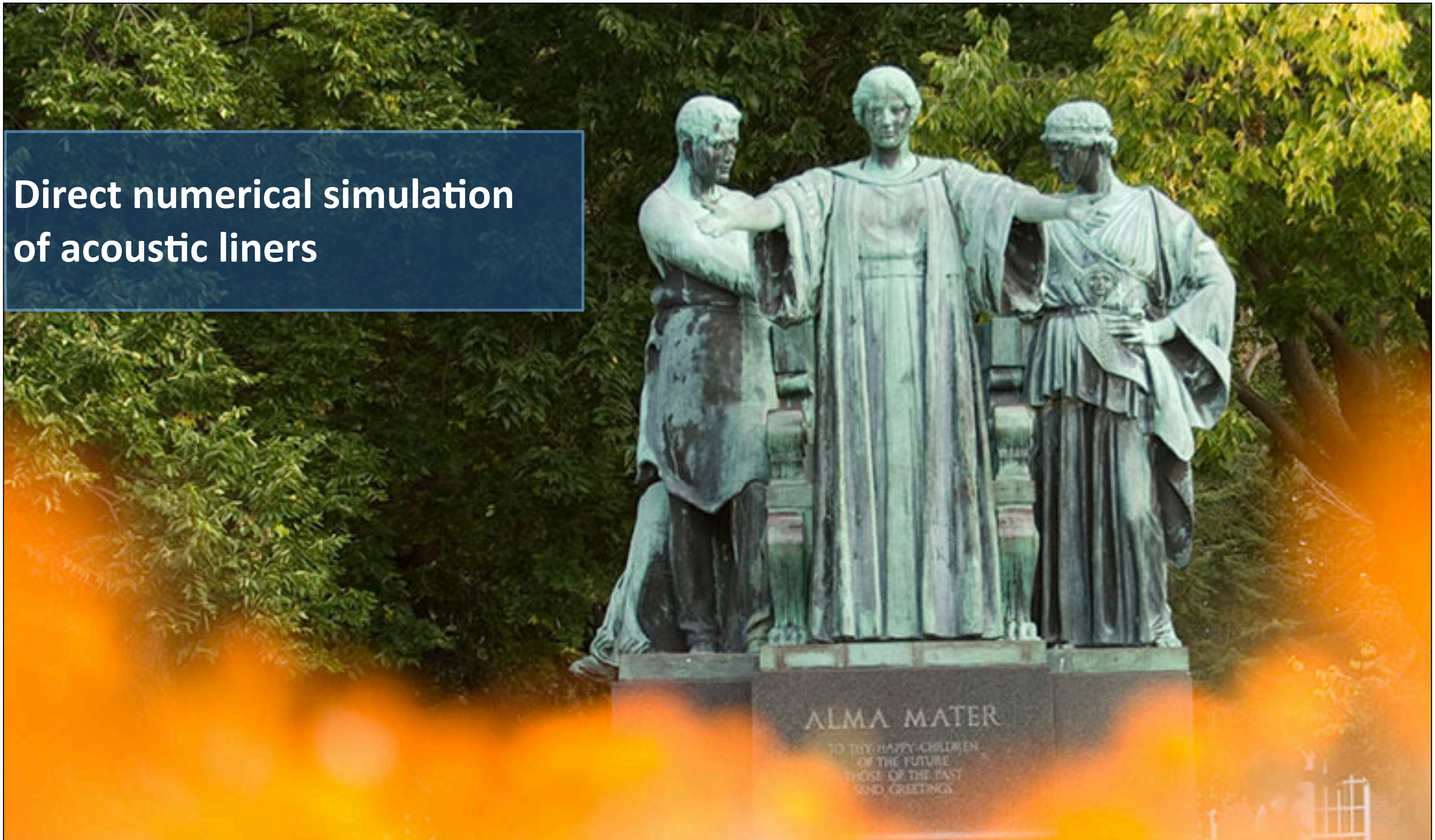
Direct numerical simulation of acoustic liners



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Acknowledgements

- Graduate student Mr. Qi Zhang
- Work supported by
  - NASA Supersonic NRA (Debonis, TM)
  - Aeroacoustic Research Consortium (AARC)
  - National Science Foundation (Computer time)

Traditional Application

- Turbofan bypass ratio increasing to lower U_j^8

engine	manuf.	application	bypass ratio
JT8D-15A	PW	727, 737, DC9	1.04
CF6-50-C2	GE	DC10-10, A300B, 747-200	4.31
CFM56-3C	CFM	737-400, -400, -500	6.00
GE90-B4	GE	777	8.40
Trent 1000, GEnx	RR, GE	787	10–11

- Lower *L/D*, lower Ω, fewer blades ⇒ greater *broadband* component with less "real estate"
- More effective use of space
- Improved eduction methodologies

Potential Application

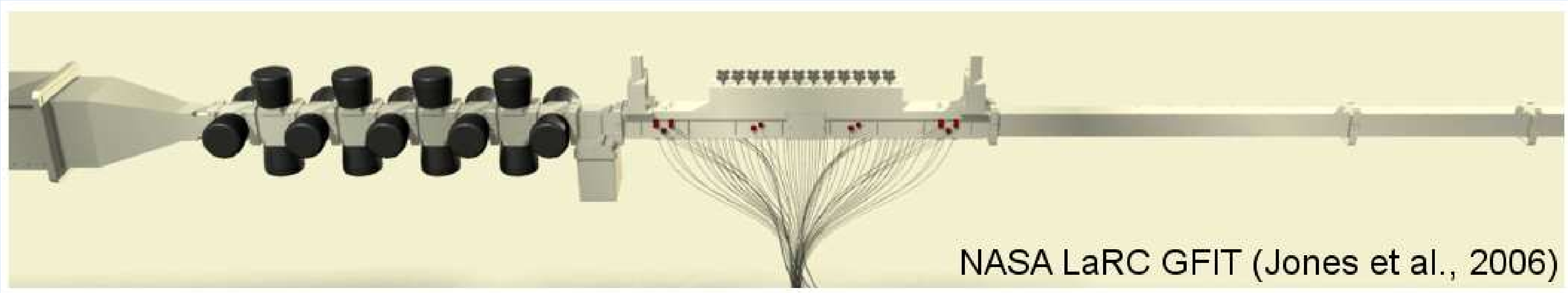
Posey *et al.* (AIAA Paper 2006-2622)

NASA

- Higher grazing flow Mach numbers
- Higher incident acoustic amplitudes

Trends in Liner Eduction

- Increase measurement bandwidth (more mics)
- Increase parameter space (M_∞; BL; curvature)
- Increase flow model complexity
  - convected Helmholtz → linearized Euler
  - 2D → 3D acoustic fields
  - 1D → 2D → 3D mean fields

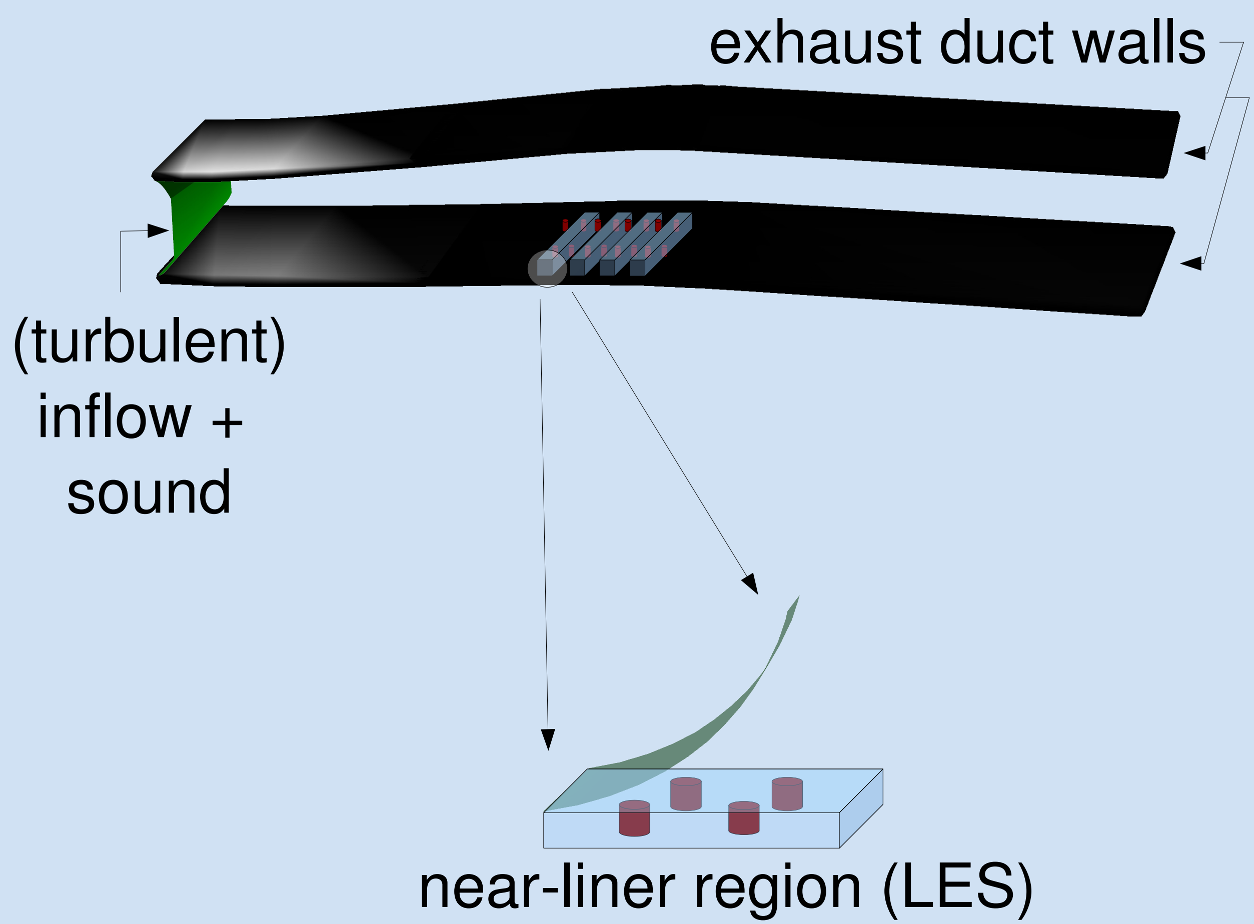


Principle Objective

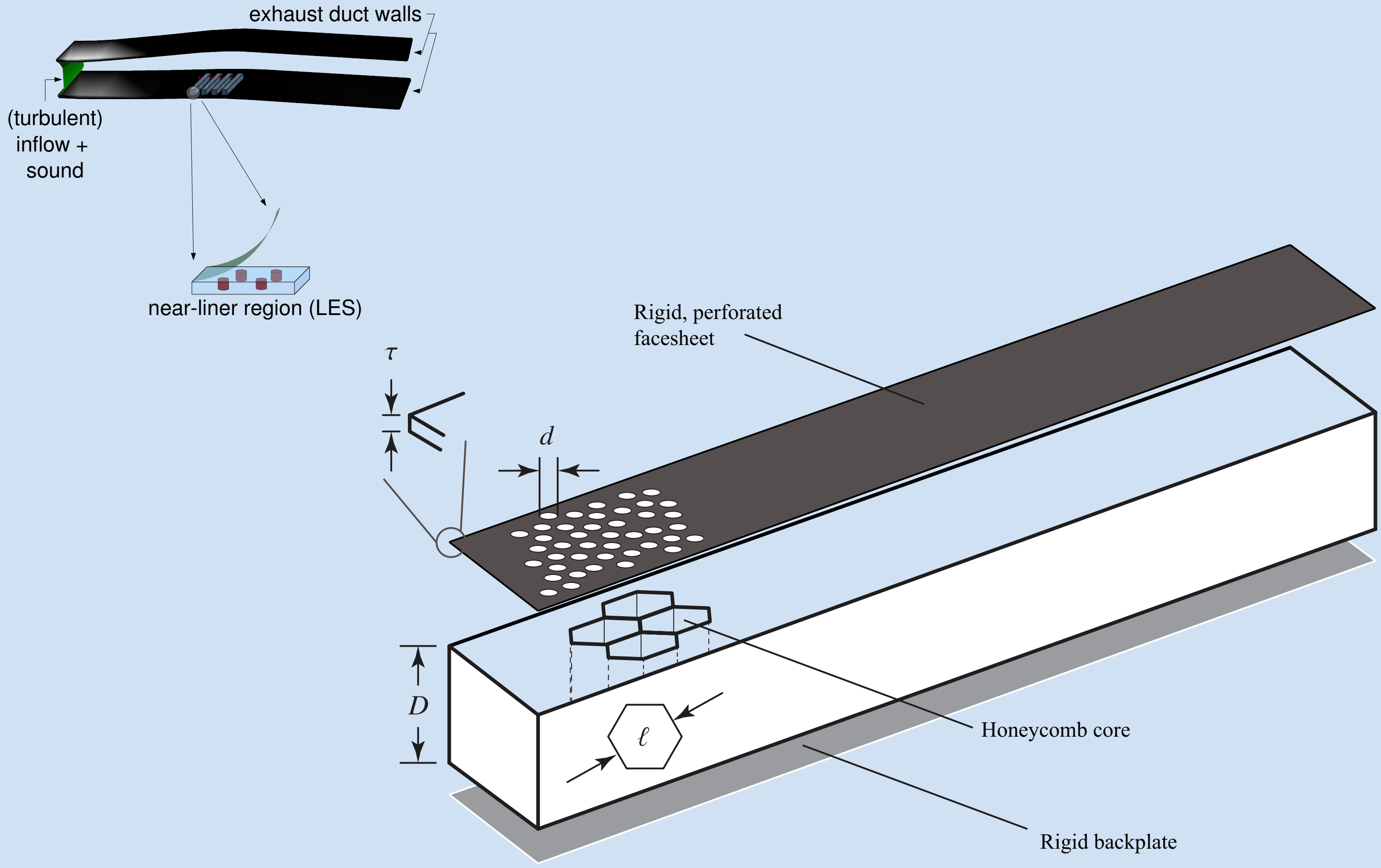
Develop a liner eduction methodology using large-eddy simulation and direct numerical simulation

- Provide a complementary physics-based tool within the current expt.-comput. approach
- Technical goals
  - Study liners in *realistic* environments
  - Provide reliable input to reduced-order models
  - Develop design protocols utilizing LES
    - Can already use LES to control jet noise and airfoil noise

LES/DNS Domain



LES/DNS Domain



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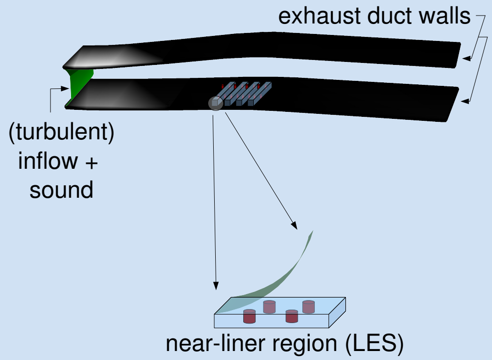
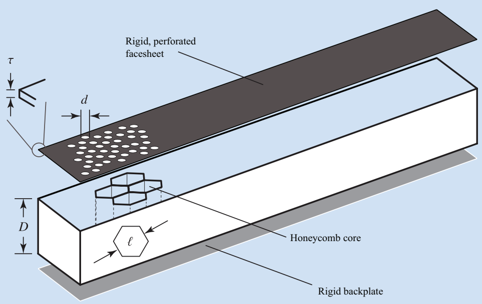
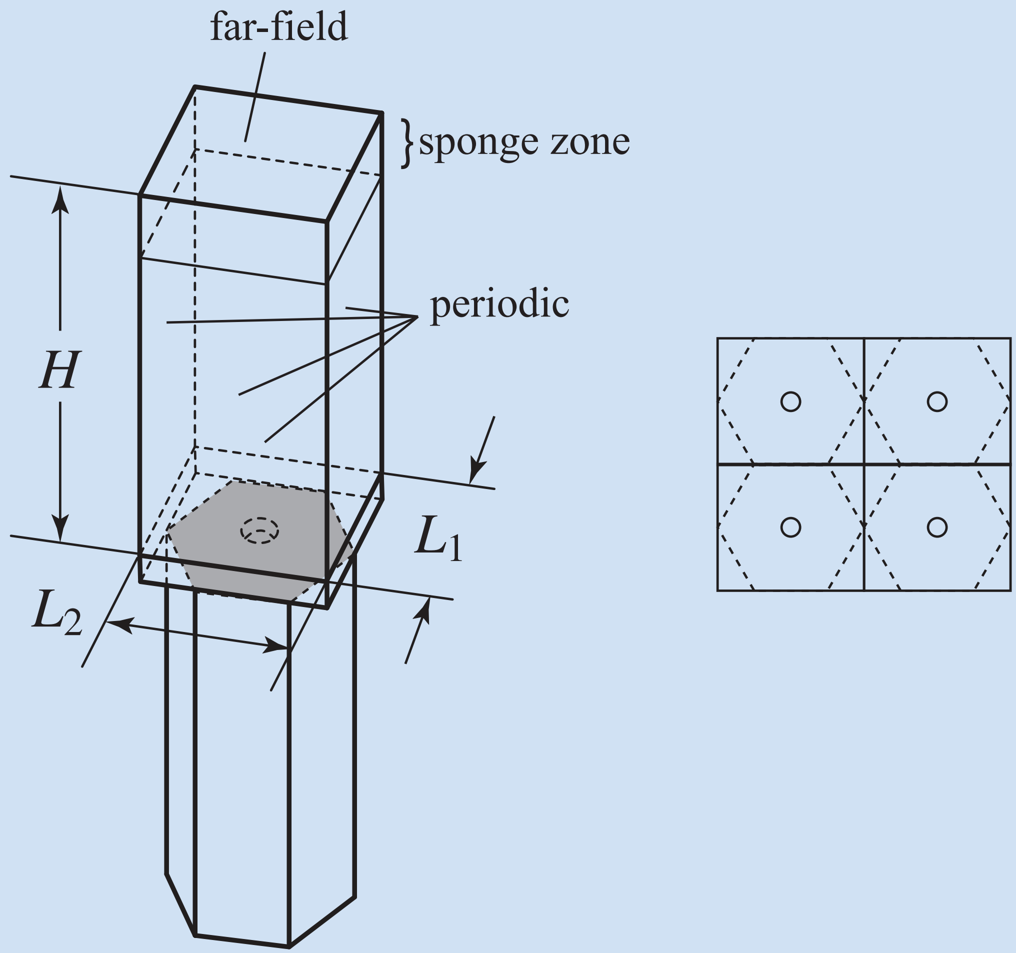
LES/DNS Domain







(a) (b)

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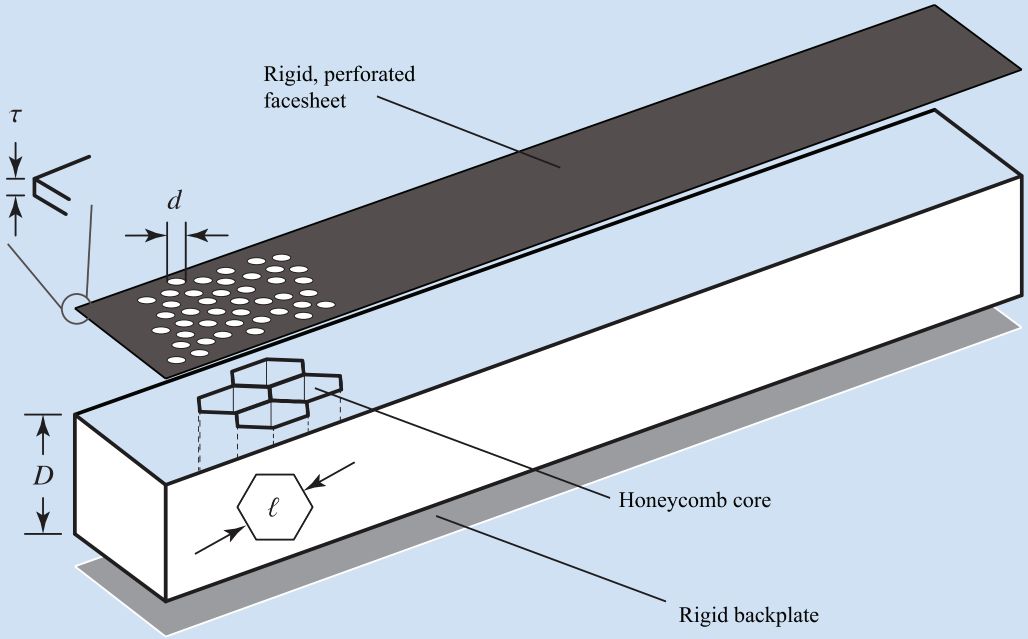
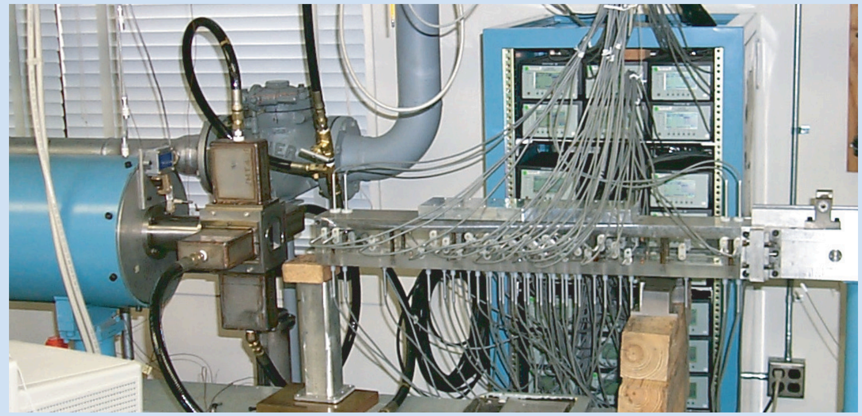
Liner Geometry



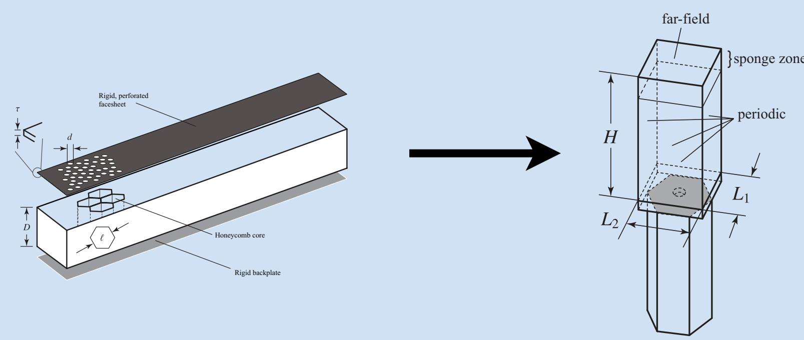
Parameter	Symbol	Dimension (mm)
Orifice diameter	d	0.99
Facesheet thickenss	τ	0.64
Honeycomb 'diameter'	ℓ	5.49
Cell depth	D	38.10

Parameter Space

Freq.	Amplitude (dB) 130	140	150	160
1.5 kHz	×			
2.0 kHz	×			
2.5 kHz	×			
3.0 kHz	×	×	×	×



Experimental data of Jones *et al.*
in NASA LaRC Grazing Incidence Tube
(AIAA Paper 2004-2837)



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Numerical Method

- Solve compressible Navier-Stokes equations

$$\frac{\partial}{\partial t}\left(\frac{\rho}{J}\right) + \frac{\partial}{\partial \xi_j}\left(\rho U_j\right) = 0$$

$$\frac{\partial}{\partial t}\left(\frac{\rho u_i}{J}\right) + \frac{\partial}{\partial \xi_j}\left(\rho u_i U_j + p\hat{\xi}_{j,i} - \tau_{ki}\hat{\xi}_{j,k}\right) = 0$$

$$\frac{\partial}{\partial t}\left(\frac{\rho E}{J}\right) + \frac{\partial}{\partial \xi_j}\left(\left\{\rho E + p\right\} U_j - \hat{\xi}_{j,i}\left\{u_k \tau_{ik} - q_i\right\}\right) = 0$$

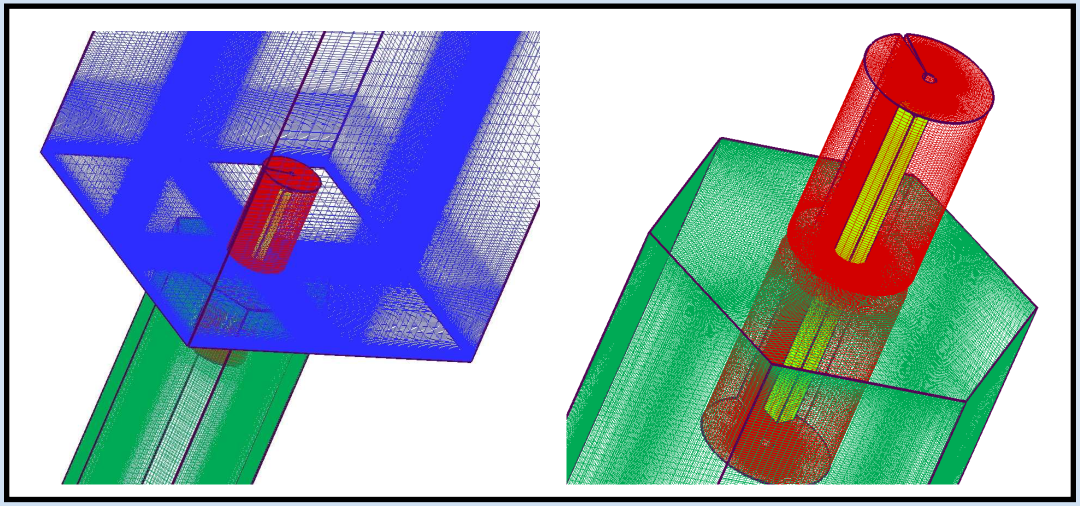
- High-order SBP finite differences

$$\partial_x f \approx P^{-1} Q \boldsymbol{f} \qquad Q + Q^T = \mathrm{diag}(-1, 0, \ldots, 0, 1)^T$$

- SAT-based boundary conditions (Bodony, J. Sci. Comput., 2010) $u_t + a u_x = -\sigma(u(0,t) - f(t))$

Numerical Method

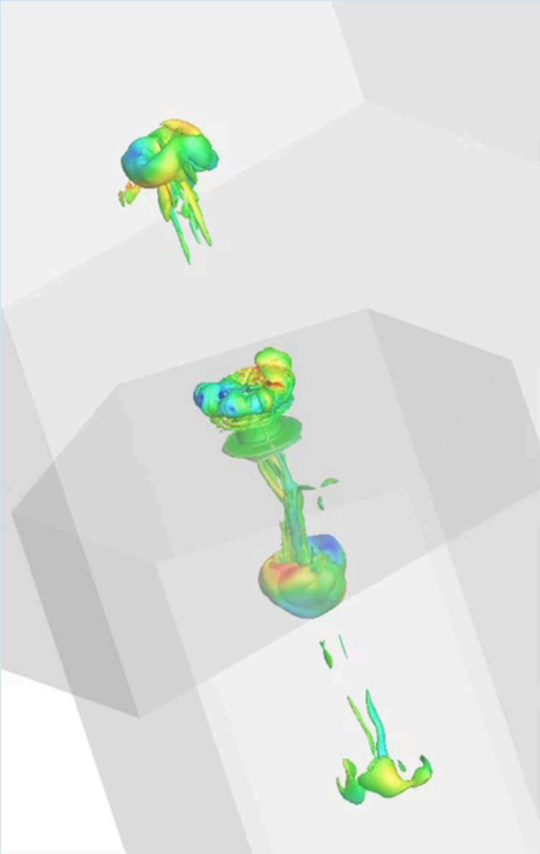
- Multiple, overlapping grids are used



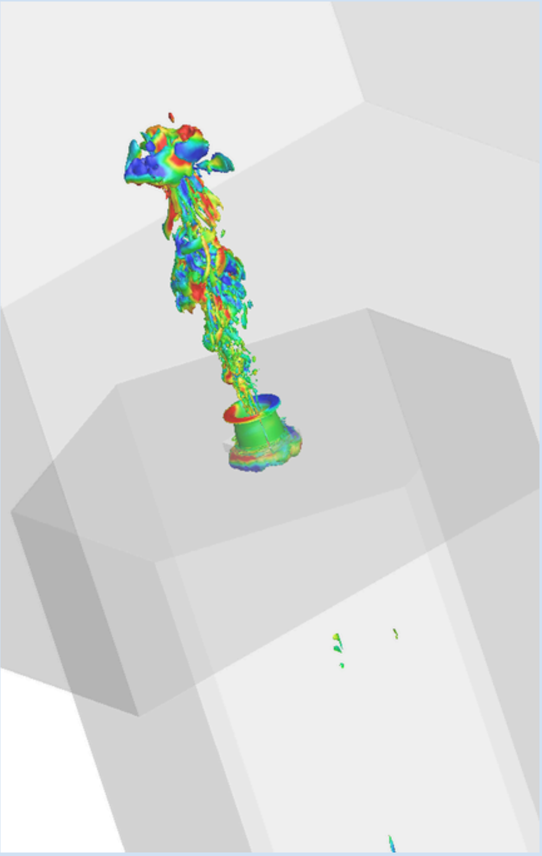
- Sixth-order Lagrange interpolation
- Grid communication determined in pre-processing step

Vorticity

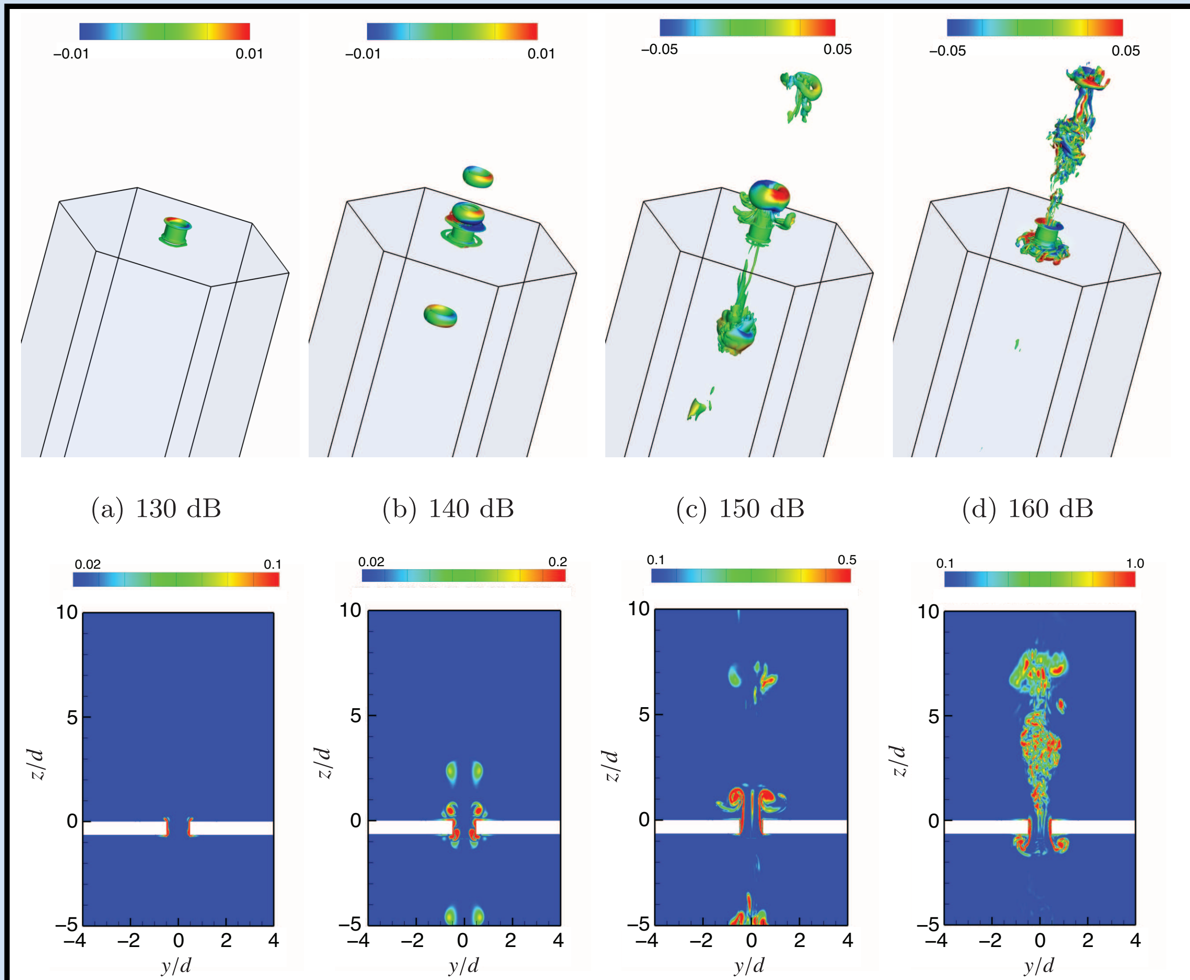
150 dB, 3 kHz



160 dB, 3 kHz



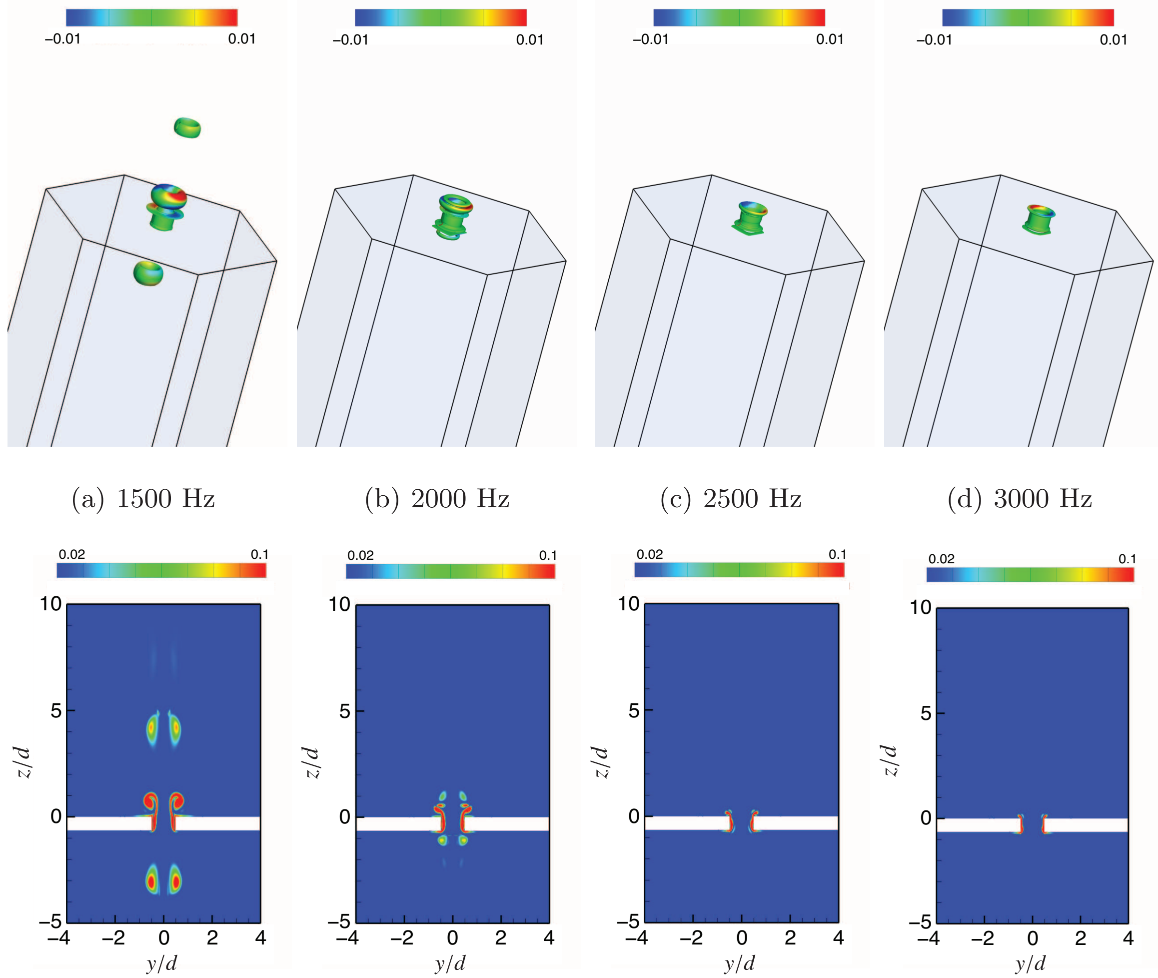
Views at 3 kHz



(a) 130 dB (b) 140 dB (c) 150 dB (d) 160 dB

(e) 130 dB (f) 140 dB (g) 150 dB (h) 160 dB

Views at 130 dB



(a) 1500 Hz (b) 2000 Hz (c) 2500 Hz (d) 3000 Hz

(e) 1500 Hz (f) 2000 Hz (g) 2500 Hz (h) 3000 Hz

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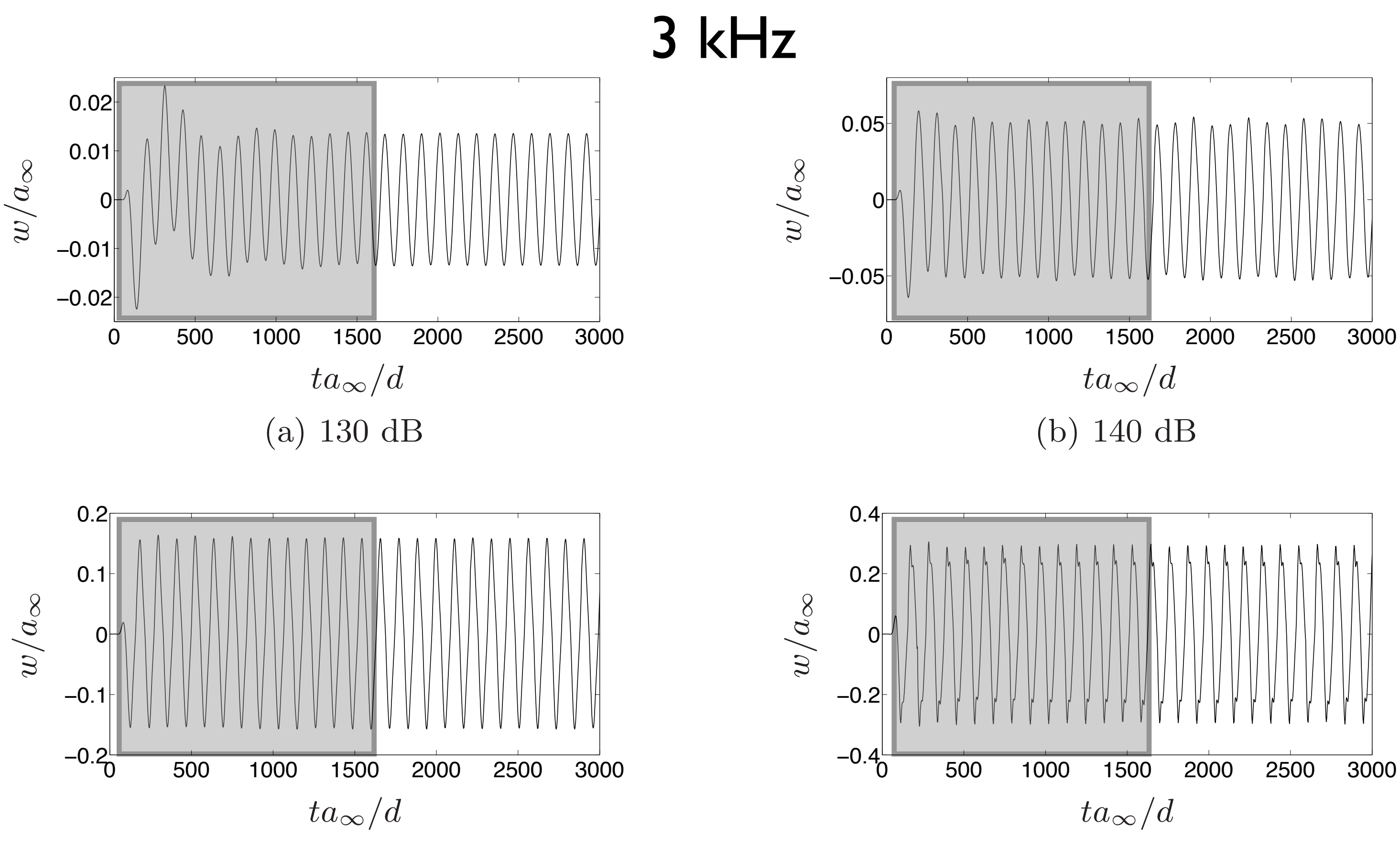
March To Steady State



(a) 130 dB

(b) 140 dB

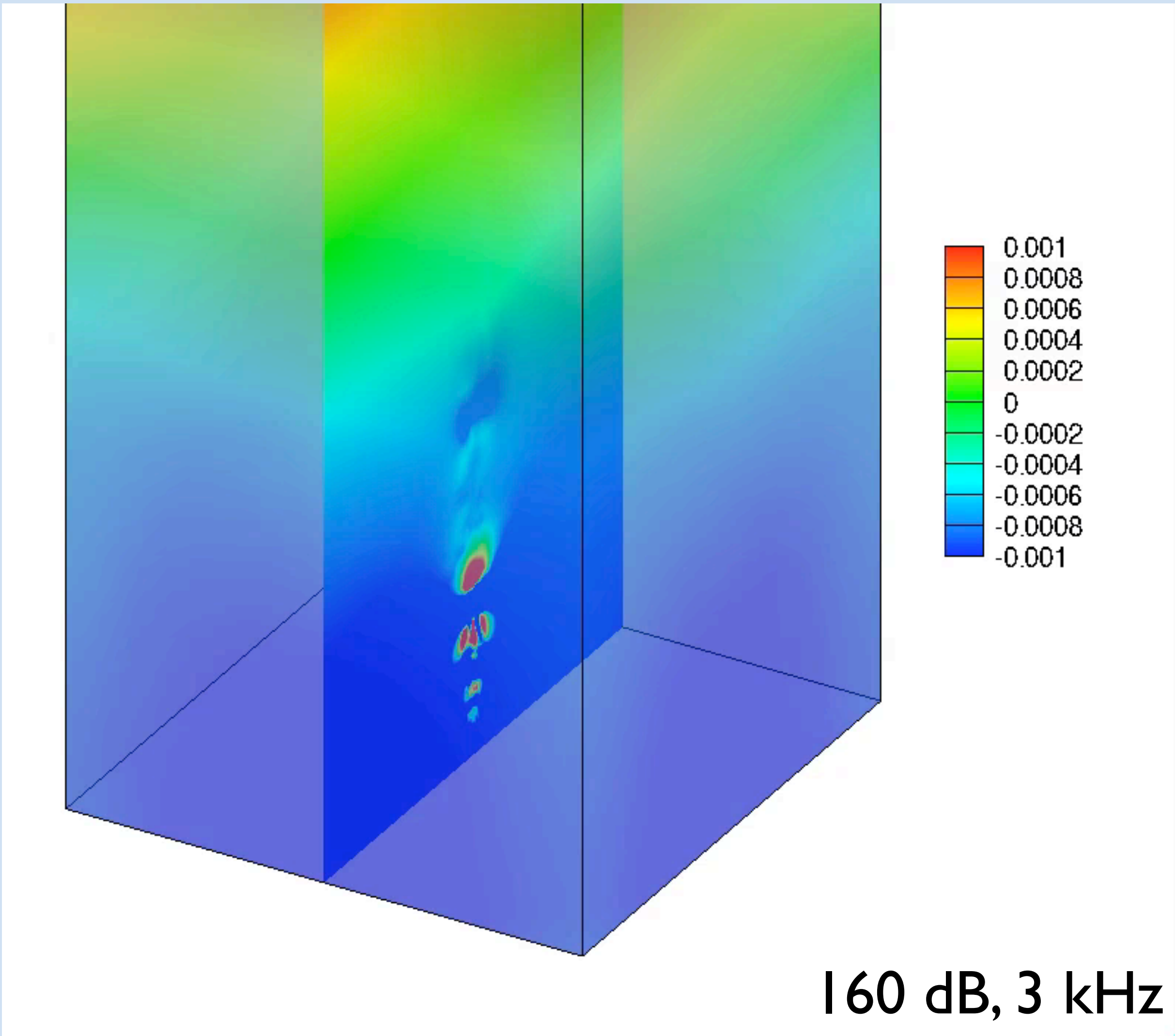
(c) 150 dB

(d) 160 dB

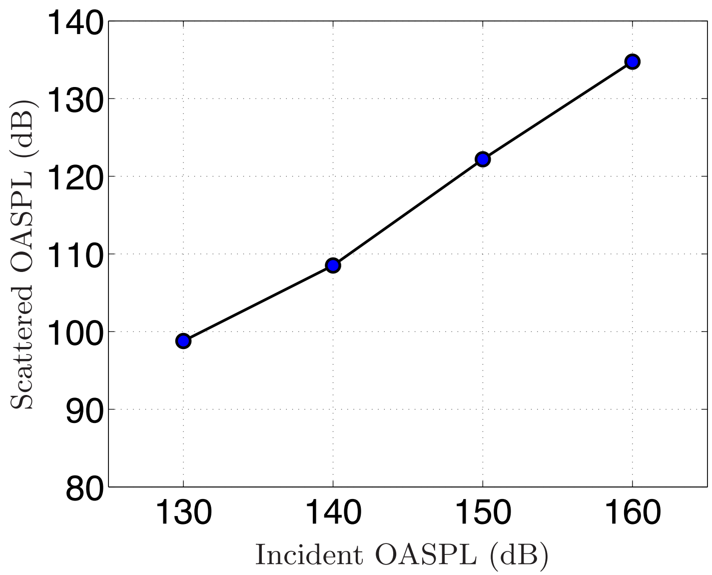
Scattered Pressure Field

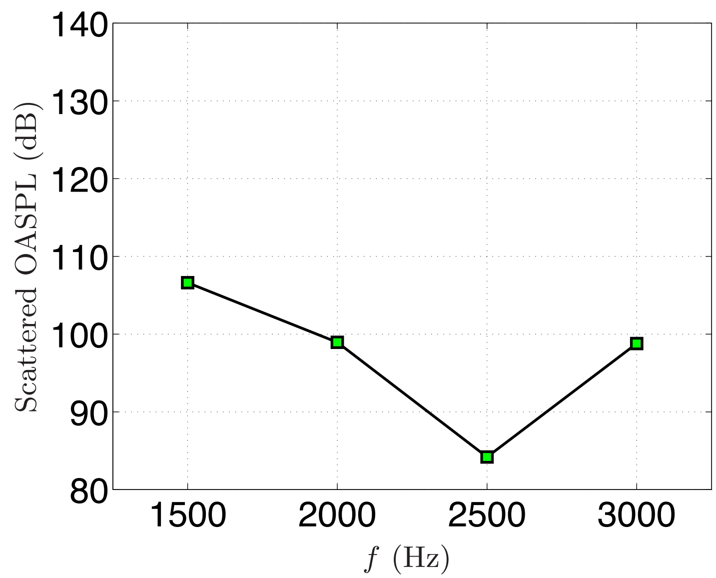
$$p'_s = p' - \underbrace{(p'_i + p'_r)}$$

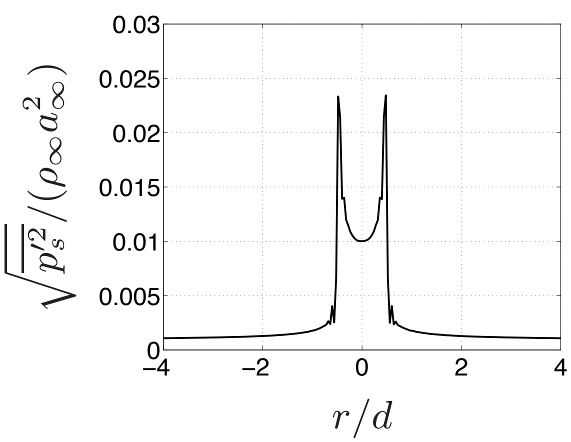
Computed by separate calculation



Self Noise





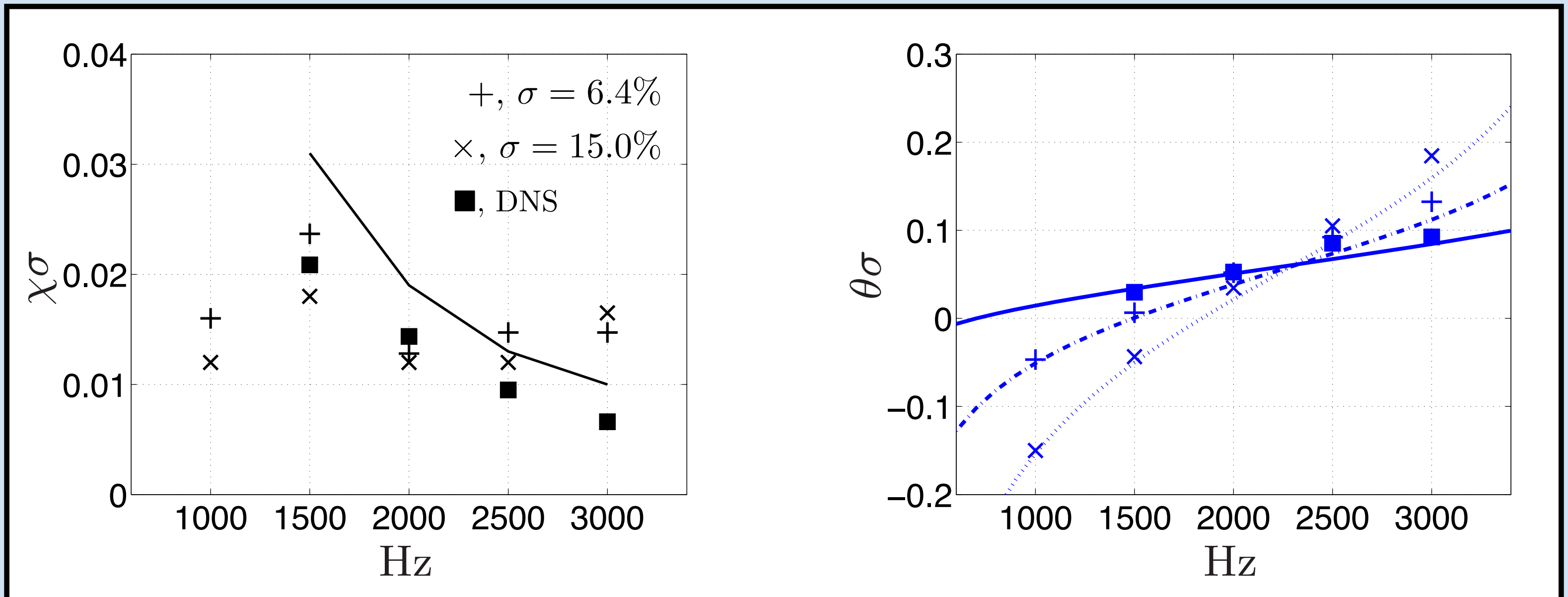


Scattered field:

- self noise < 20 dB
- Mics > 2 *d*

Impedance Prediction

$$\frac{Z}{\rho_\infty a_\infty} = -\mathrm{i}\frac{|\hat{p}_A|}{|\hat{p}_B|}\frac{e^{\mathrm{i}\phi}}{\sin kH}$$



(a) Resistance (b) Reactance

$$\frac{R}{\rho_\infty a_\infty} = \frac{1}{\rho_\infty a_\infty}\left[R_\mu + \frac{1.2}{\overline{C}_D^2}\left(\frac{1-\sigma^2}{\sigma}\right)\frac{\rho_\infty}{2}w_{\mathrm{rms}}\right]$$

(Melling, 1973)

$$\frac{X}{\rho_\infty a_\infty} = -\coth kH + \frac{k(\tau + \epsilon d)}{\sigma} \qquad \epsilon = 0.85(1 - 0.7\sqrt{\sigma})$$

(Motzinger & Kraft, 1995)

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Impedance Prediction

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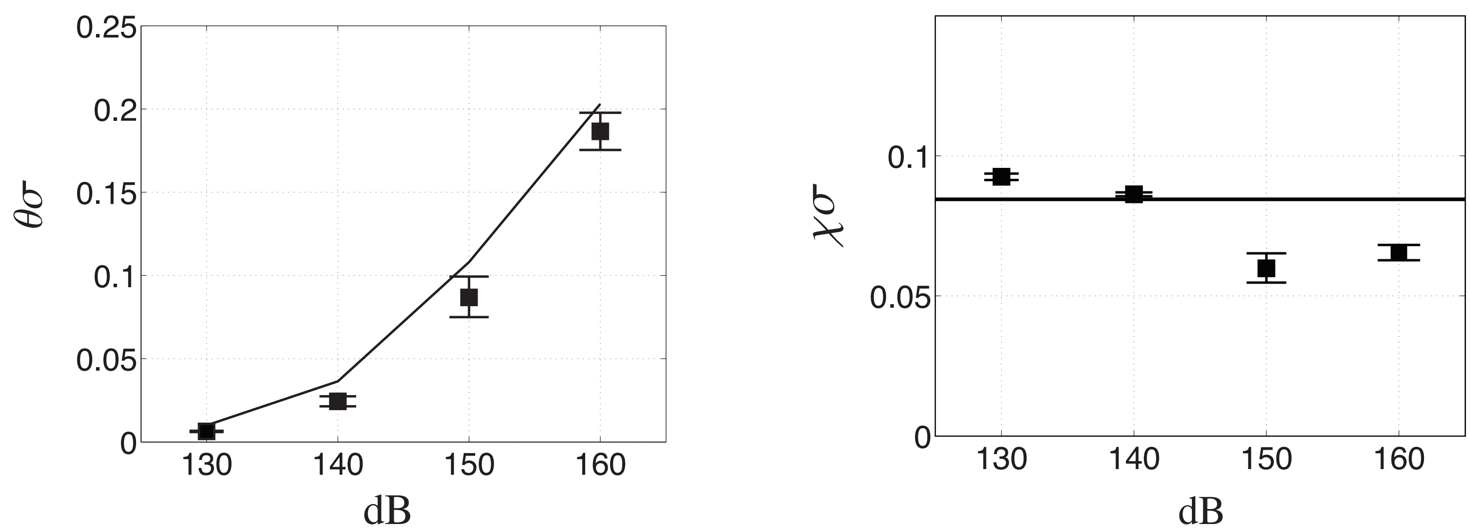

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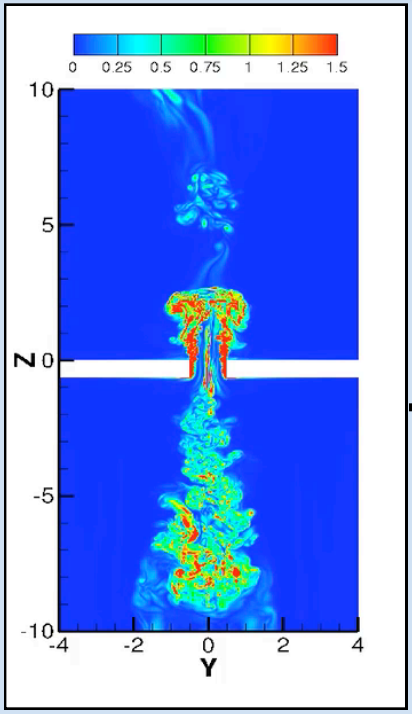
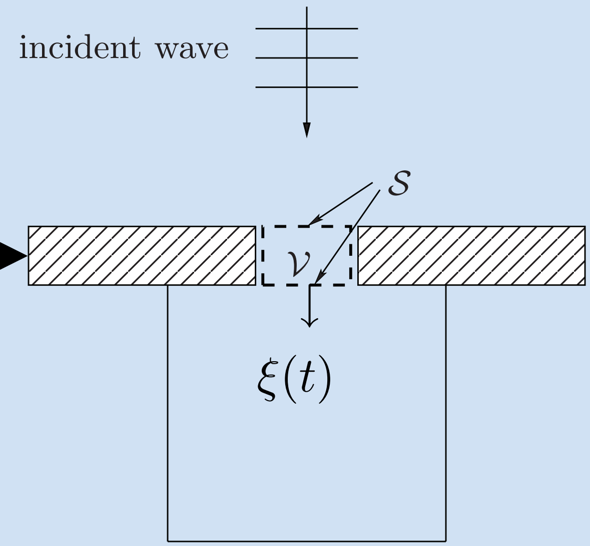
(Motzinger & Kraft, 1995)

Reduced-Order Models

- DNS/LES is great, but, …
  - It's expensive.
  - It focuses on very small domains.
- Probably the best place for DNS/LES is to provide data for improved ROMs
  - Several decades of linear, frequency domain models
    - Sivian, Ingard *et al.*, Rice, Tester *et al.*, …
  - More recent extensions
    - non-linear, single frequency scenario (Cummings & Eversman; Hersh, Walker & Celino; …)
    - time domain impedance (Tam *et al.*)

ROM Objective





$$\frac{\partial}{\partial t}\left(\frac{\rho}{J}\right)+\frac{\partial}{\partial \xi_j}\left(\rho U_j\right)=0$$

$$\frac{\partial}{\partial t}\left(\frac{\rho u_i}{J}\right)+\frac{\partial}{\partial \xi_j}\left(\rho u_i U_j+p\hat{\xi}_{j,i}-\tau_{ki}\hat{\xi}_{j,k}\right)=0$$

$$\frac{\partial}{\partial t}\left(\frac{\rho E}{J}\right)+\frac{\partial}{\partial \xi_j}\left(\{\rho E+p\}U_j-\hat{\xi}_{j,i}\{u_k\tau_{ik}-q_i\}\right)=0$$

$$\rho\tau S\frac{\mathrm{d}^2\xi}{\mathrm{d}t^2}+\rho\frac{1-C_D}{C_D}S\left|\frac{\mathrm{d}\xi}{\mathrm{d}t}\right|\frac{\mathrm{d}\xi}{\mathrm{d}t}+P_cS=P_0Se^{i\omega t}$$

ROM Parameters

$$\rho \tau S \frac{\mathrm{d}^2 \xi}{\mathrm{d}t^2} + \rho \frac{1 - C_D}{C_D} S \left| \frac{\mathrm{d}\xi}{\mathrm{d}t} \right| \frac{\mathrm{d}\xi}{\mathrm{d}t} + P_c S = P_0 S e^{i\omega t}$$

Momentum storage

Momentum flux

Cavity pressure

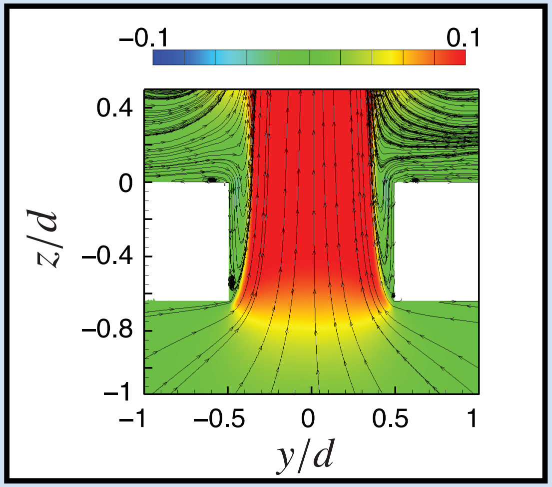
Forcing pressure

ROM Parameters

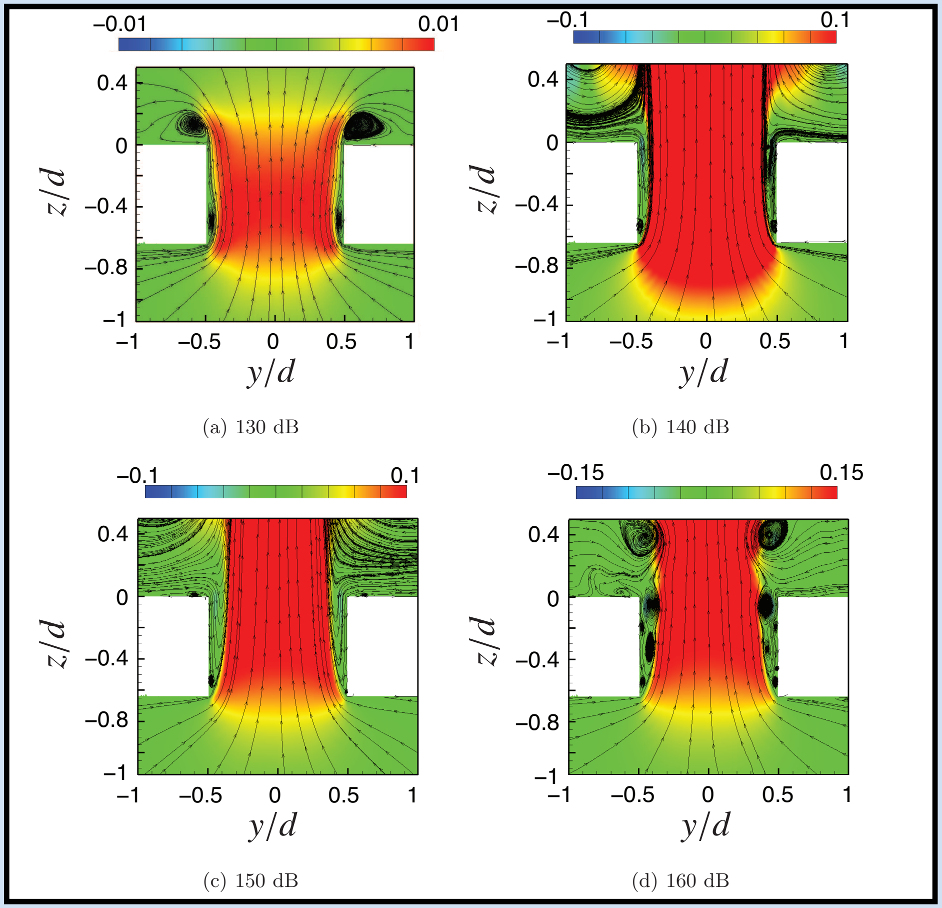
$$\rho\tau S\frac{\mathrm{d}^2\xi}{\mathrm{d}t^2}+\boxed{\rho\frac{1-C_D}{C_D}S\left|\frac{\mathrm{d}\xi}{\mathrm{d}t}\right|\frac{\mathrm{d}\xi}{\mathrm{d}t}}+P_cS=P_0Se^{i\omega t}$$

Momentum storage | Momentum flux | Cavity pressure | Forcing pressure

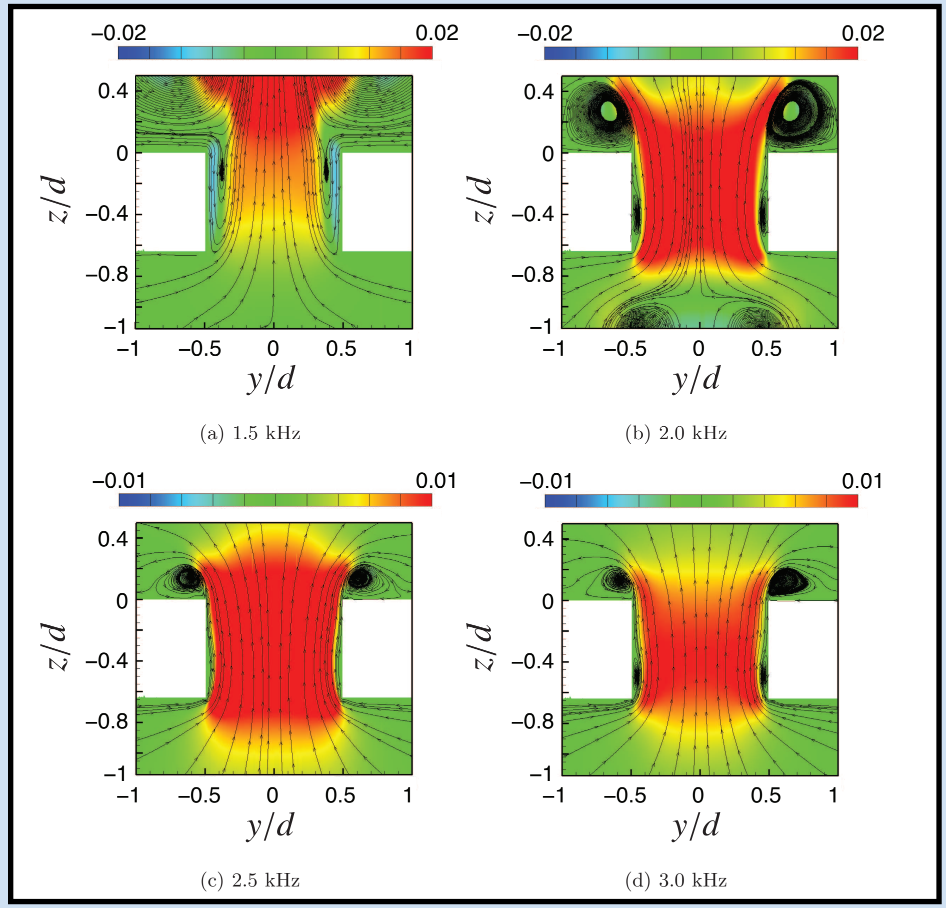
- Discharge coefficient, C_D
  - accounts for flow losses
  - related to boundary layer thickness
  - difficult to model



Phase-Averaged Near-Orifice Flow



3 kHz



130 dB

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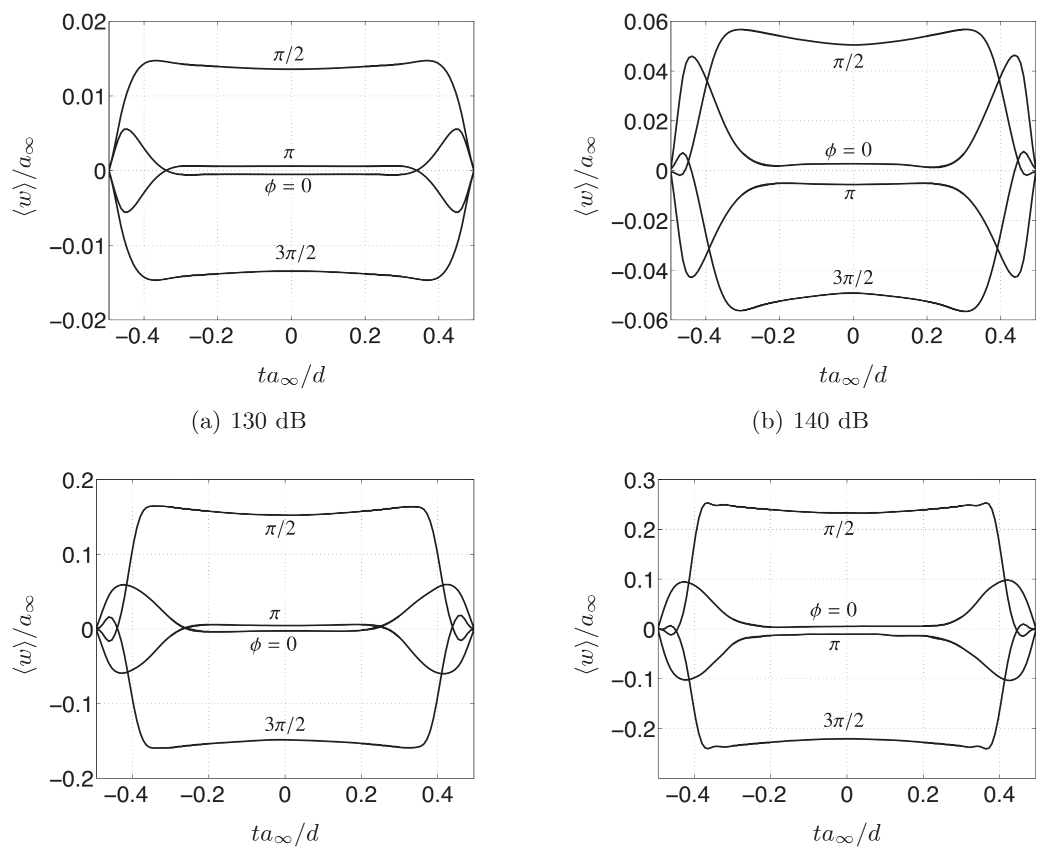
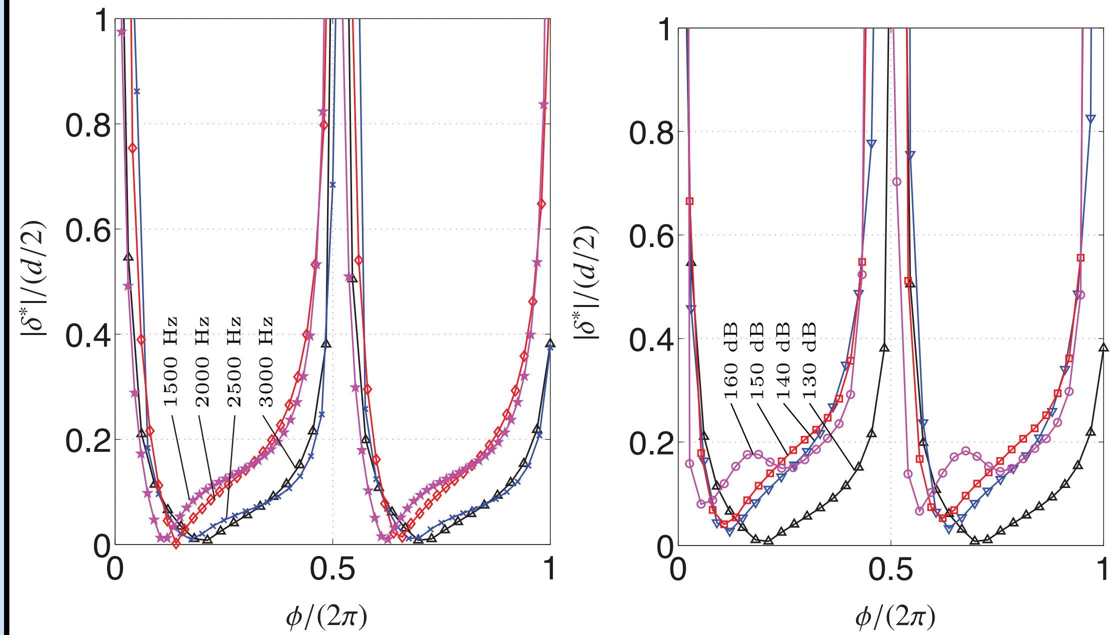
Phase-Averaged Profiles



(a) 130 dB
(b) 140 dB
(c) 150 dB
(d) 160 dB

3 kHz

Phase-Averaged BL Profiles



(a) 130 dB (b) 3 kHz

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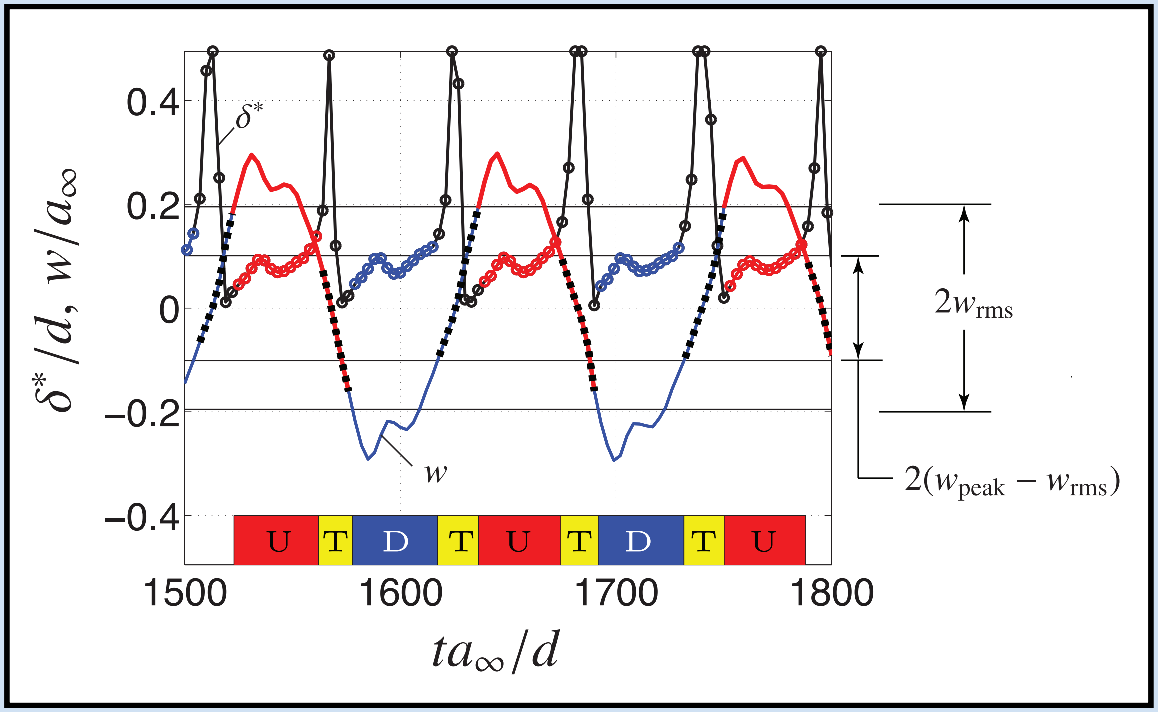
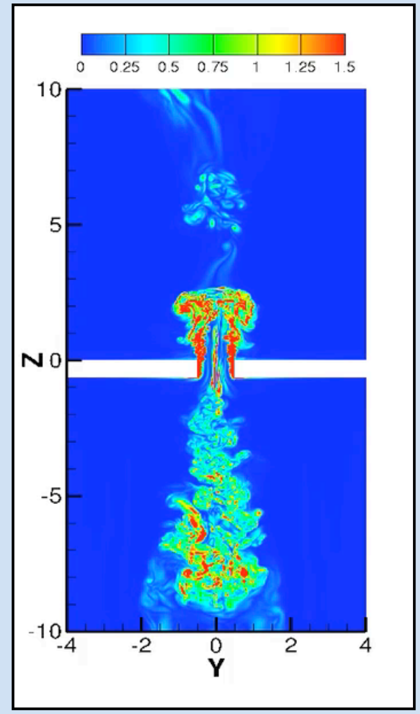
Discharge Coefficient

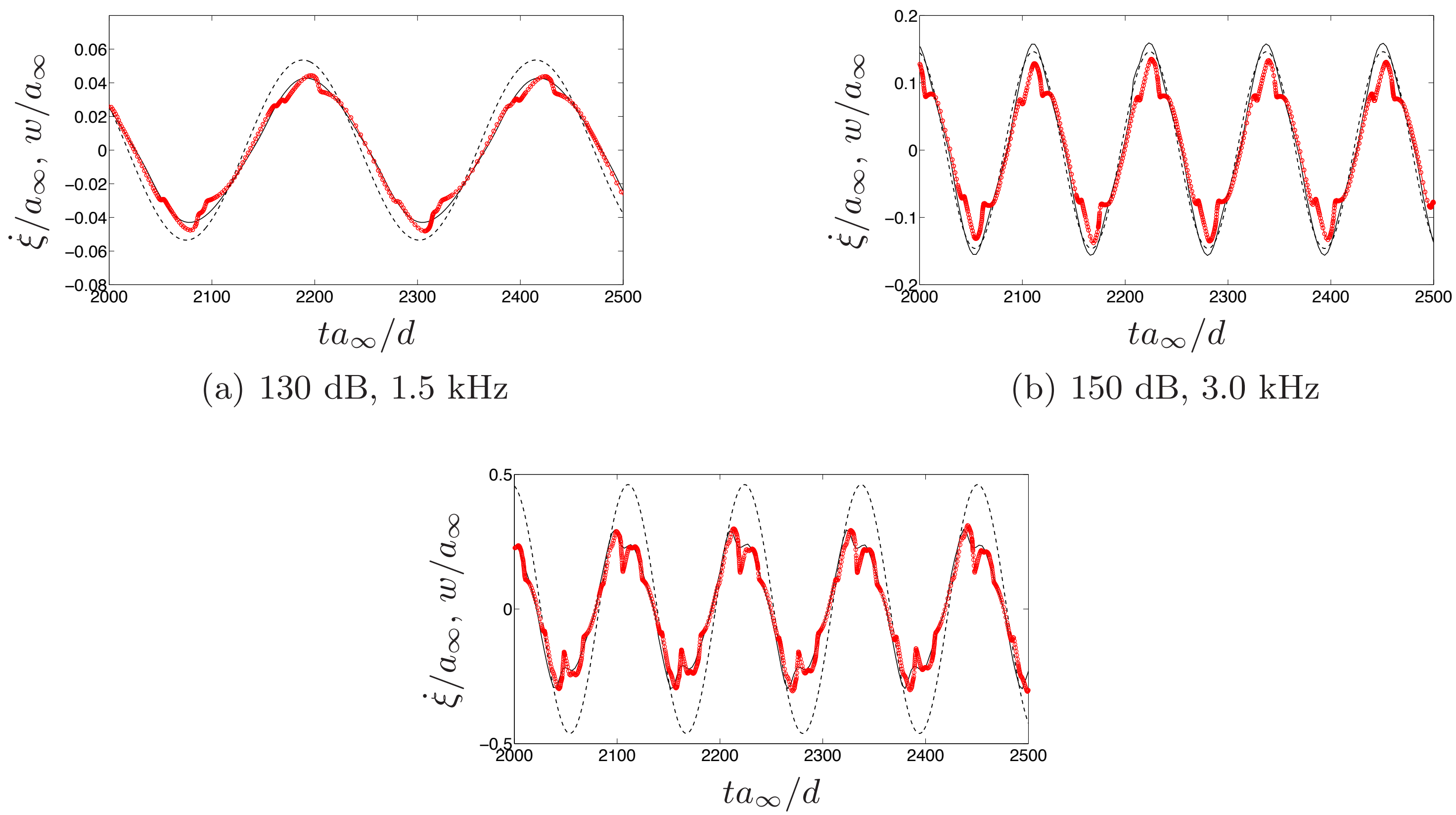




$$C_D \approx \frac{\pi(d/2-\delta^*)}{\pi d^2/4} = \left(1 - \frac{\delta^*}{d/2}\right)^2$$

Case	δ^*_u/d	δ^*_d/d	$\overline{\delta^*}/d$	$\overline{C}_D$
130 dB, 1.5 kHz	0.076	0.075	0.0755	0.72
130 dB, 2.0 kHz	0.073	0.073	0.0730	0.73
130 dB, 2.5 kHz	0.038	0.038	0.0380	0.85
130 dB, 3.0 kHz	0.037	0.036	0.0365	0.86
140 dB, 3.0 kHz	0.078	0.081	0.0795	0.71
150 dB, 3.0 kHz	0.082	0.079	0.0805	0.70
160 dB, 3.0 kHz	0.084	0.082	0.0830	0.69

Prediction with $C_D(t)$



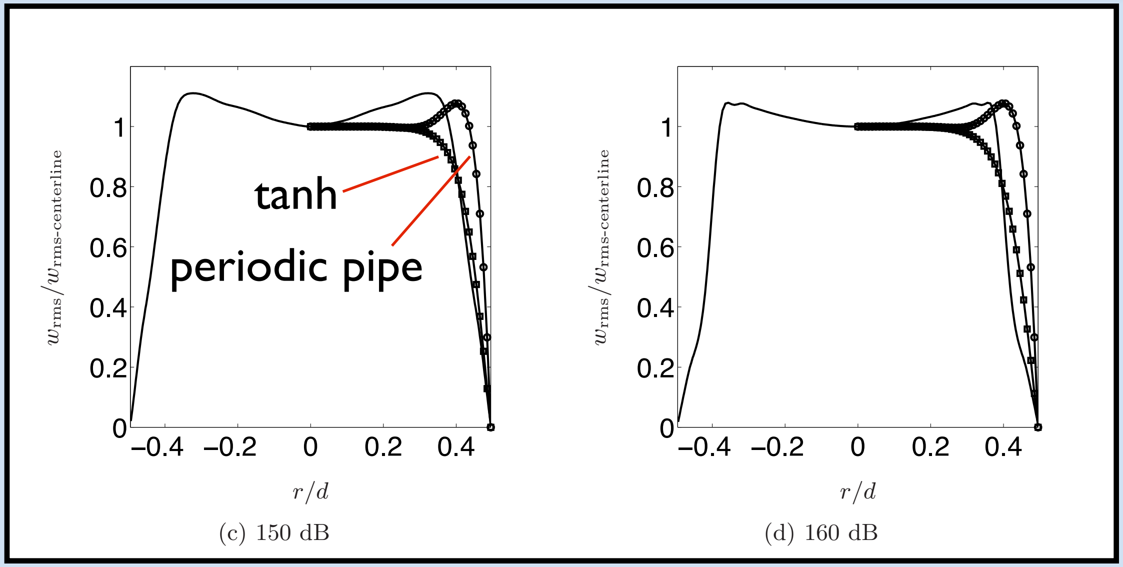
(a) 130 dB, 1.5 kHz

(b) 150 dB, 3.0 kHz

(c) 160 dB, 3.0 kHz

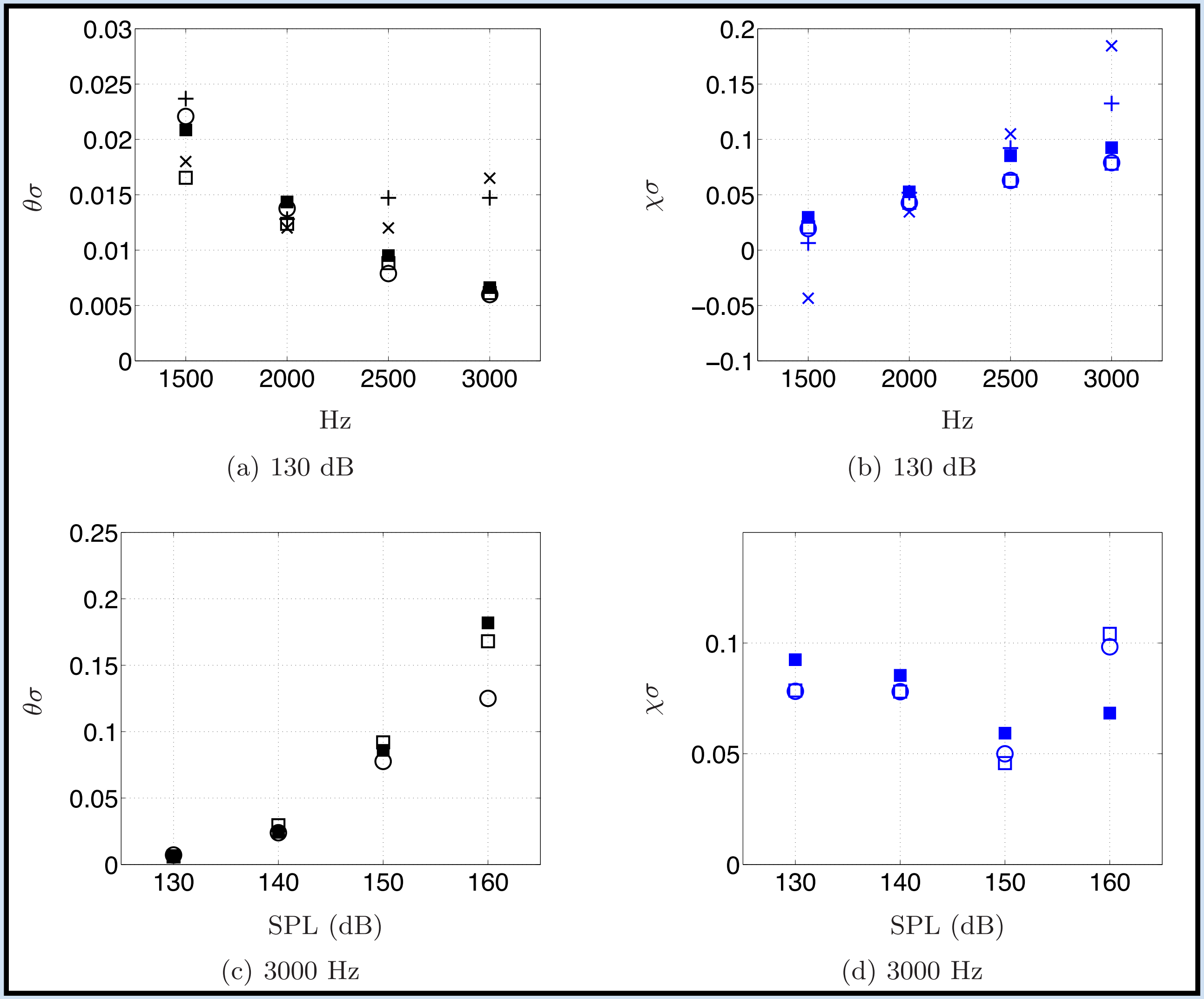
$$\rho \tau S \frac{\mathrm{d}^2 \xi}{\mathrm{d}t^2} + \rho \frac{1 - C_D}{C_D} S \left| \frac{\mathrm{d}\xi}{\mathrm{d}t} \right| \frac{\mathrm{d}\xi}{\mathrm{d}t} + P_c S = P_0 S e^{i\omega t}$$

Modeling the BL



- DNS ⇒ modeling **the boundary layer** is a "good thing"
- Attempt two naive strategies
  - Analytical profile from periodic pipe flow
  - Tanh profile with DNS provided $\delta^*(\phi)$

ROM Predictions of Z



+	15%, LaRC
×	6.4%, LaRC
■	DNS
□	pipe $V(r)$
○	tanh $V(r)$

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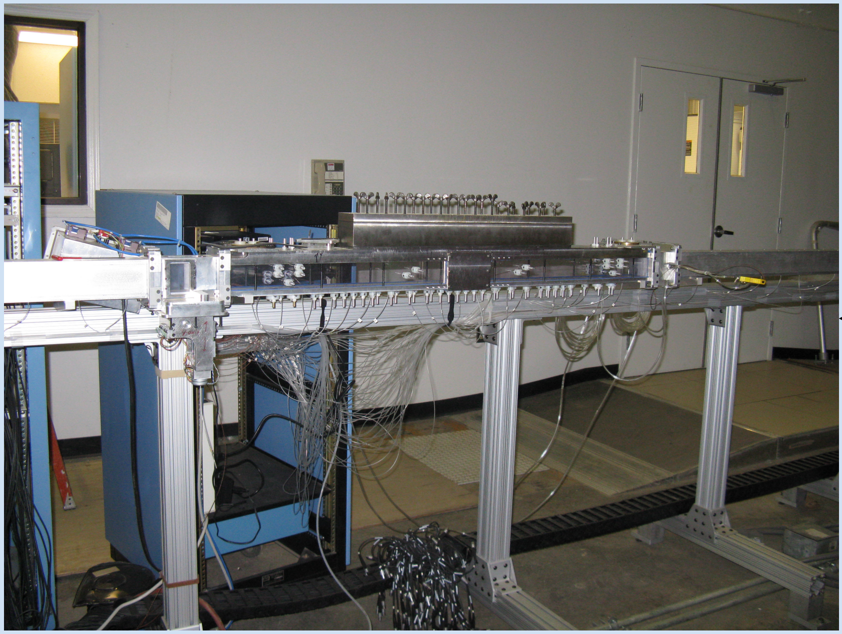
Summary

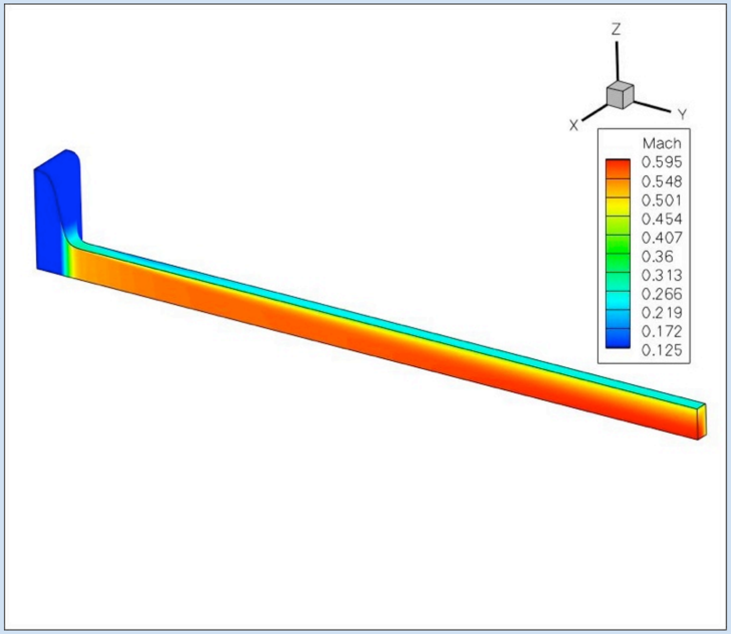
- DNS of compressible flow through single aperture reasonably agrees with NASA impedance data
- Examining DNS data gives clues to what is more important (C_D) and how to model it (δ)
  - Two simple models give some evidence of this
  - Existing BL models likely useful
- Where do we go from here?

Turbulent Grazing Flow

NASA LaRC GFIT (courtesy M. Jones)

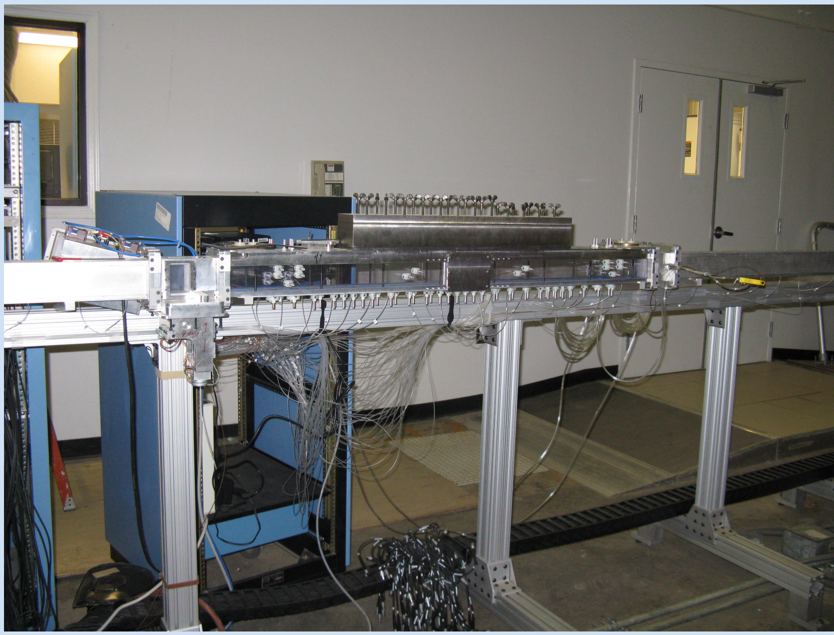


GFIT Mean Flow

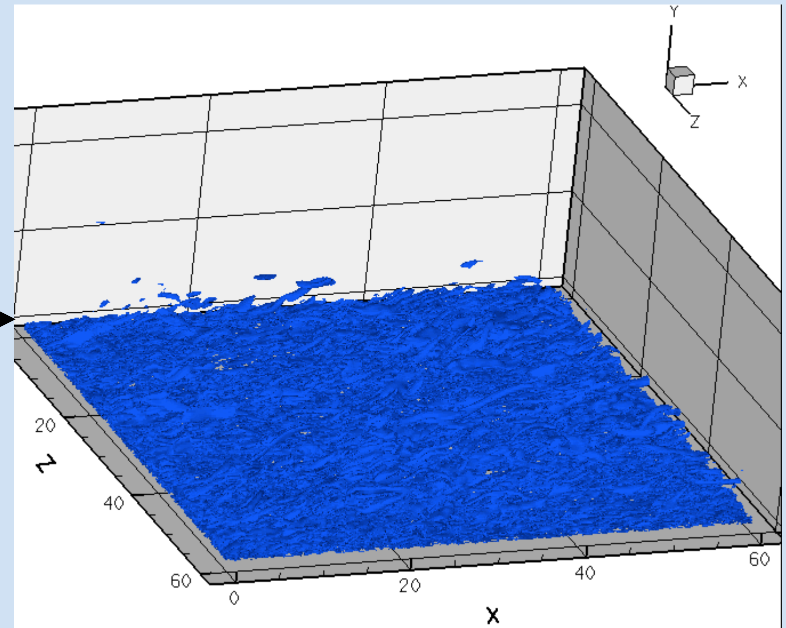


Turbulent Grazing Flow

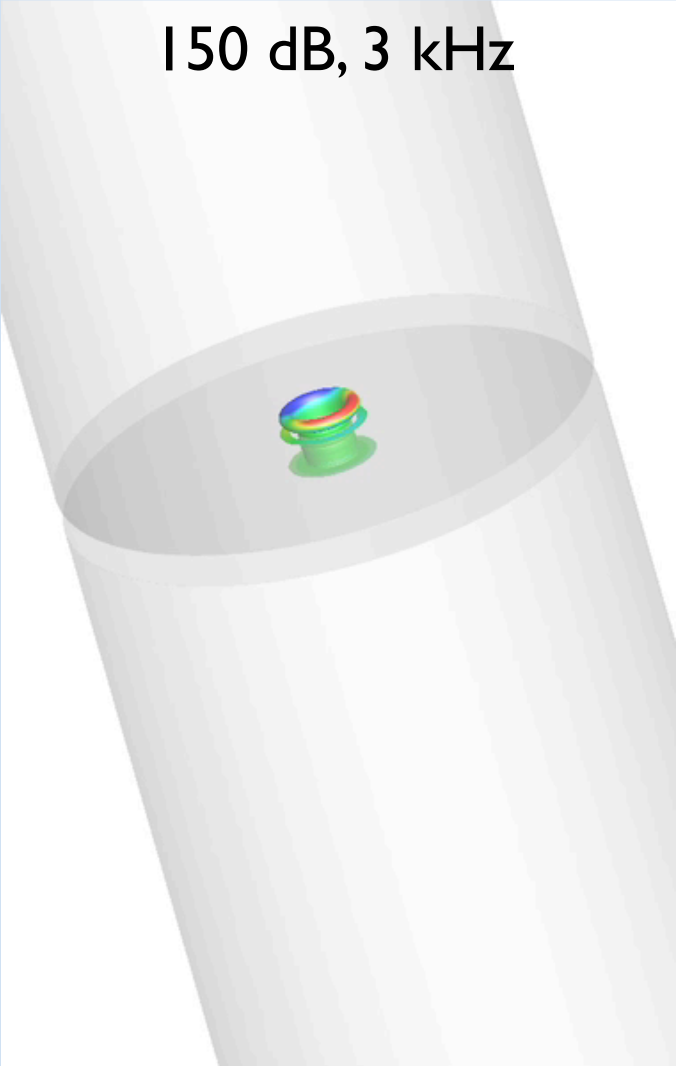
NASA LaRC GFIT (courtesy M. Jones)

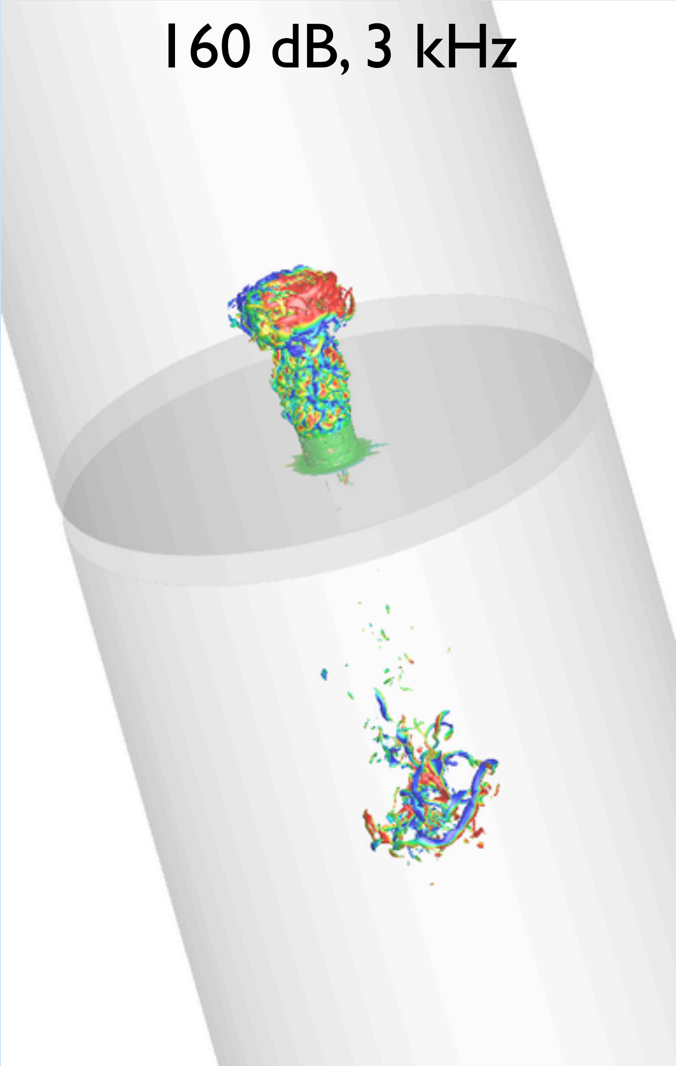


Compressible Turbulent BL



Circular Cavity Simulations





- Thank you for your attention!

- More information available at
  - Zhang & Bodony, AIAA Papers 2011-0843, -2727.
  - Zhang & Bodony, *AIAA J.*, 49(2), 2011.
  - Zhang & Bodony, submitted *JFM*.

Liner Design & Analysis

- Liner design based on joint experiment and computation
  - *indirect*: measure complex-valued pressure field over liner and infer liner boundary condition (Langley, GE, Goodrich, Spirit)
  - *in situ*: measure pressure on surface and in cavity and model cavity (UTRC)
- Successful, but with some unknowns
  - fluid model (indirect)
  - average over liner (*in situ*)
  - translate to realistic environment (both)
    - Grazing M_∞; *BL/d* ratio; curvature; grazing vs. normal incidence, broadband, non-linearity, ...