# Current and Planned Updates to Liner Technology Facility Rigs and Data Analysis Techniques

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# Liner Physics Team

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Scott Haigler

LINER TECHNOLOGY FACILITY

# Overview

**Facility and Data Analysis Upgrades to Support New Testing Capability**

- Review of Pridmore-Brown modal analysis in Curved Duct Test Rig (CDTR)
- Preview of upcoming High Intensity Modal Impedance Tube (HIMIT) testing

**Updates from Liner Physics Team**

- Experiment
- Modeling
- Analysis

# Pridmore-Brown Modal Analysis

**Objectives**

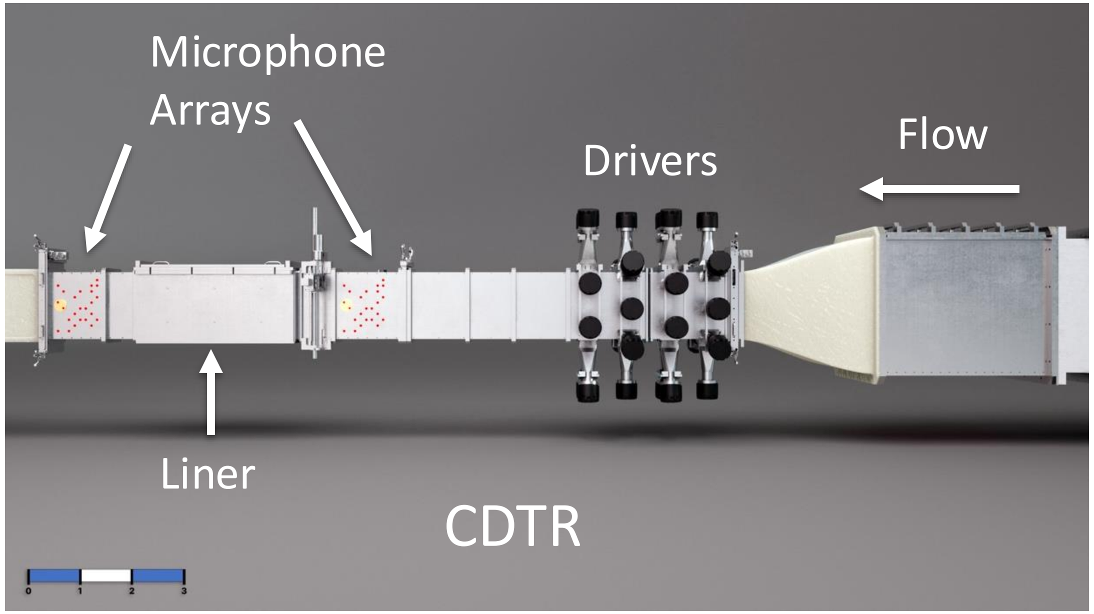
- Understand effect of shear flow on acoustic modes
- Improve accuracy of analysis at higher frequencies

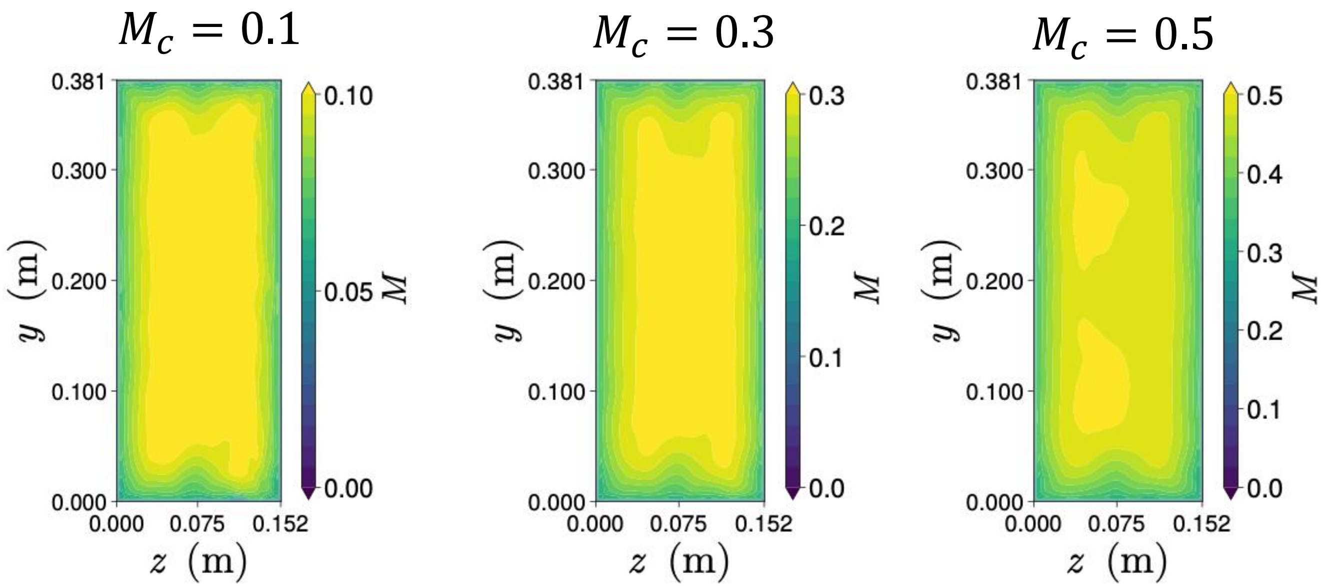
**Process**

- Test in Curved Duct Test Rig (CDTR)
- $400 \leq f \leq 3000$ Hz
- Centerline Mach numbers: 0.1, 0.3, and 0.5
- Convective Helmholtz Eqn. (CHE) modal analysis
- Pridmore-Brown Eqn. [ref. 1] (PBE) modal analysis

**Results Presented in Following Slides**

- Assessment of accuracy – comparison between CHE and PBE
- Examination of wavenumbers and mode structure



# Pridmore-Brown Modal Analysis

**PBE Analysis**

- Differs from CHE mode decomposition in several ways [refs. 2,3]
  - Perform Galerkin projection with Chebyshev basis
  - Solve nonlinear eigenvalue problem for wavenumbers, $\kappa$
  - Becomes computationally expensive as # of basis functions ($\widetilde{M} \times \widetilde{N}$) is increased
- $\widetilde{M} = 14$ and $\widetilde{N} = 10$ found to be sufficient

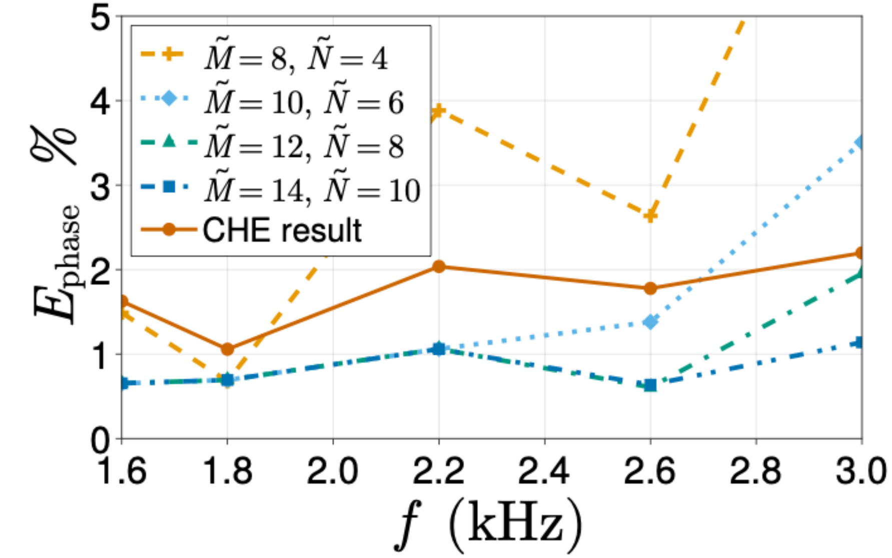
**Microphone Reconstruction Error**

- Quantifies ability of computed modes to reconstruct measurements made at microphones
- Phase (and SPL) at mics show slightly improved agreement

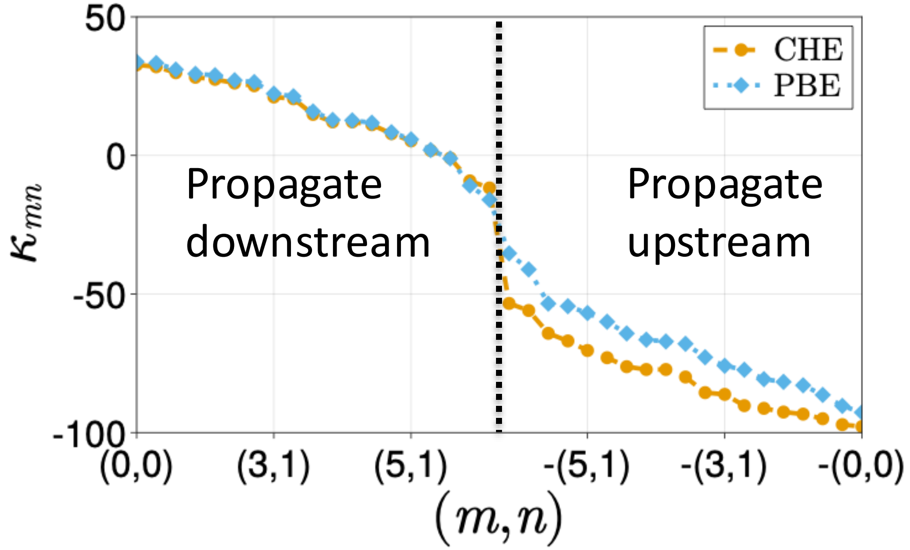
**Wavenumbers**

- CHE and PBE wavenumbers similar for modes propagating in same direction as flow
- Noticeable difference between CHE and PBE for negative modes
- As $M_c$ and $f$ increase, so does deviation between CHE and PBE

Phase Reconstruction Error, $M_c = 0.5$ and (0,1) mode




CHE and PBE wavenumbers, $M_c = 0.5$ and $f = 2600$ Hz



# Pridmore-Brown Modal Analysis

**Mode Structure**

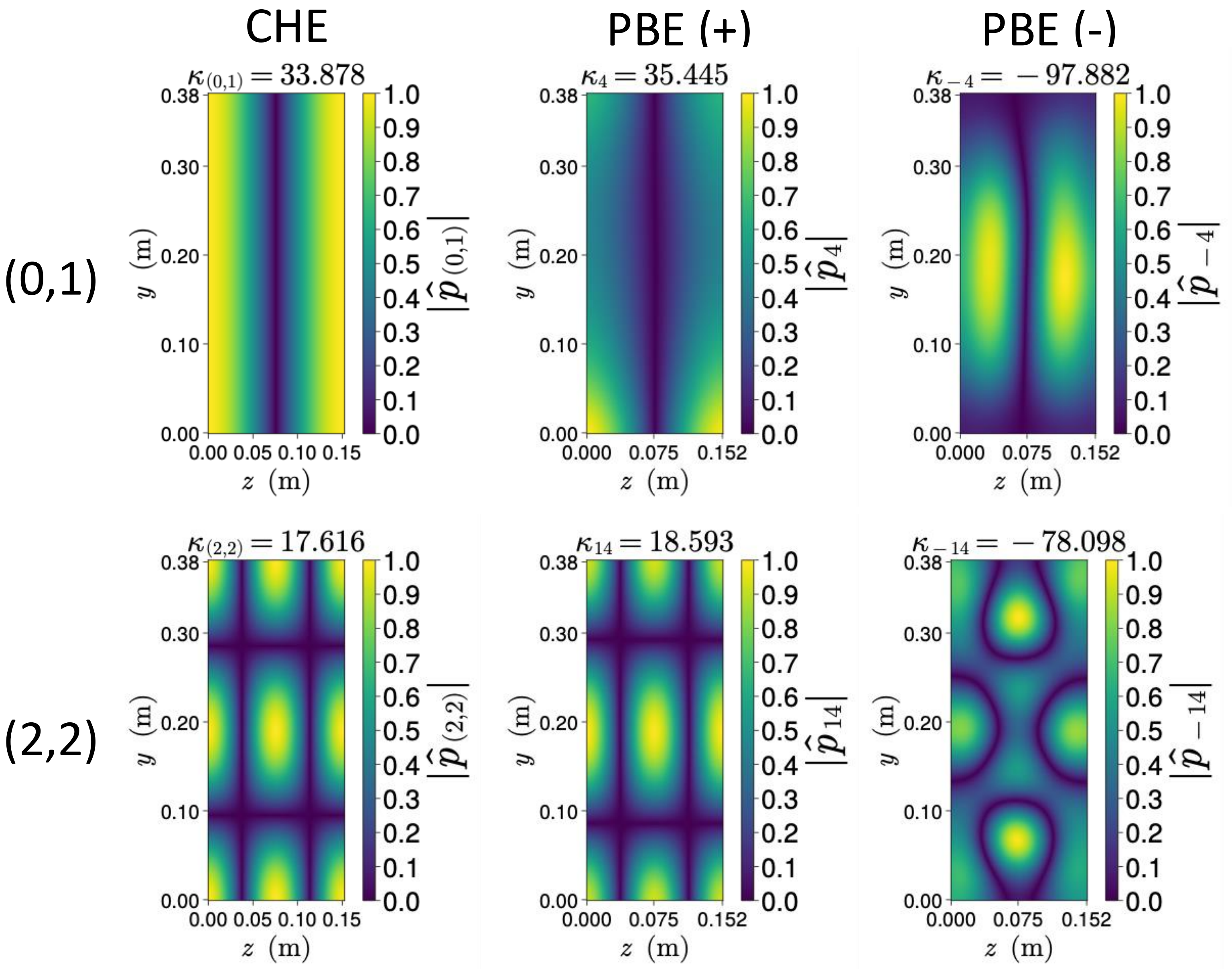
- Mode structure, $|\hat{p}_j|$, deviates more significantly from CHE as $M_c$ and $f$ increase
- $f = 3000$ Hz and $M_c = 0.5$ results shown

**CHE mode structure**

- Symmetry between positive and negative modes
- Structure formed from cosine basis

**PBE mode structure**

- Asymmetry between positive and negative modes
- Positive mode structure is more consistent with CHE modes (in general)
- Possible "mode switching?" (next slide)



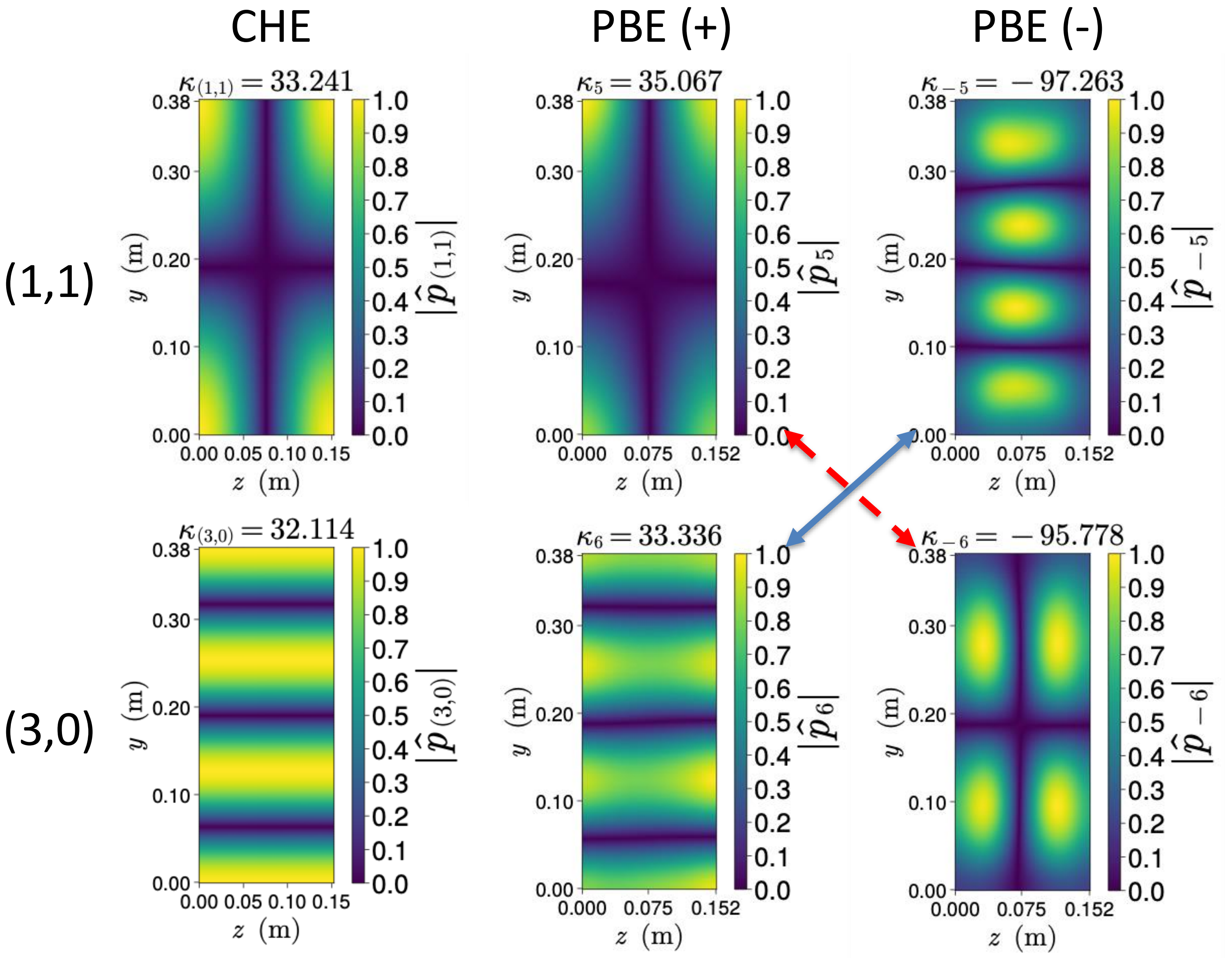
# Pridmore-Brown Modal Analysis

**“Mode Switching”**

- PBE negative mode structure sometimes corresponds to different positive mode order
- How should PBE mode be defined? Its structure or wavenumber?

**Future Work**

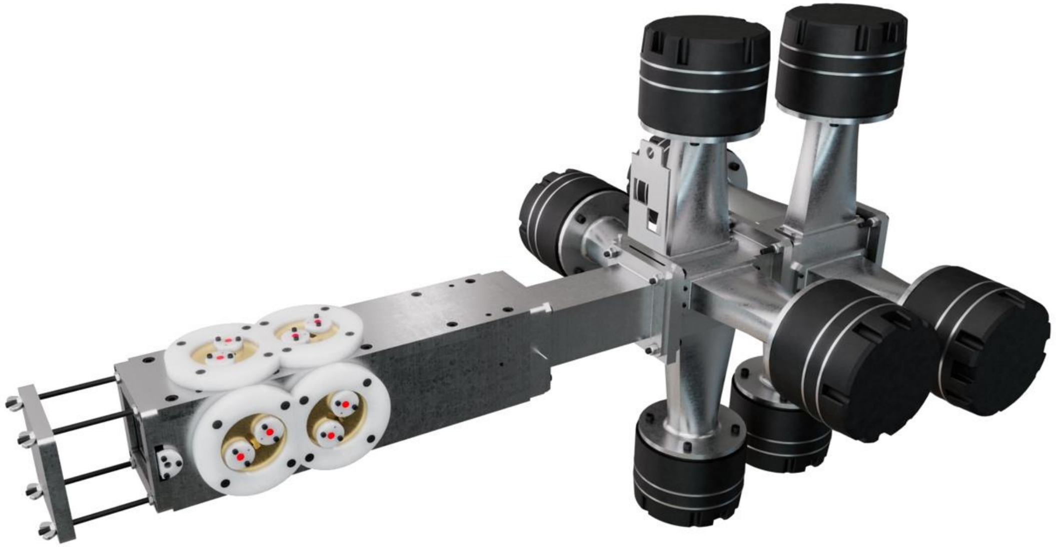
- Support future investigations of flow direction effects on impedance eduction



# HIMIT Upgrades and Analysis

**High Intensity Modal Impedance Tube (HIMIT) Objective**

- Developed to increase impedance tube testing range to 6 kHz
- Higher-order modes present above ~3.4 kHz
  - Modal analysis requires single dominant mode for best accuracy (mode control)
  - Unclear how to set consistent level across different modes for nonlinear liner samples
  - Mode scattering may complicate impedance eduction



**Approach**

- Modify existing mode control algorithm to ignore uncontrollable reflected modes
- Test methods to set level
  - Mode SPL or power level
  - Average SPL at liner surface
- Assess different methods for educing impedance


# HIMIT Upgrades and Analysis

**Control Algorithm (In Development)**

- Original CDTR mode control assumes anechoic termination and optimizes microphone response [refs. 4,5]
- Instead use leaky LMS algorithm to optimize incident mode response ($a_m^{(-)}$, where $m = 1, \dots, nmodes$)
- $H_{mn}^*$ is transfer function between driver signal and mode coefficient

$$x_n(k+1) = (1-\alpha\beta)\underbrace{x_n(k)}_{\text{Driver signal}} - \alpha H_{mn}^*\Big(\overbrace{d_m(k)}^{\text{Desired mode response}} - \underbrace{a_m(k)}_{\text{Actual mode response}}\Big)$$

**Mode Plates**

- Mode plates are an alternative form of mode control for higher-order modes [ref. 6]
- Plane wave mode cannot be controlled, but is usually the preferred mode without control

(0,0) (1,0) (0,1) (1,1)

# HIMIT Upgrades and Analysis

**Methods to Set Source Level**

- Incident vs. total
- Mode SPL (same as NIT at plane wave frequencies)
- Mode power level
- Average SPL across sample face

$$\zeta_{mn,mn} = \left(\frac{k}{\kappa_{mn}}\right)\frac{1 + R_{mn,mn}}{1 - R_{mn,mn}}$$

$$\zeta = \frac{1}{\rho c}\frac{P}{U_1}$$

$$\zeta_{qr} = \left(\frac{k}{\kappa_{qr}}\right)\frac{1 + \sum_n^\infty \sum_m^\infty R_{mn,qr}(\psi_{mn}/\psi_{qr})}{1 - \sum_n^\infty \sum_m^\infty (\kappa_{mn}/\kappa_{qr}) R_{mn,qr}(\psi_{mn}/\psi_{qr})}$$

**Methods to Educe Impedance**

- Same-mode impedance
- Modal impedance (include all modes in reflected field)
- Total impedance (all cut-on modes contribute, sensitive to mode decomposition uncertainty?)

Samples for upcoming test

Linear ↕ Nonlinear

| Sample | POA |
|---|---|
| CSQ30S1 | N.A. |
| SDOFPS1 | 21.9 |
| SDOFPS2 | 23.9 |
| SDOFPS3 | 5.4 |
| SDOFPS4 | 3.1 |

**Future Work**

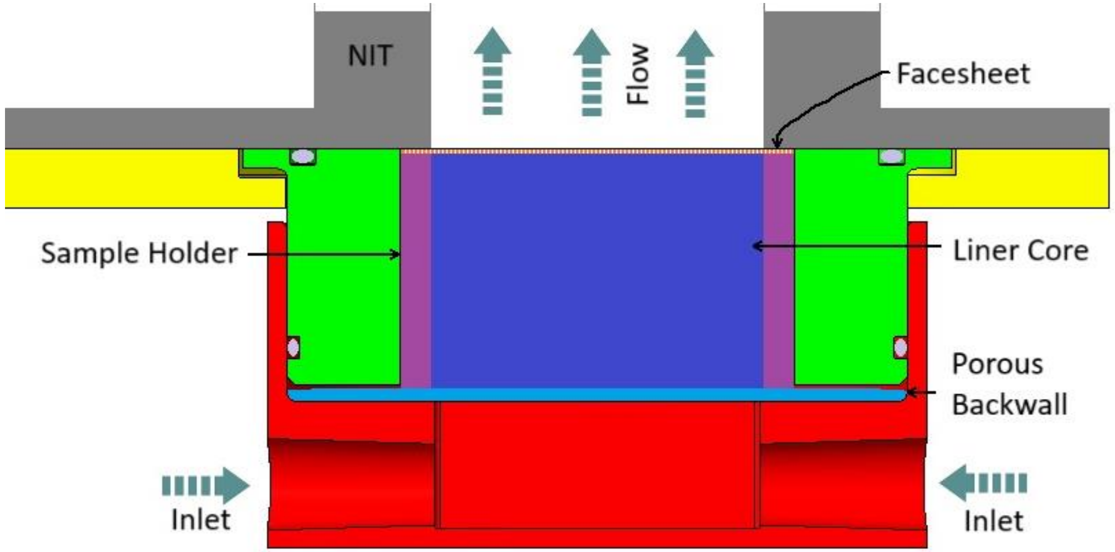
- Testing will assess ability of HIMIT to effectively
  - Set a consistent source level across different sample types
  - Educe impedance and/or interpret results with mode scattering
  - Characterize liner samples up to 6 kHz

# Updates from Liner Physics Team

# Experiment

**Normal Incidence Tube (NIT)**

- Implementing bias flow testing capability
- Feed shop air through a plenum and porous backwall to sample
- Examine effects of bias flow on
  - Broadening frequency range of attenuation of liners
  - In-situ impedance control

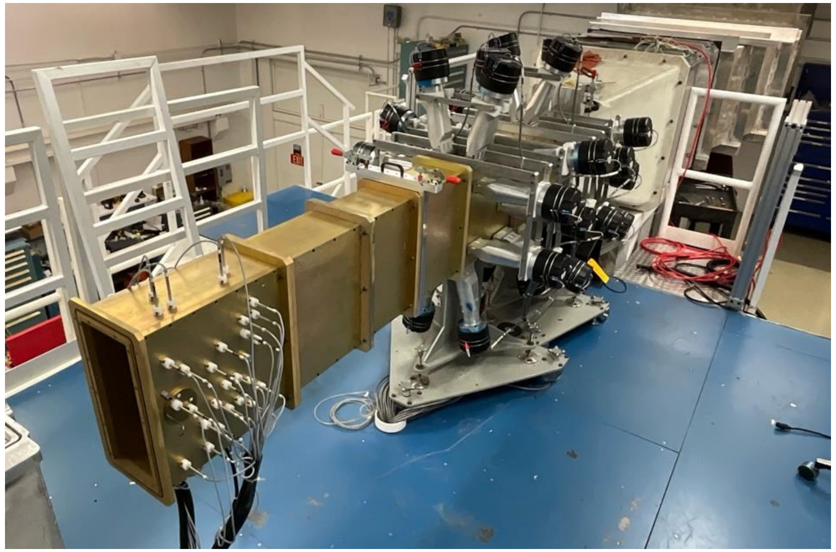



Flow capability: 100 to 750 SLM

POC: Scott Haigler

**CDTR Chromate Conversion Coating**

- Oxidation of aluminum due to humidity exposure
- Aluminum flaking at high Mach numbers
  - Buildup in grid caps of mics
  - Hot-wire breakage
- Chromate conversion coating applied to prevent further oxidation

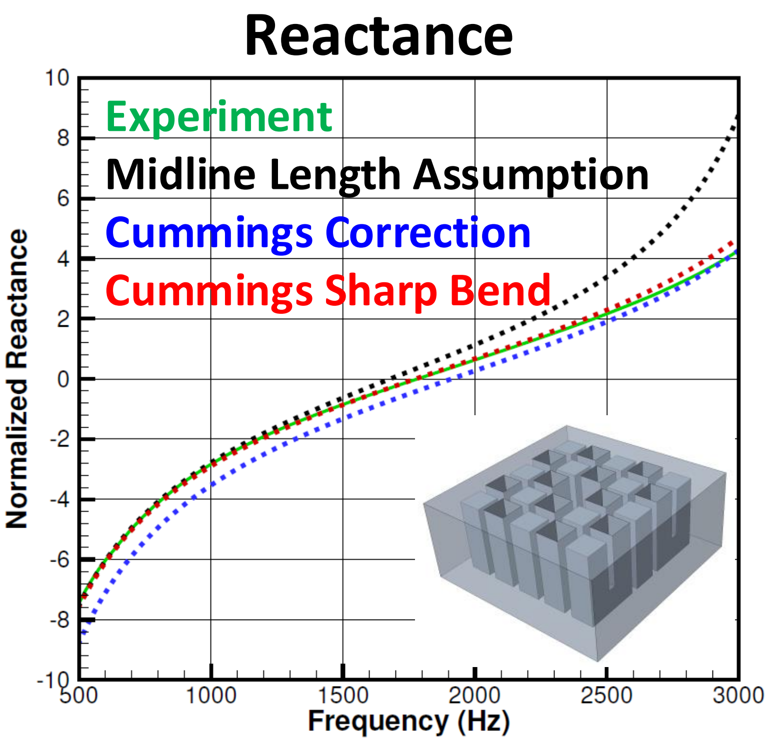


POCs: Alex Carr, Martha Brown, Max Reid

# Modeling

## Bent Chambers

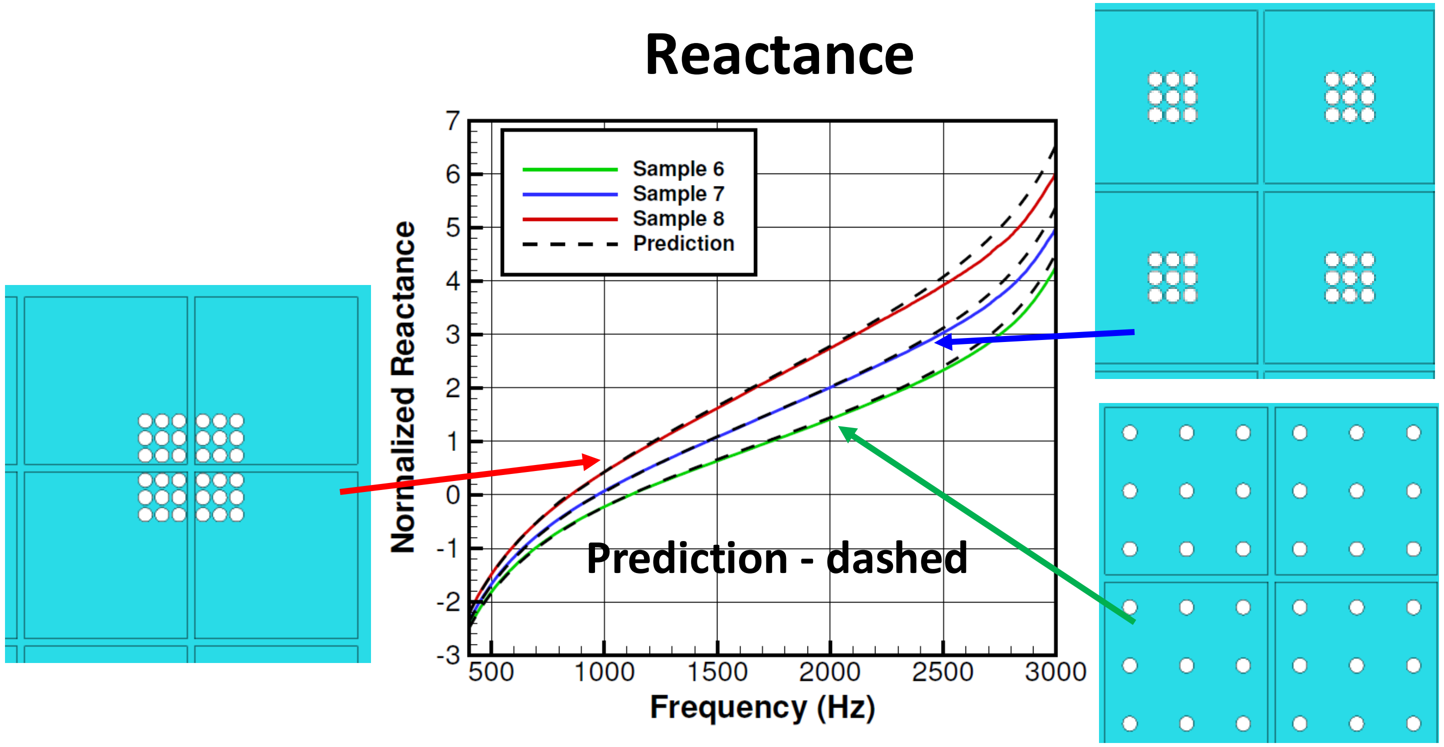
Effort to model effect of bent chambers on reactance [7]




POC: Jordan Kreitzman

## Hole Clustering

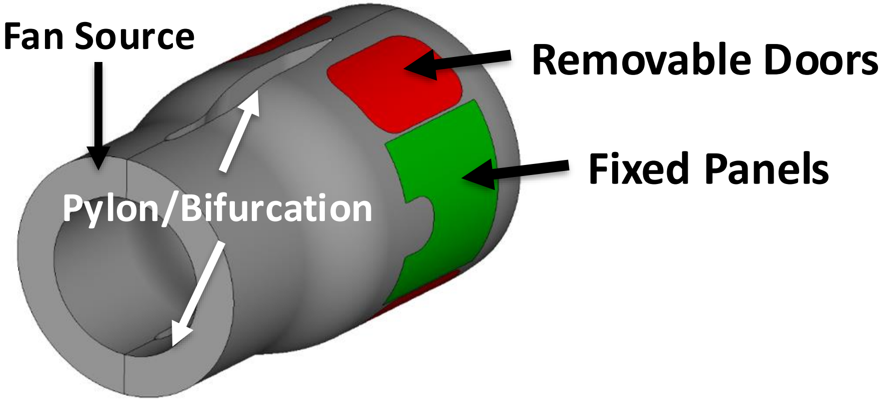
Perforate model developed to capture influence of hole position. Accuracy for both constant- and variable-depth liners



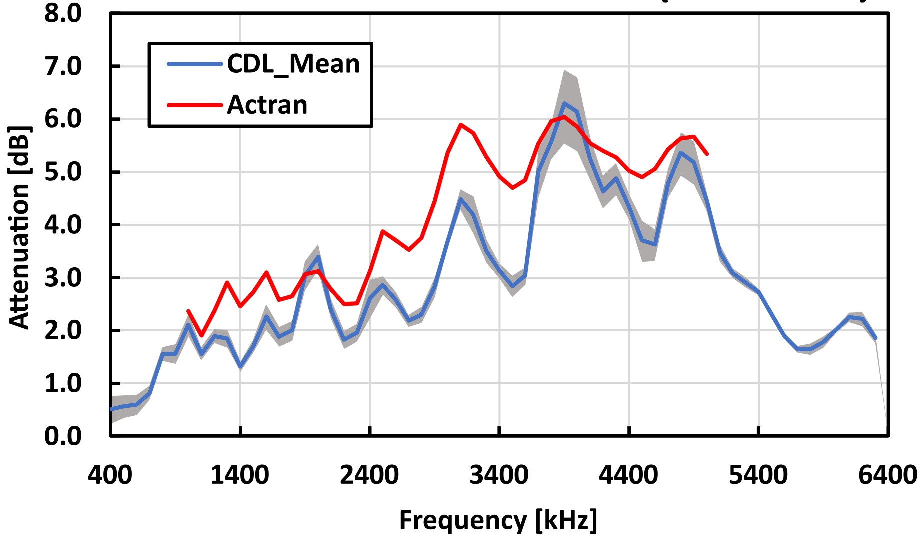

POC: Jordan Kreitzman

# Analysis

## Honeywell Static Engine Test

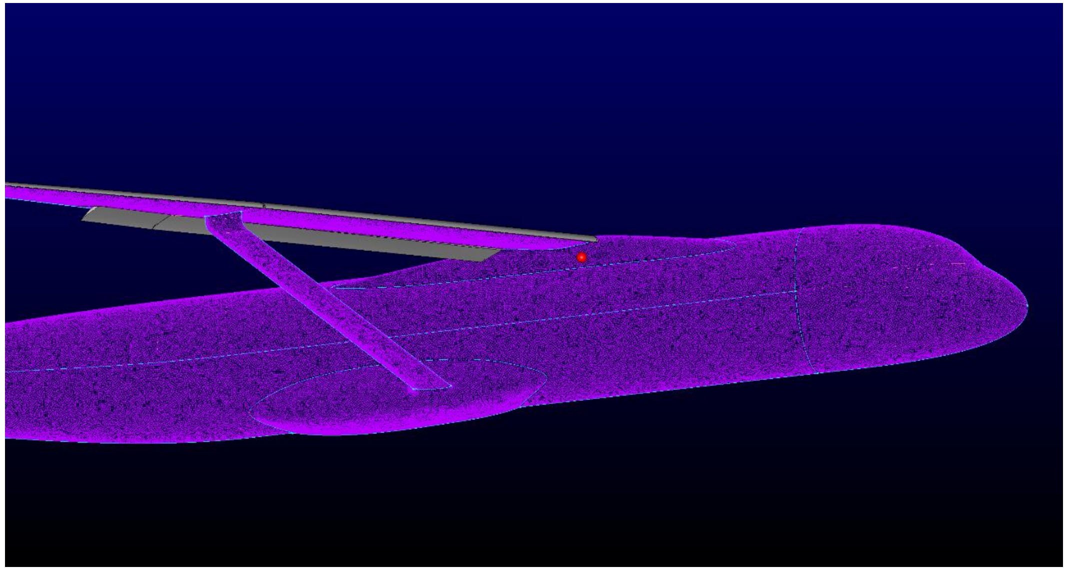



**Predicted In-Duct Attenuation (two-zone)**



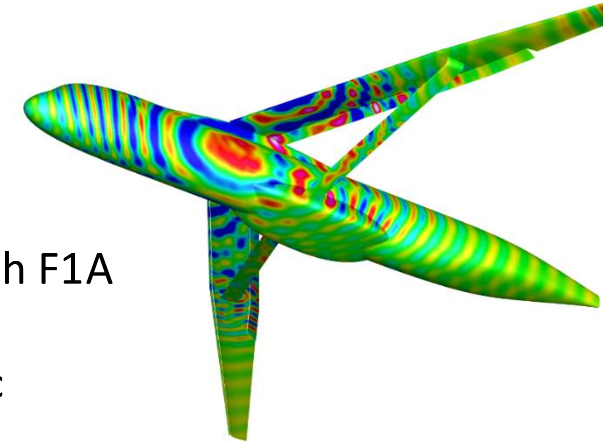

POCs: Doug Nark, Jordan Kreitzman

## Time Domain Acoustic Scattering (TDFAST)



TTBW (Open configuration)

- Approach and takeoff configurations
- Enhanced incident source specification, coupling with F1A (ANOPP2)
- Explore effects of acoustic treatment on fuselage



POCs: Doug Nark, Fang Hu (ODU)

# External Collaborations

**Space Act Agreements (SAA)**

- Hexcel: Exploration of novel liner core designs
- Honeywell: Static engine test data analysis and bifurcation liner design/testing
- MRAS: Exploration of novel liner facesheet designs
- MTU: Poroelastic liner research
- Sierra Space: Liner Design for LIFE Habitat Fan Noise Reduction

**Other collaborations**

- IFAR (International agreement) – Evaluate effects of flow direction or multitone source on impedance
- ODU (NIA) – Time-domain method to study acoustic scattering with liners
- AARC – Comparison of predicted (Avallone) and measured (NASA LaRC and UFSC) impedances
- Regular interactions with NASA GRC acoustics branch

# Recent Publications

**Conference Papers (AIAA/CEAS Aeroacoustics 2024)**

- B.M. Howerton, “Acoustic Liner Drag: Measurement Uncertainty Reduction and Application to Novel Perforate Geometries,” AIAA 2024-3247.
- J. Kreitzman, M.G. Jones, “Influence of Source Type on Acoustic Liner Impedance in No Flow,” AIAA 2024-3249.
- D.M. Nark, M.G. Jones, J. Kreitzman, B. Schuster, “Bypass Duct Acoustic Liner Design with and without Bifurcation Effects,” AIAA 2024-3250.
- F.Q. Hu, D.M. Nark, “An Extension of the Truncated Ingard-Myers Boundary Condition for High Mach Number Grazing Flows,” AIAA 2024-3291.
- M.G. Jones, D.M. Nark, and B.M. Howerton, “NASA Investigation of Flow Direction Effects on Impedance Eduction for Acoustic Liners,” AIAA 2024-3297.
- B.M. Howerton, J. Kreitzman, C. Solano, “Extending Acoustic Liner Bandwidth with Simple Embedded Septa,” AIAA 2024-3302.
- A.N. Carr, “Acoustic Mode Decomposition in Rectangular Ducts with Sheared Flow,” AIAA 2024-3368.
- J.C. June, E. Nesbitt, D.M. Nark, M.G. Jones, “Comparison of Inlet Broadband Acoustic Liner Predictions to Quiet Technology Demonstrator 3 Flight Data,” AIAA 2024-3371.

**Technical Documents**

- M.G. Jones, J.R. Kreitzman, D.M. Nark, “Examination of Perforate Facesheet Impedance Prediction Models,” NASA TP-20240006417, August, 2024.
- J.R. Kreitzman, and M.G. Jones, “An Experimental and Predictive Study of Bent-Chamber Acoustic Liners”, NASA/TM-20240014376, 2024

# Questions?

# References

[1] Pridmore-Brown, D. C., “Sound propagation in a fluid flowing through an attenuating duct,” *Journal of Fluid Mechanics*, Vol. 4, No. 4, 1958, pp. 393–406. https://doi.org/10.1017/S0022112058000537.

[2] Rienstra, S. W., “Numerical and asymptotic solutions of the Pridmore-Brown equation,” *AIAA Journal*, Vol. 58, No. 7, 2020, pp. 3001–3018. https://doi.org/10.2514/1.J059140.

[3] Alexander N. Carr. "Acoustic Mode Decomposition in Rectangular Ducts With Sheared Flow," AIAA 2024-3368. *30th AIAA/CEAS Aeroacoustics Conference (2024)*. June 2024. https://doi.org/10.2514/6.2024-3368.

[4] S. J. Elliott, C. C. Boucher and P. A. Nelson, "The behavior of a multiple channel active control system," *IEEE Transactions on Signal Processing*, Vol. 40, No. 5, 1992, pp. 1041-1052. https://doi.org/10.1109/78.134467.

[5] Carl Gerhold, Randolph Cabell and Martha Brown. "Development of an Experimental Rig for Investigation of Higher Order Modes in Ducts," AIAA 2006-2637. *12th AIAA/CEAS Aeroacoustics Conference (27th AIAA Aeroacoustics Conference)*. May 2006. https://doi.org/10.2514/6.2006-2637.

[6] Todd Schultz, Louis N. Cattafesta and Mark Sheplak, “Modal decomposition method for acoustic impedance testing in square ducts,” *Journal of the Acoustical Society of* America, Vol. 120, No. 6, 2006, pp. 3750–3758. https://doi.org/10.1121/1.2360423.

[7] J.R. Kreitzman, and M.G. Jones, “An Experimental and Predictive Study of Bent-Chamber Acoustic Liners,” NASA/TM-20240014376, 2024.

# Backup Slides

# Modal Analysis

- Acoustic pressure field may be expressed as

$$P(x,y,z;\omega) = \sum_{j=1}^{J} \chi_j \overbrace{\sum_{n=0}^{\tilde{N}} \sum_{m=0}^{\tilde{M}} a_{mn}^{(j)} \psi_{mn}(y,z) e^{i\kappa^{(j)}x}}^{\hat{p}_j}$$

- $\chi_j$ are the complex mode coefficients
- Microphone measurements provide $P(x,y,z;\omega)$ at specific in-duct locations
- Then, linear least-squares regression may be used to determine $\chi_j$
- Once $\chi_j$ are determined, the following quantities are of interest
  - Mode SPL, $\mathrm{SPL}_{\mathrm{mode},j} = 10 \log \left( \frac{\chi_j \chi_j^*}{2p_{ref}^2} \right)$
  - Reconstruction error in SPL and phase

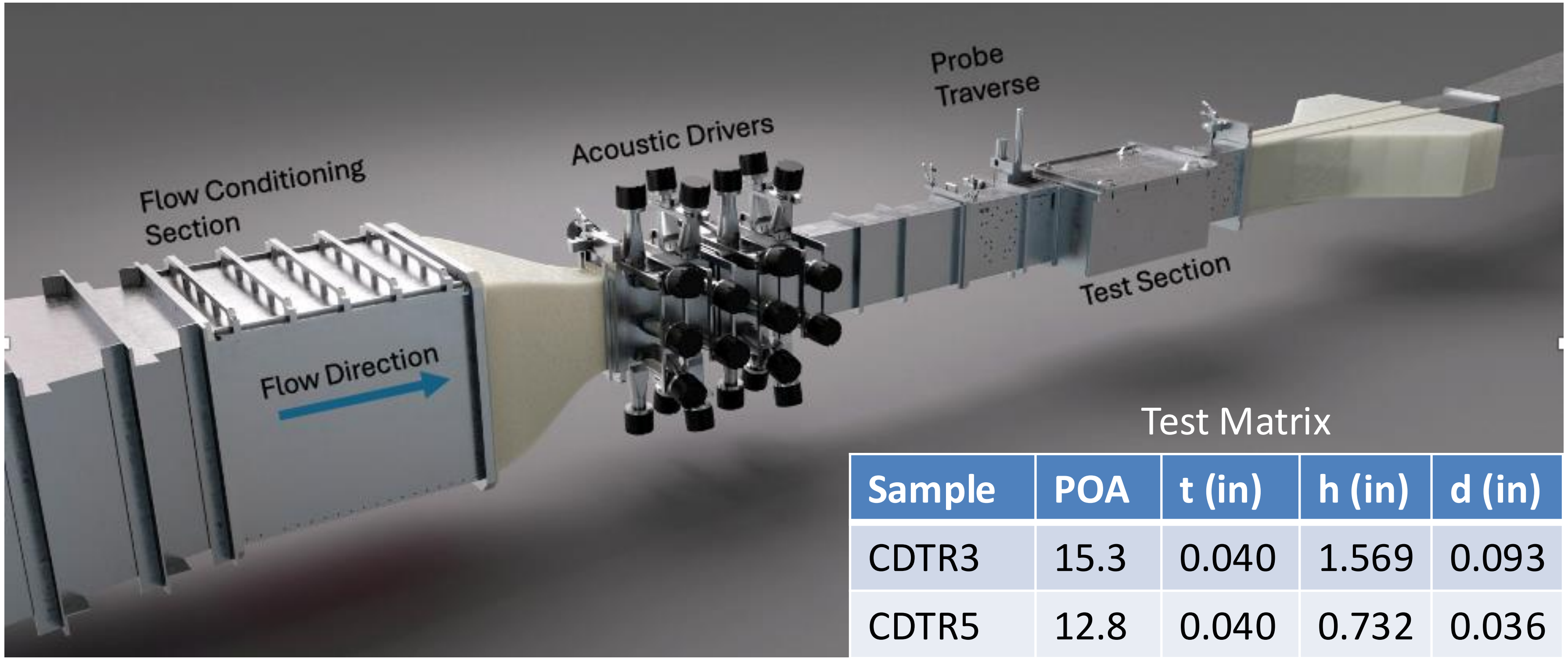
$$E_{\mathrm{SPL,PBE}} = \frac{\|\mathrm{SPL}_{\mathrm{PBE}} - \mathrm{SPL}_{\mathrm{measured}}\|_2}{\|\mathrm{SPL}_{\mathrm{measured}}\|_2}$$

$$E_{\mathrm{phase,PBE}} = \frac{1}{N_{\mathrm{mics}}} \sum_{i=1}^{N_{\mathrm{mics}}} \frac{\min(s, s^c)}{\pi}$$

$$s = |\theta_{\mathrm{measured}} - \theta_{\mathrm{PBE}}| \qquad s^c = |2\pi - s|$$

# Experimental Setup

- Curved Duct Test Rig (CDTR) – open-loop wind tunnel capable of $M_c = 0.5$ in test section
- 15 x 6 in test section
- 32 acoustic drivers – mode control
- Probe traverse for flow measurements along cross-section before and after test section
- Test matrix: CDTR3 and CDTR5 liner samples at $M_c = 0.1$, 0.3, and 0.5



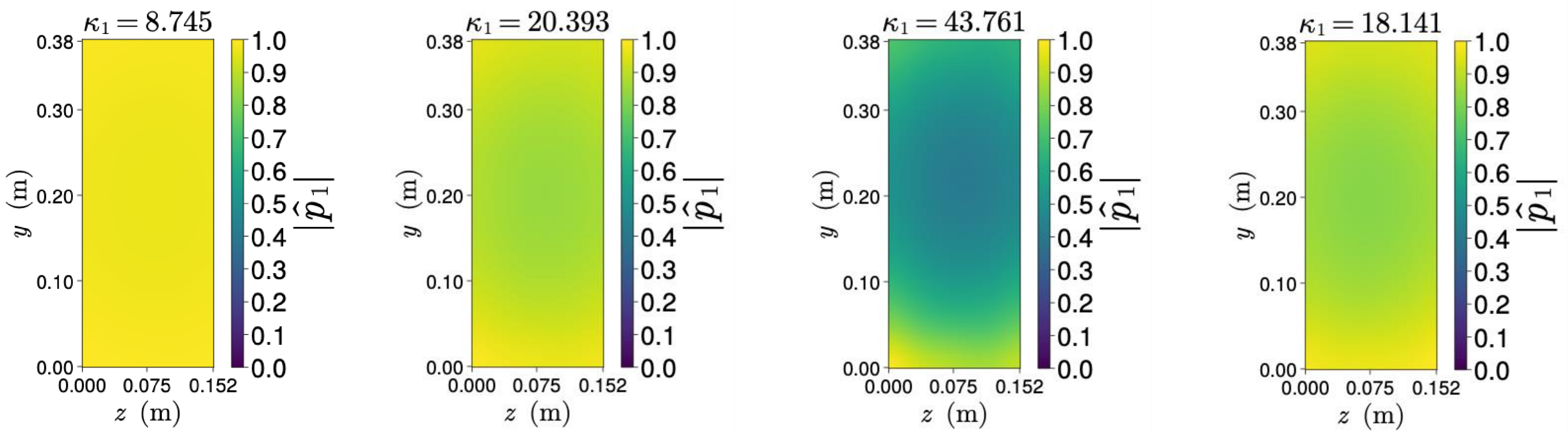

Test Matrix

| Sample | POA | t (in) | h (in) | d (in) |
|---|---|---|---|---|
| CDTR3 | 15.3 | 0.040 | 1.569 | 0.093 |
| CDTR5 | 12.8 | 0.040 | 0.732 | 0.036 |

# Modal Structure

- As frequency and Mach number increase, modal structure becomes more “distorted” relative to traditional CHE mode structure
- Lowest-order mode becomes increasingly non-planar as flow speed and frequency increase (shown below)
- Asymmetry between positive and negative mode structures also present (shown on next slide)
- Lowest-order mode is first mode to exhibit this asymmetry (ref. 3)

$\min(|\hat{p}_1|) = 0.41$ $\min(|\hat{p}_1|) = 0.32$

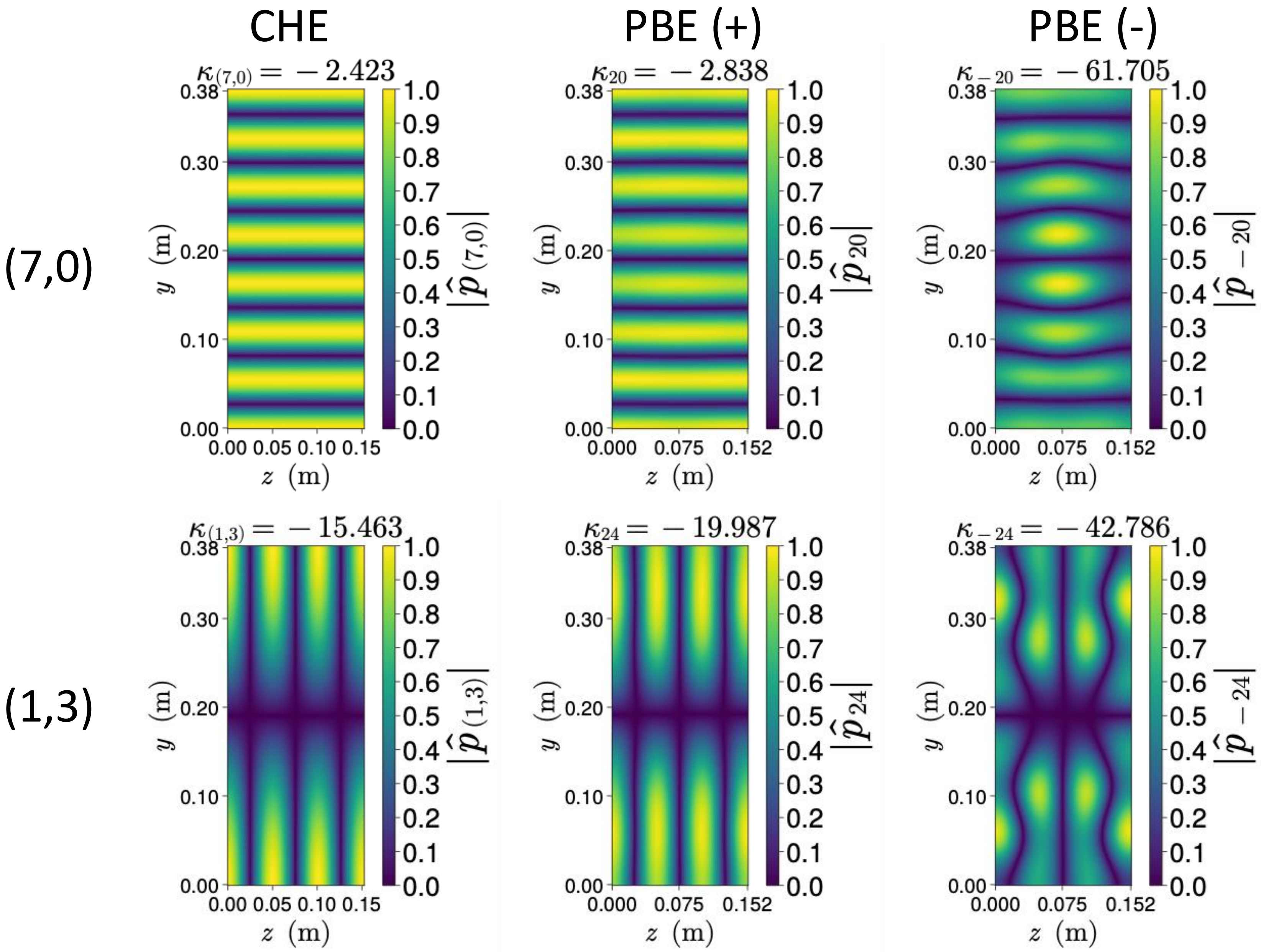



$f = 600$ Hz and $M_c = 0.3$ $f = 1400$ Hz and $M_c = 0.3$ $f = 3000$ Hz and $M_c = 0.3$ $f = 3000$ Hz and $M_c = 0.5$

# Modal Structure (Flow Direction Effects)

**Additional Mode Structure Plots**

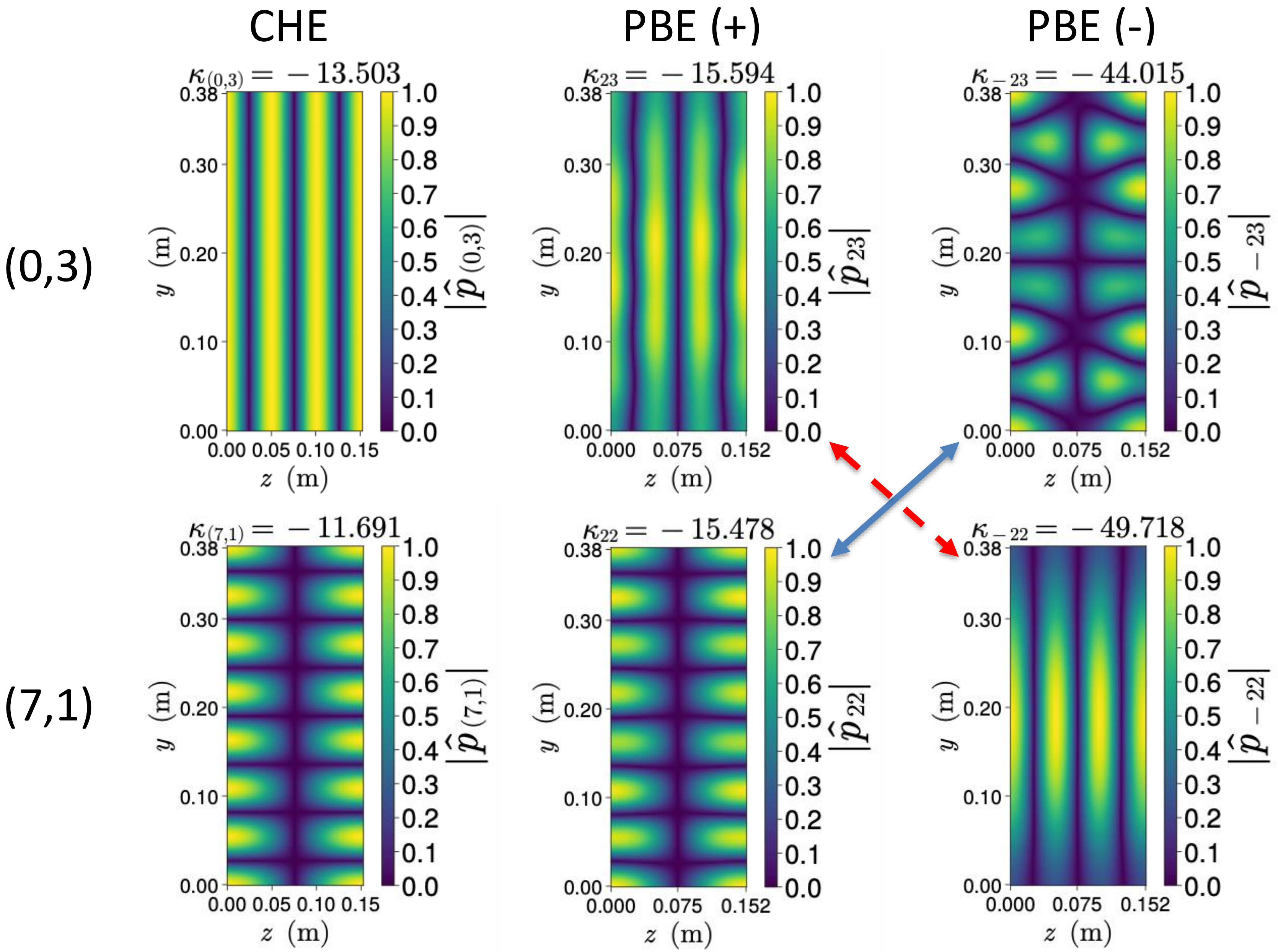
- $f = 3000$ Hz and $M_c = 0.5$
- PBE modes
- Positive modes top row, negative modes bottom row
- Positive modes exhibit structure closer to CHE modes
- Negative mode structure is vastly different



# Modal Structure (“Mode Switching”)

**Additional Mode Structure Plots**

- $f = 3000$ Hz and $M_c = 0.5$
- Another case of mode switching presented here



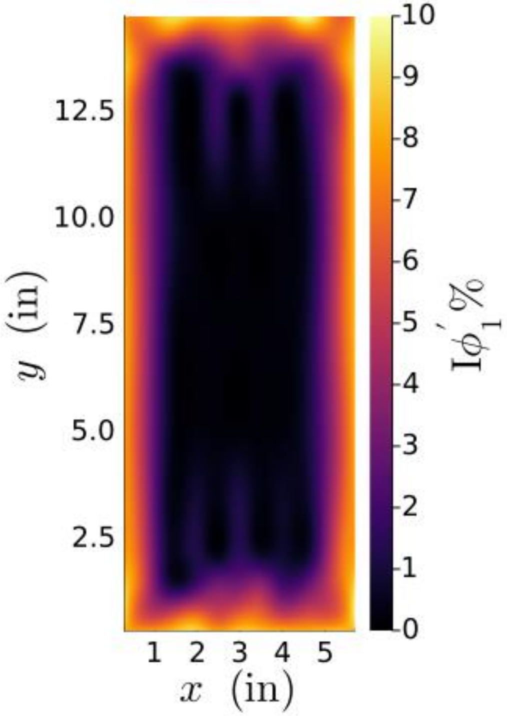
# Hot-Wire Measurements in CDTR

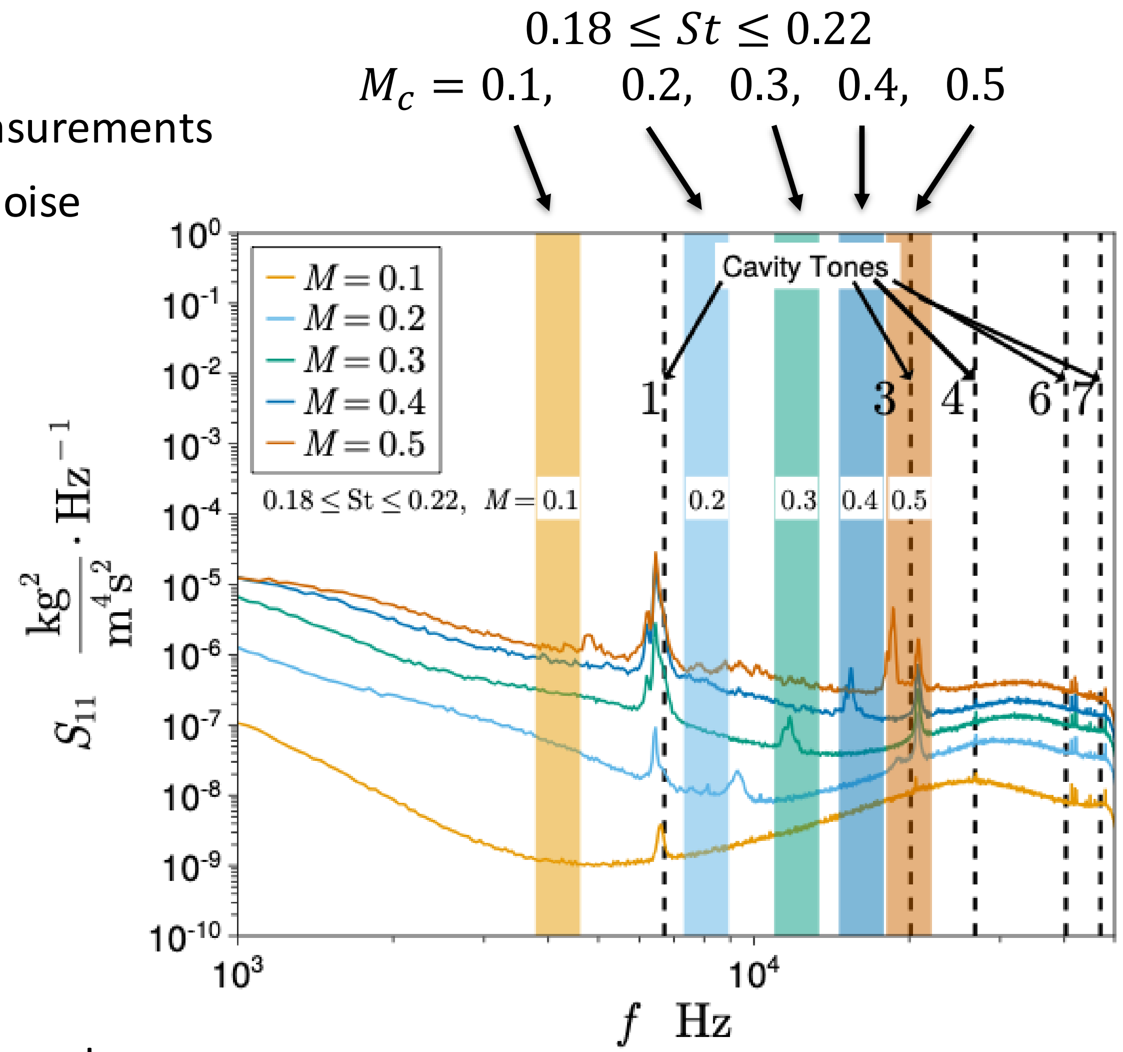
**Objectives**

- Support treated-airfoil testing and boundary layer turbulence measurements
- Assess flow quality and identify sources of coherent background noise

**Background Turbulence Assessment**

- Less than 1% turbulence intensity in core region
- Cavity tones appeared in core region turbulence spectra
  - Due to porous liner inserts separating acoustic drivers from flow – act as resonators
- Vortex shedding from upstream total pressure probe




**Solutions**

- Remove upstream probe, use static pressure differential for flow speed measurement
- Porous inserts can be replaced with hardwall inserts if needed

# Hot-Wire Measurements in CDTR

**CDTR Chromate Conversion Coating**

- Frequent hot-wire breakage during testing
- Determined cause – particulate impact
  - Aluminum pitting in duct from humidity exposure
  - Ingesting unfiltered air from outside
- Solutions
  - Chromate conversion coating of duct to prevent further pitting
  - Exploring filter options for inlet ($10\mu m$ filter)