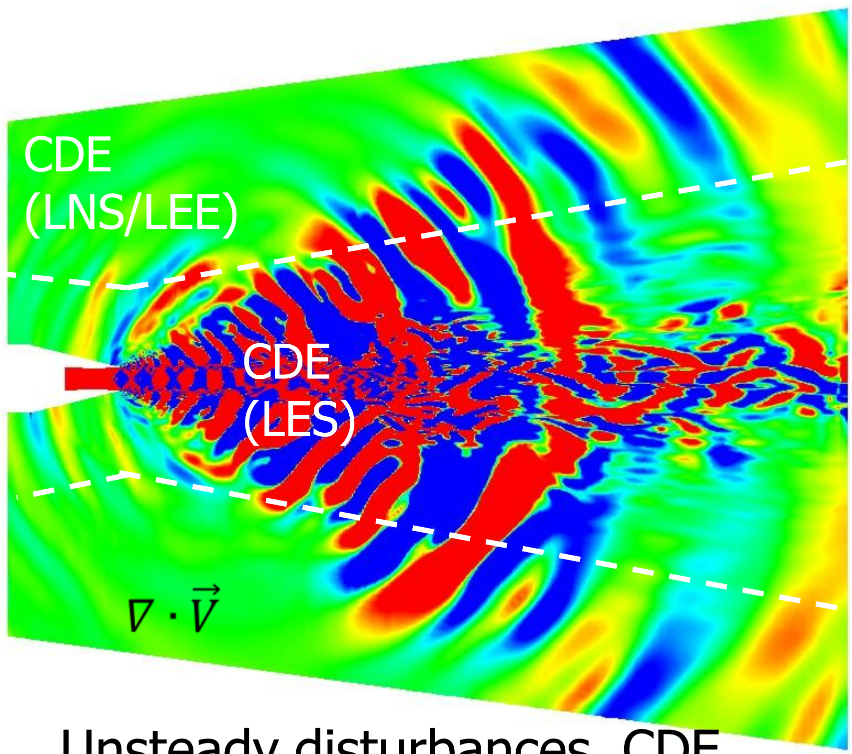
Reduced Equations Embedded in the CDE		
Equations	Viscous disturbances	Nonlinear terms
Full NS	Yes	Yes
LNS	Yes	No
Full Euler	No	Yes
LEE	No	No

Qualitative Demonstration

- Base flow: RANS simulation (S-A model)
- Unsteady disturbances: CDE
  - α=1 near the shear layer, α=0 outside.



Base, steady RANS computation



Unsteady disturbances, CDE

2D supersonic jet, Mj=1.5

Implementation

- Major features of CFD solver: CHOPA
  - Multi-block structured meshes
  - URANS and CDE
  - Spalart-Allmaras, Standard DES, Implicit LES
  - 4th order DRP
  - Dual-time stepping for unsteady simulations
    - Multi-grid
    - Implicit residual smoothing

- Yongle Du, Ching-Wen Kuo, Philip J. Morris and Dennis K. McLaughlin, 2012. Simulations and measurements of the flow and noise in hot supersonic jets. *Noise Control Engineering Journal.* 60(5): 577-594.
- Yongle Du and Philip J. Morris, 2012. Numerical investigation of the noise source locations of supersonic jets using the beamformed method. AIAA-2012-1169.
- Ching-wen Kuo, Yongle Du, Dennis K. McLaughlin and Philip J. Morris, 2012. Experimental and computational study of near field/far Field correlations in supersonic jet noise. AIAA 2012-1170.
- Yongle Du and Philip J. Morris, 2011. Supersonic jet noise simulations for chevron nozzles. AIAA 2011-2787.

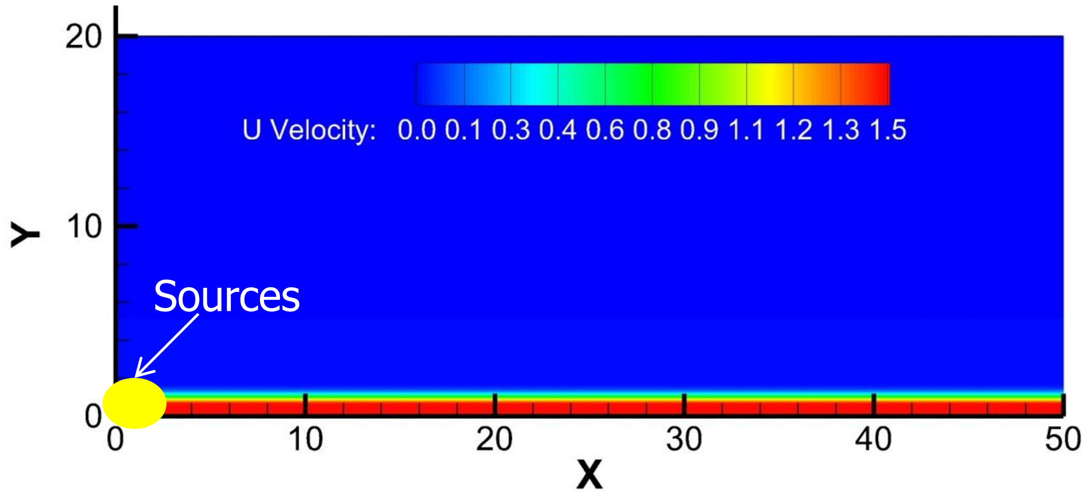
First Application: Acoustic Waves in a 2D Jet

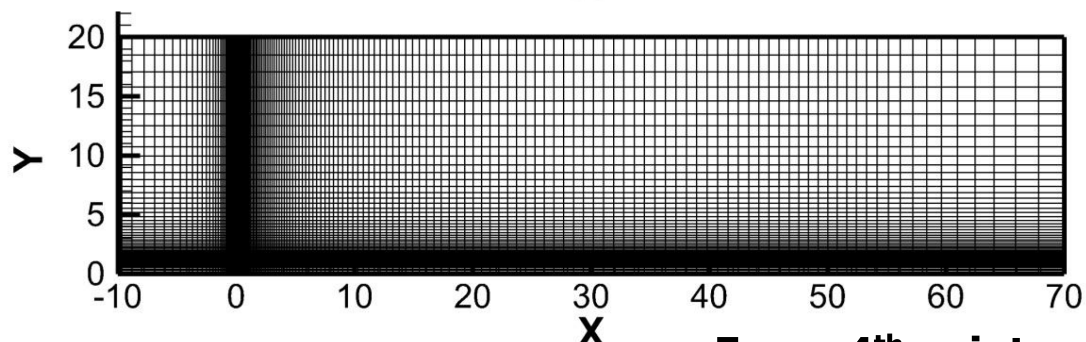
3rd CAA Workshop

- Purpose:
  - Accuracy of the LEE embedded in CDE

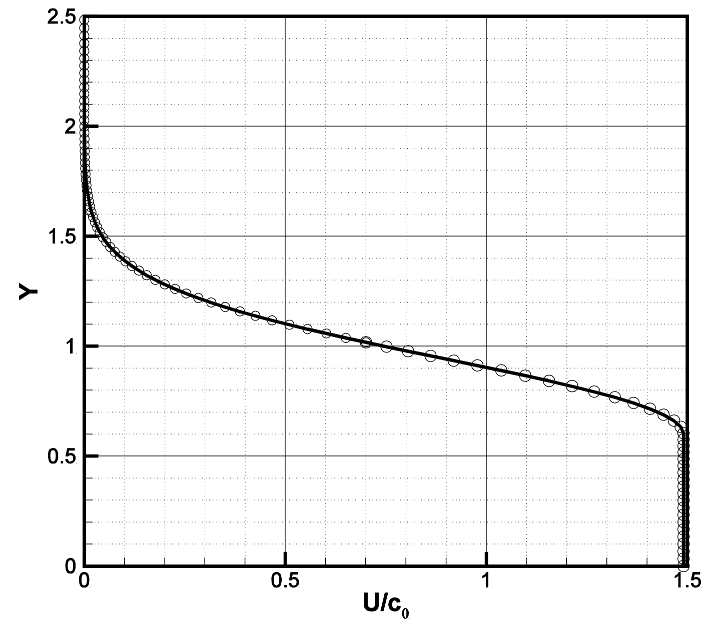
$$p_s = A \exp\left[-B \ln 2\left(x^2+y^2\right)\right]\cos(\omega t)$$

$P'/P_0 \sim 10^{-12}$



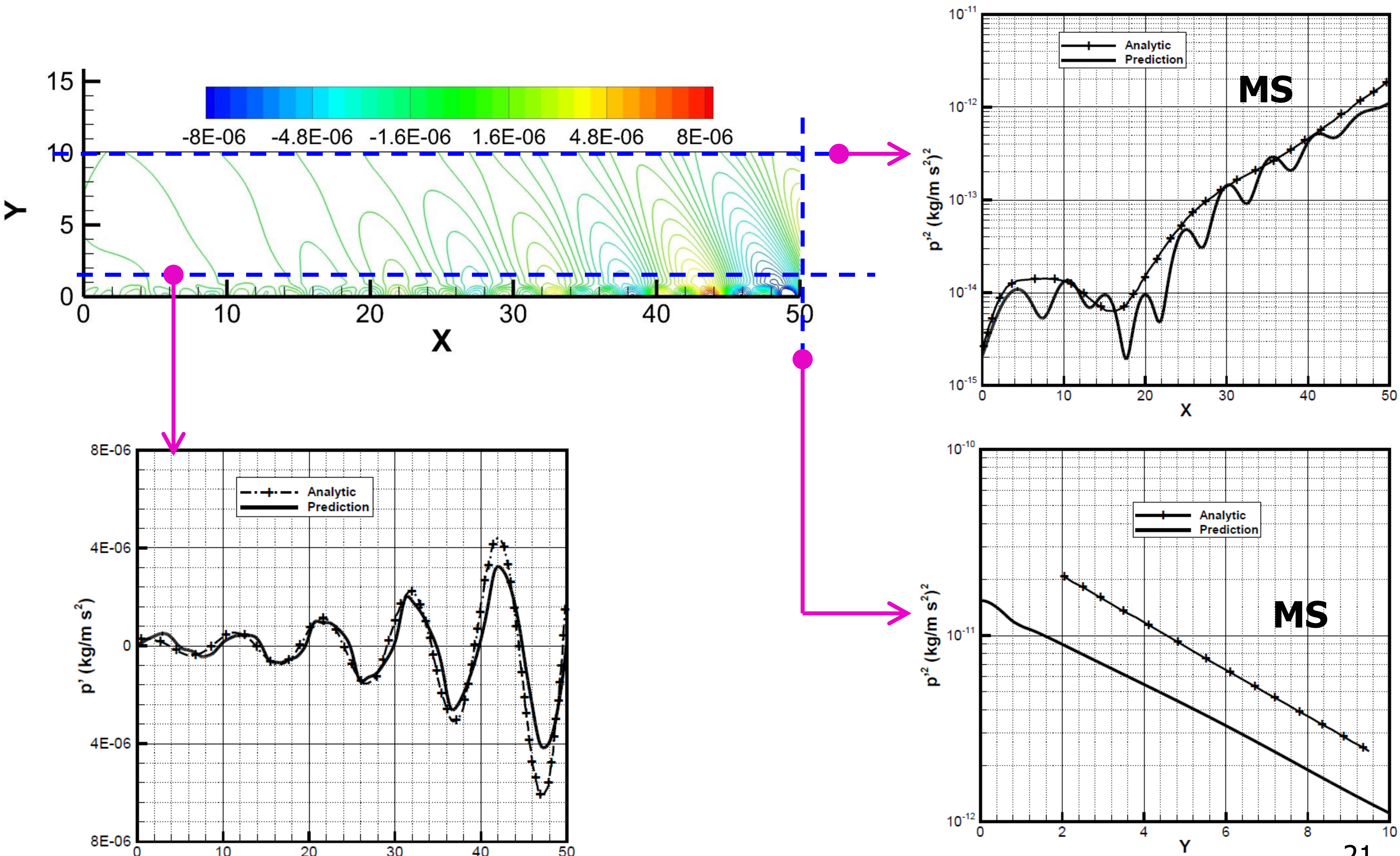


Every 4th point



Mean axial velocity

First Application: Acoustic Waves in a 2D Jet

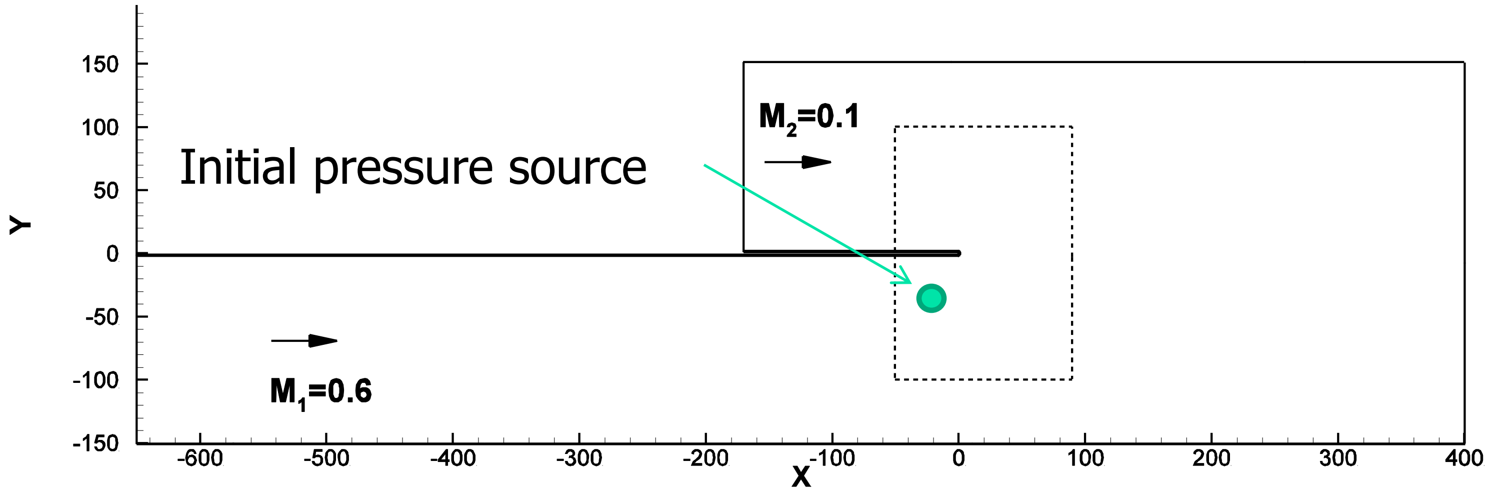


t=90 and y=1

Second Application: Trailing Edge Scattering

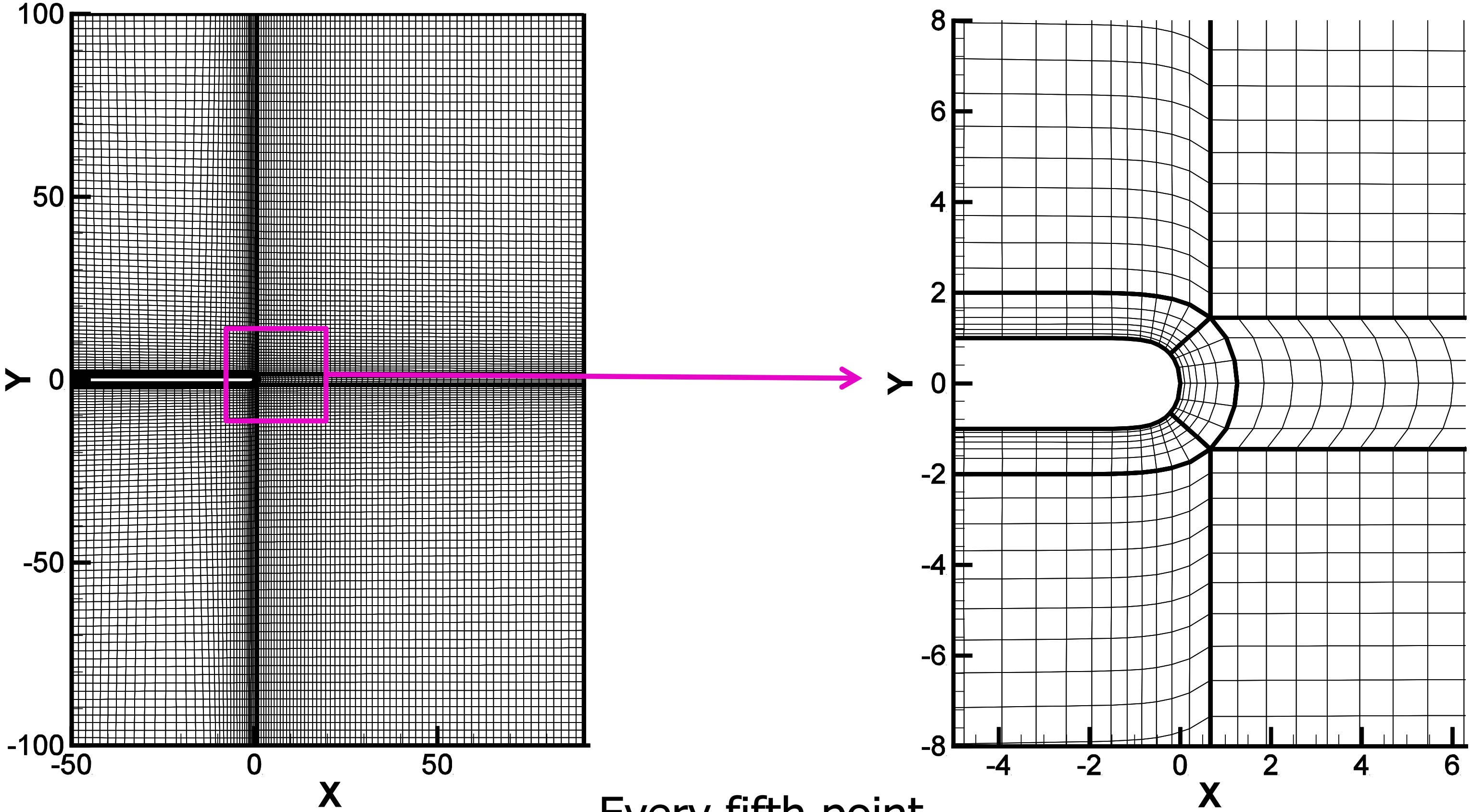
4th CAA Workshop

- Purpose
  - Viscous computations: CDE recovers the full NS
  - Two-step computation:
    - 1. Steady laminar, 0.14M points
    - 2. Unsteady CDE, 0.26M points
  - CDE computation in a reduced domain



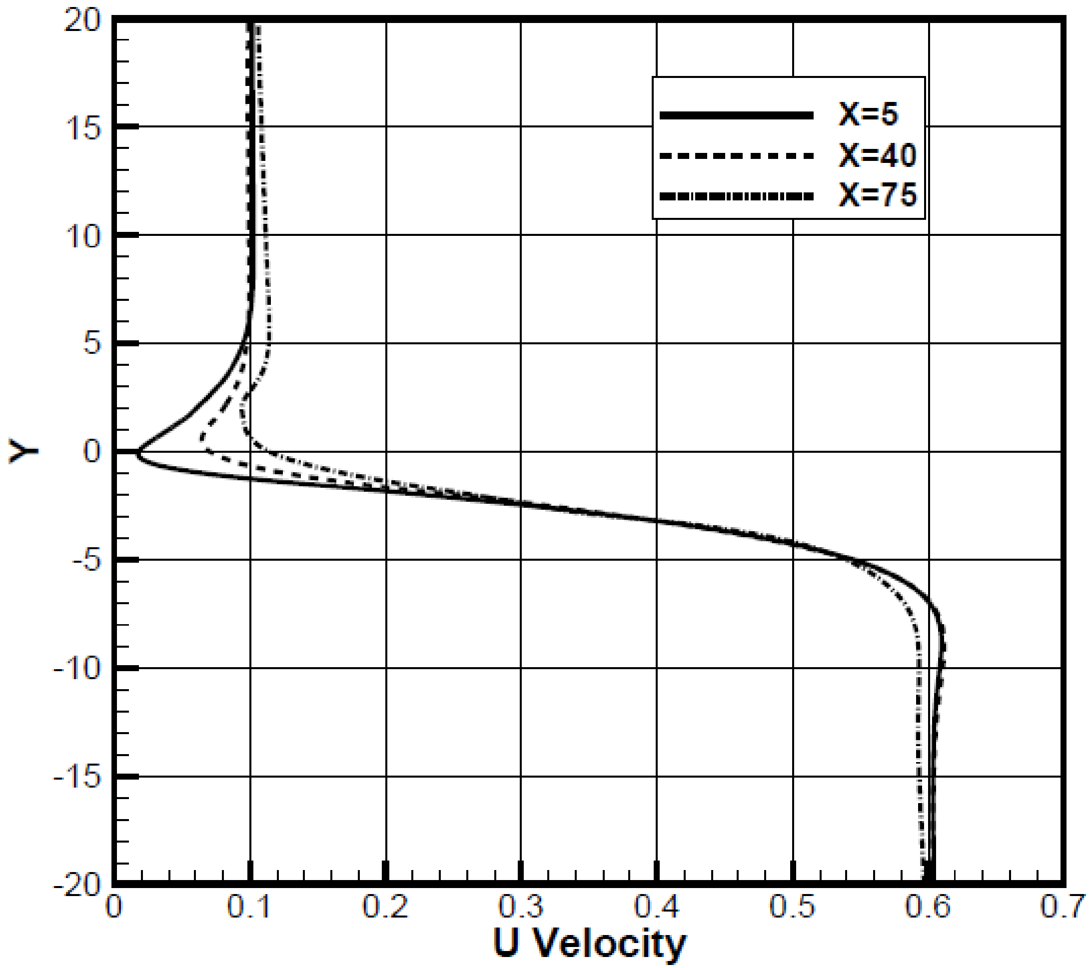
Second Application: Trailing Edge Scattering

- No sponge zone
- Dong's radiation BC based on disturbances around the local base flows



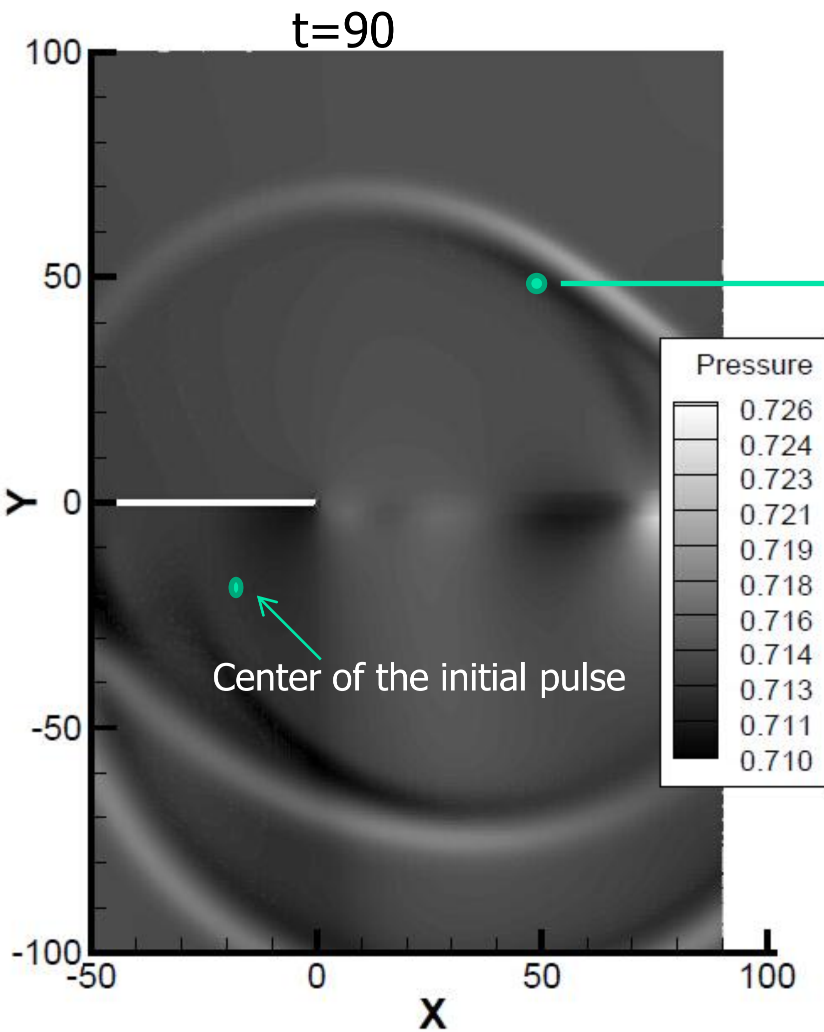
Every fifth point

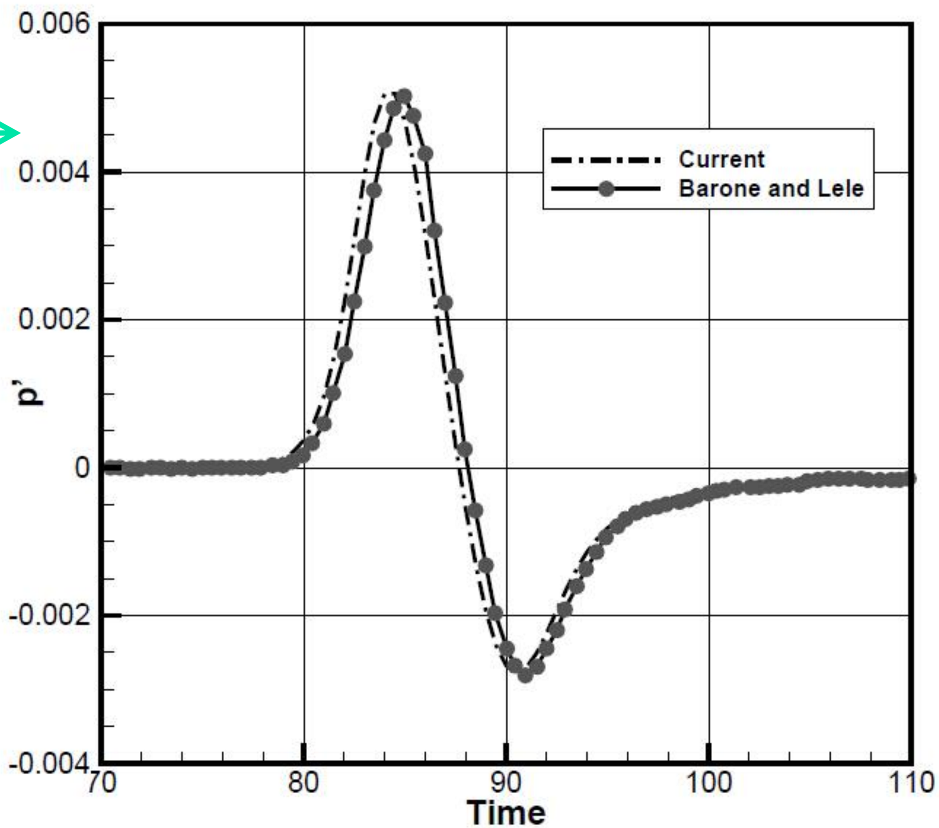
Steady State Laminar Solution



Second Application: Trailing Edge Scattering

- Solutions

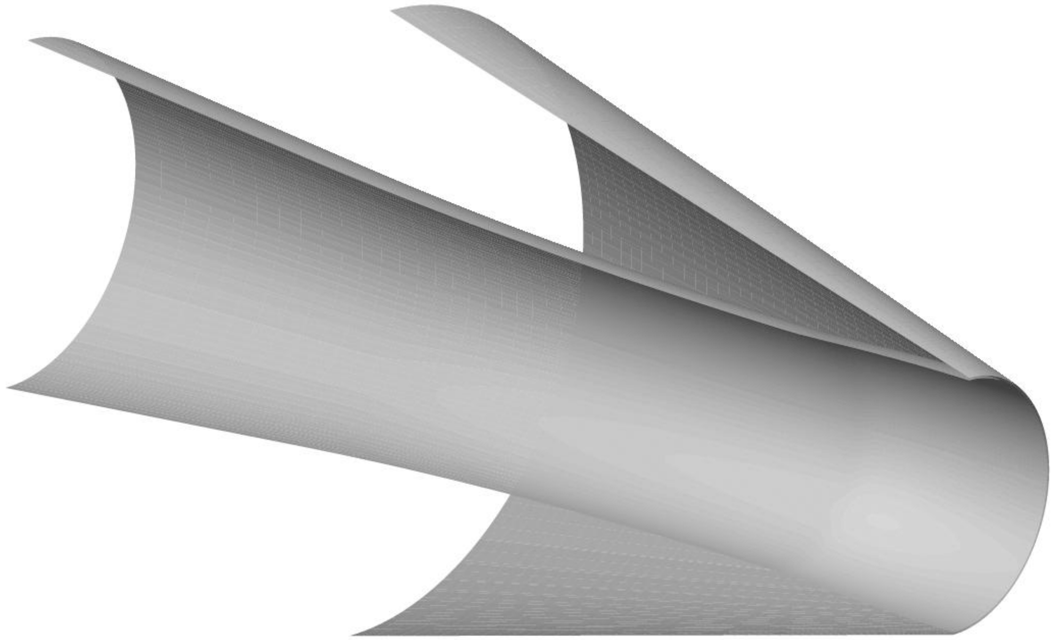




Third Application: Supersonic Jet Noise

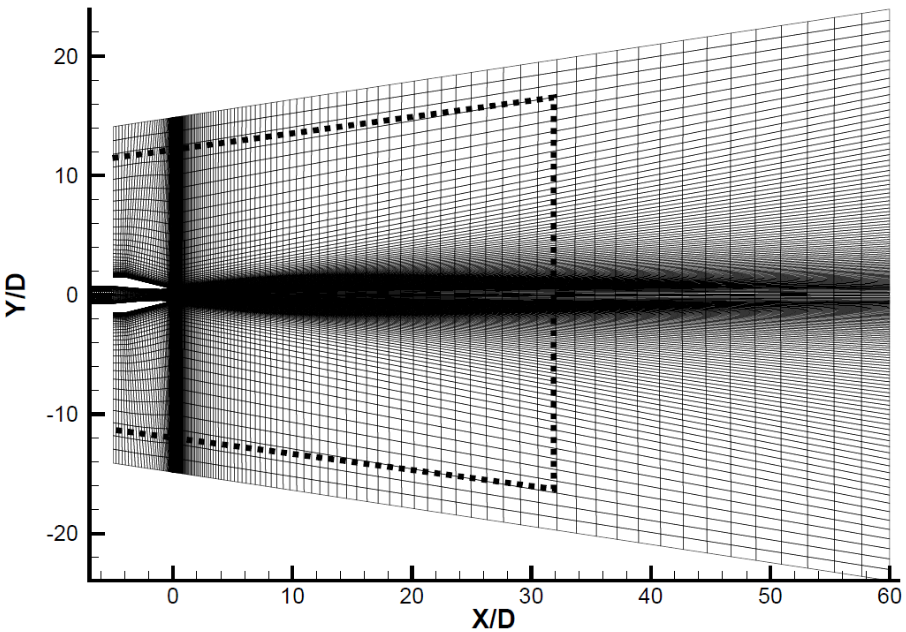
- SMC-015

$$M_d = 1.4,\ M_j = 1.4,\ TTR = 2.3$$

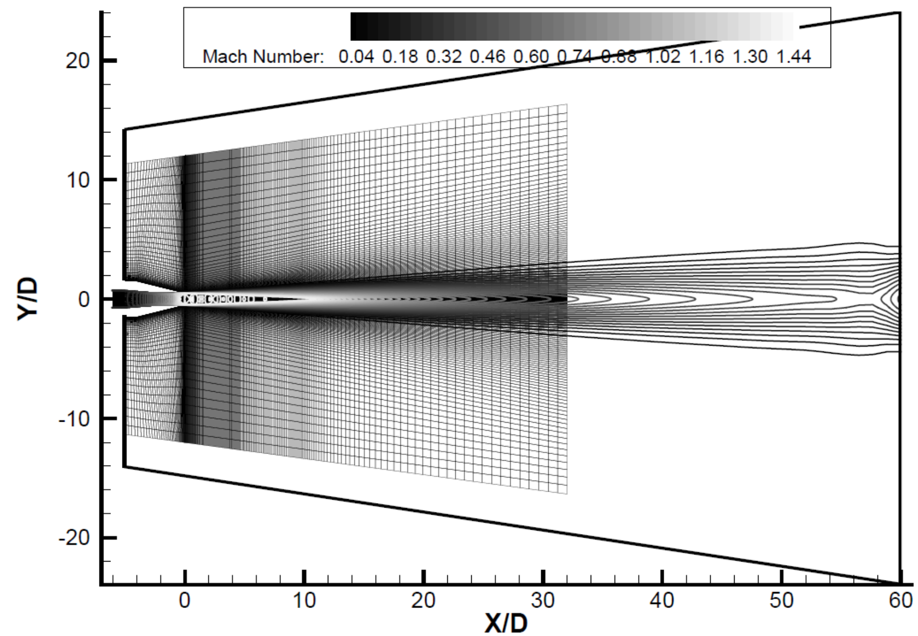


Third Application: Supersonic Jet Noise

- RANS and CDE domains
  - Viscous disturbances not included - additional ~30% saving of computational load



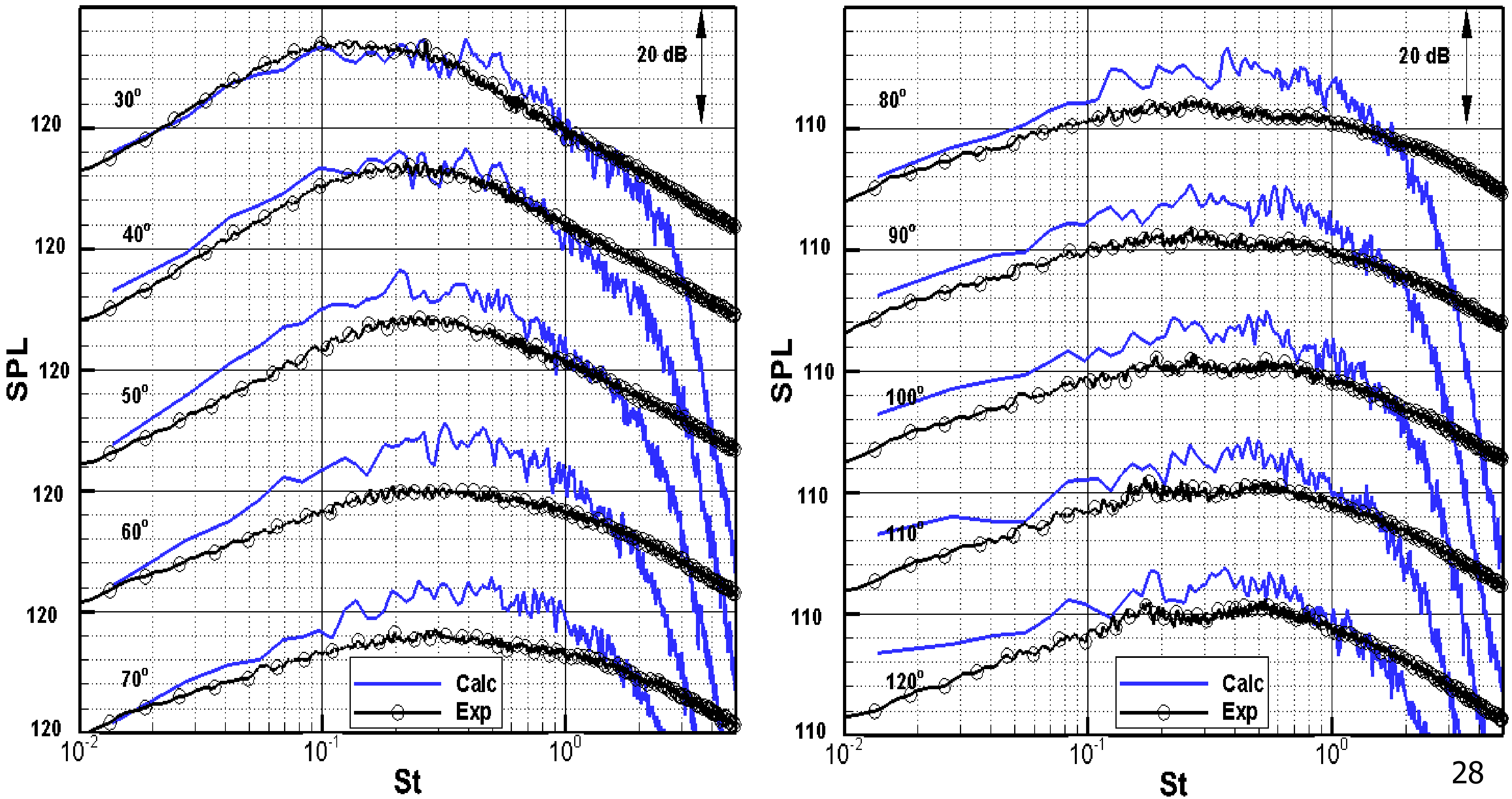
Steady base, 7M points



CDE unsteady, 13M points
Can be further reduced in radial direction

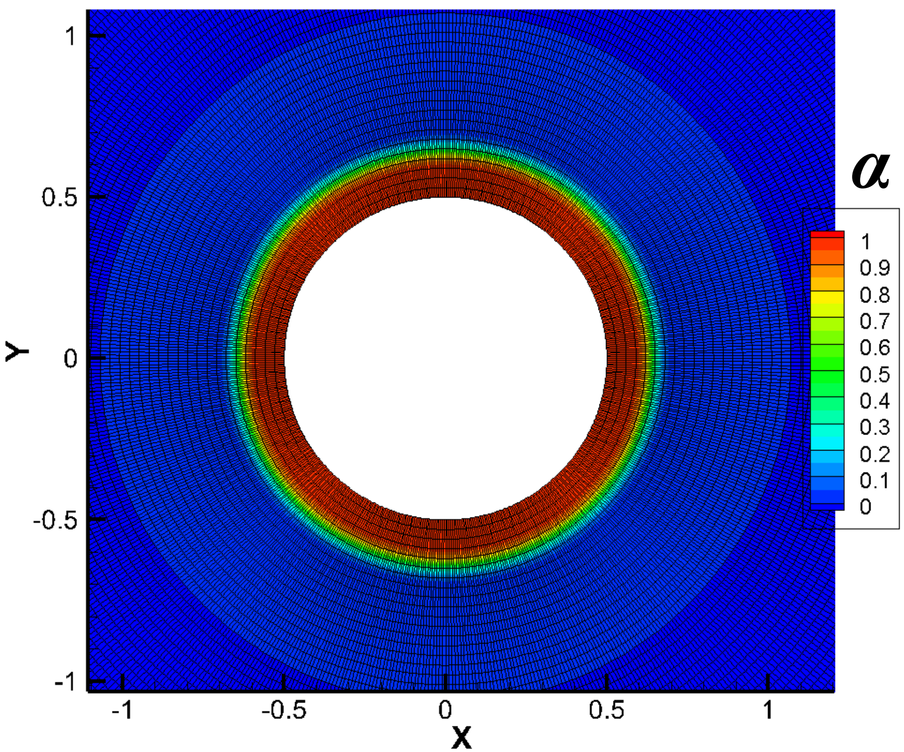
Third Application: Supersonic Jet Noise

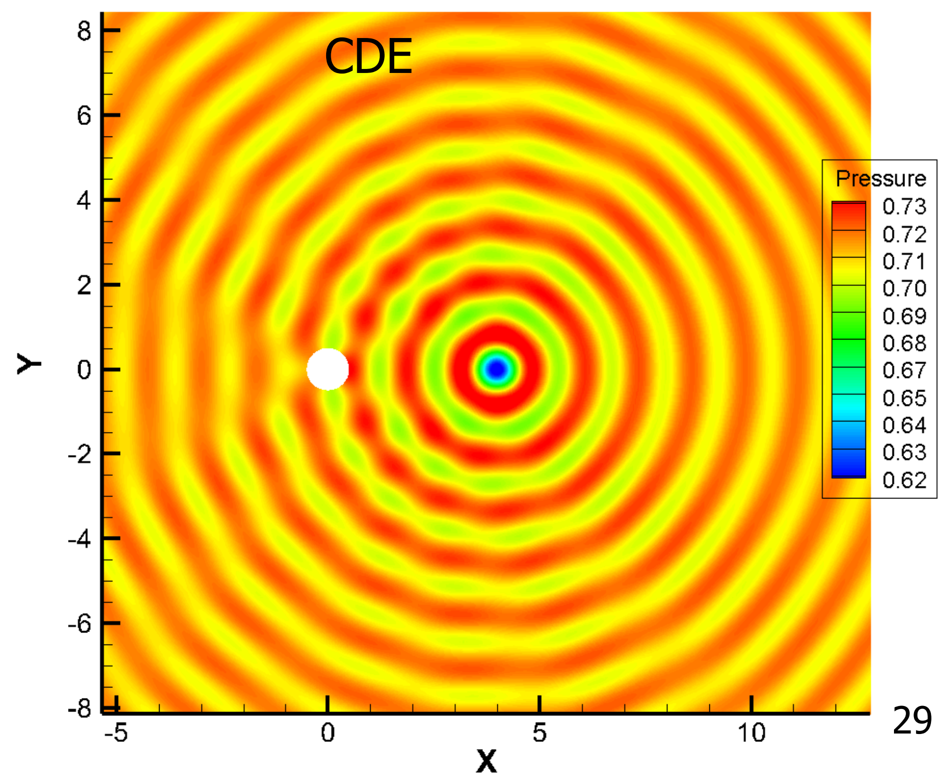
- Noise spectra



An Ongoing Test

- Acoustic scattering from a circular cylinder
  - Diameter of the cylinder: D=1
  - α specified currently for validation purpose
    - Effects of the sizes of the nonlinear region, the transition between nonlinear and linear regions.)





Conclusions & Future work

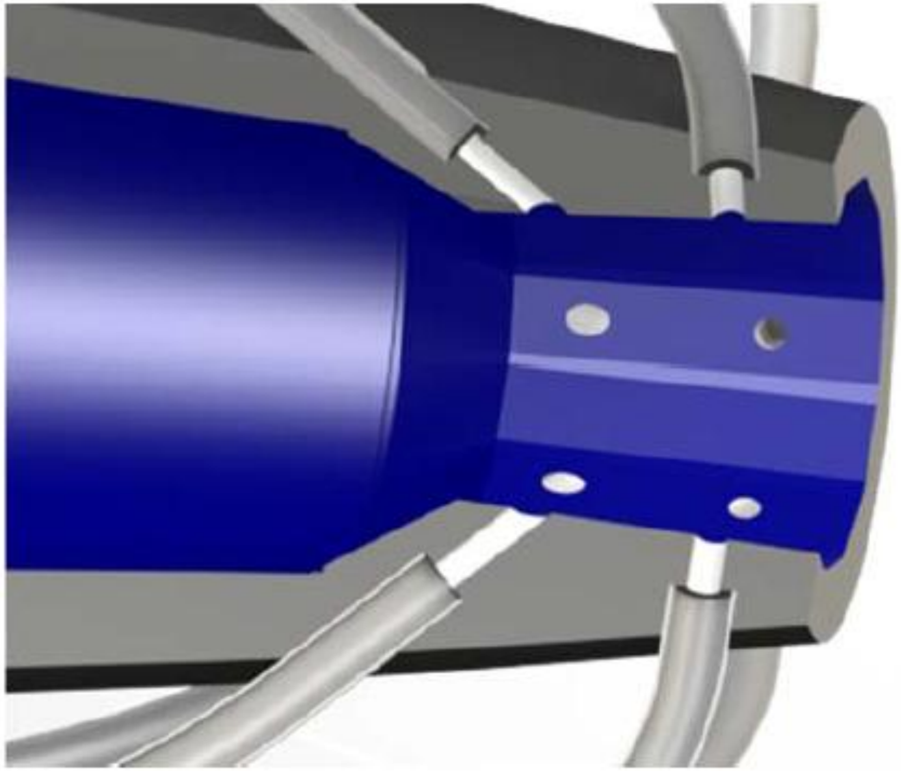
- Compact Disturbance Equations
  - Rearrangement of the NS equation
  - Minor changes in existing codes to implement
- Two-step computation:
  - Steady base simulation in a larger, complex domain
  - Unsteady disturbances in a smaller, simpler domain
- Benefits demonstrated by three benchmark tests:
  - Reduced computational cost
  - Optimal grid distribution for unsteady simulations
  - Closely coupled CFD/CAA for installed jet noise simulations

Jet Noise Reduction

Penn State Aerospace Engineering

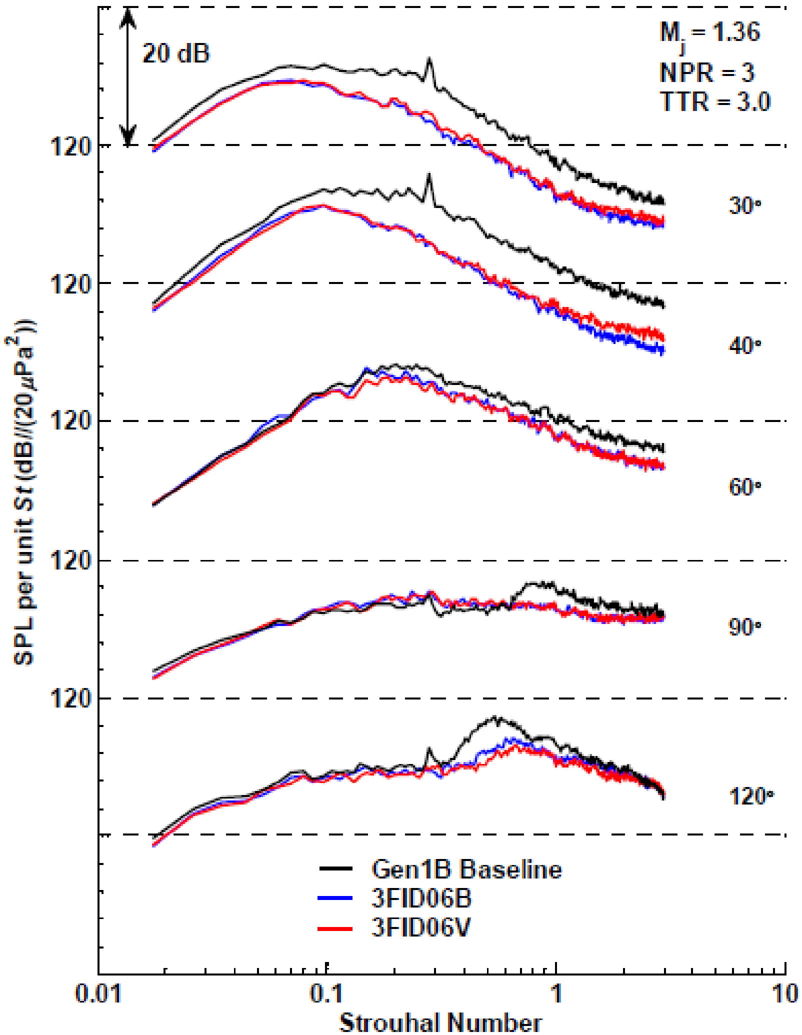
- Noise from tactical fighter aircraft may cause Noise Induced Hearing Loss (NIHL)
- Sailors exposed to high levels of noise before and during take-off
- Hearing protection is not sufficient (helmets and earplugs)
- Need for noise reduction at the source
- Experiments at Penn State demonstrate a new fluidic injection method for noise reduction
- Based on the corrugated seal concept by Seiner

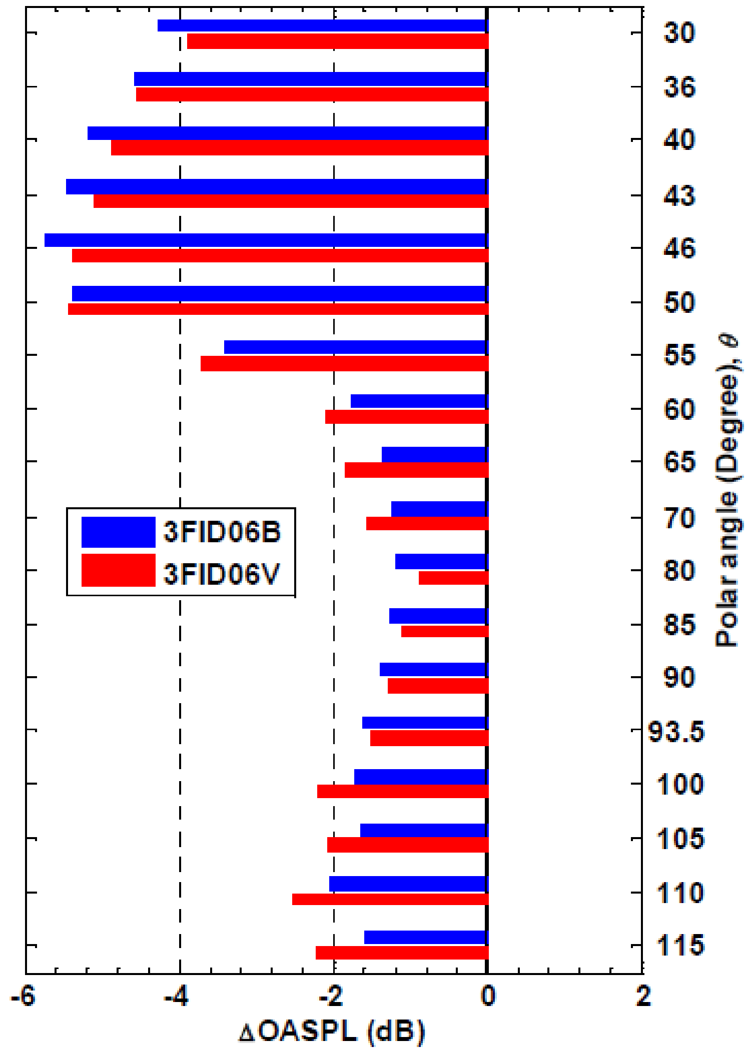
Fluidic Inserts



12 injectors and 6 fluidic inserts

Jet Noise Reduction

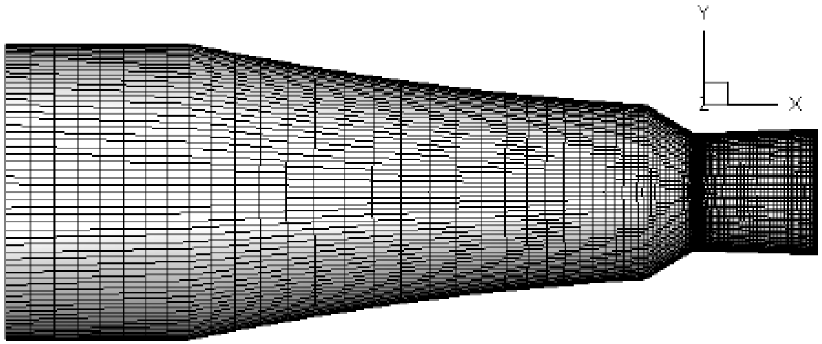




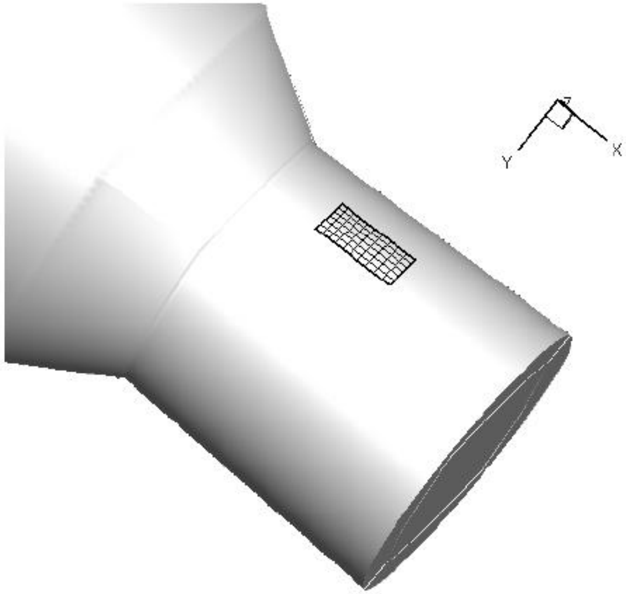
Future Opportunities

- Optimum design for noise reduction
  - Adjoint Methods
    - Unsteady adjoint solutions
      - Wei & Freund – 2006 (Noise controlled free shear layer)
      - Kim, Bodony & Freund - 2011 (Mach 1.3 Jet)
    - Steady solutions
      - Sikarwar & Morris – 2014 (Blowing in C-D nozzle)

Optimum Blowing Example

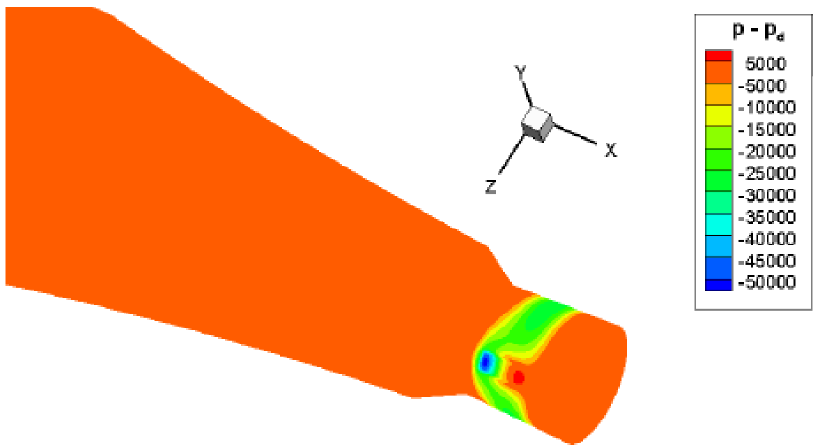


C-D Nozzle

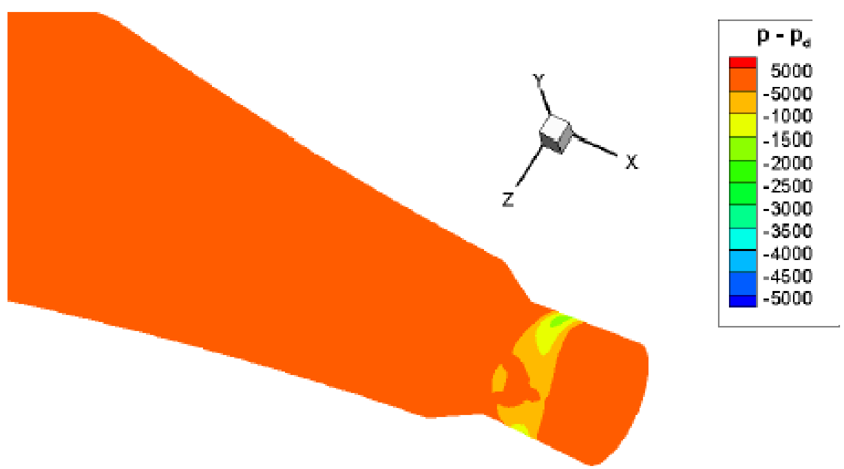


Blowing ports

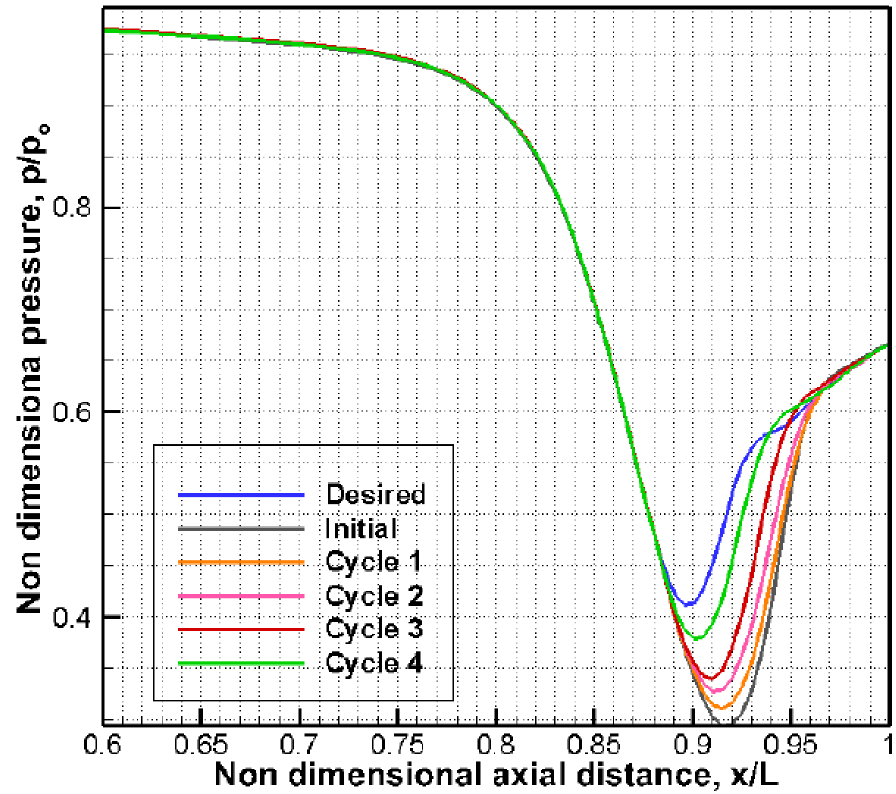
Optimum Blowing Example



Initial pressure difference



After four design cycles



Centerline pressure difference

Comments and Future Plans

Aerospace Engineering

- The noise reductions hold up in forward flight
- Transition to larger scale at PSU
- CFD to examine effects of Reynolds on injectors.
- Consider non-circular nozzles
- Improve correspondence of CFD adjoint work with experimental geometry
- Work with General Electric to examine issues at a 7 x larger scale – there are significant engineering challenges,

Effect of Forward Flight