AATT Propulsion Technologies: Liner Physics Team Technical Challenge Roadmap

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NASA Glenn, Cleveland OH

Liner Physics Team

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Technical Approach – Overview of Technical Challenge

TC Goal: **Predict, model, and assess** the ability for next-generation propulsors to meet market-driven goals for noise (4 dB reduction) and efficiency (3-5% fuel burn reduction) *with integration effects*, relative to 2021 best-in-class propulsors, and reduce risk to a new single-aisle aircraft in the 2030s.

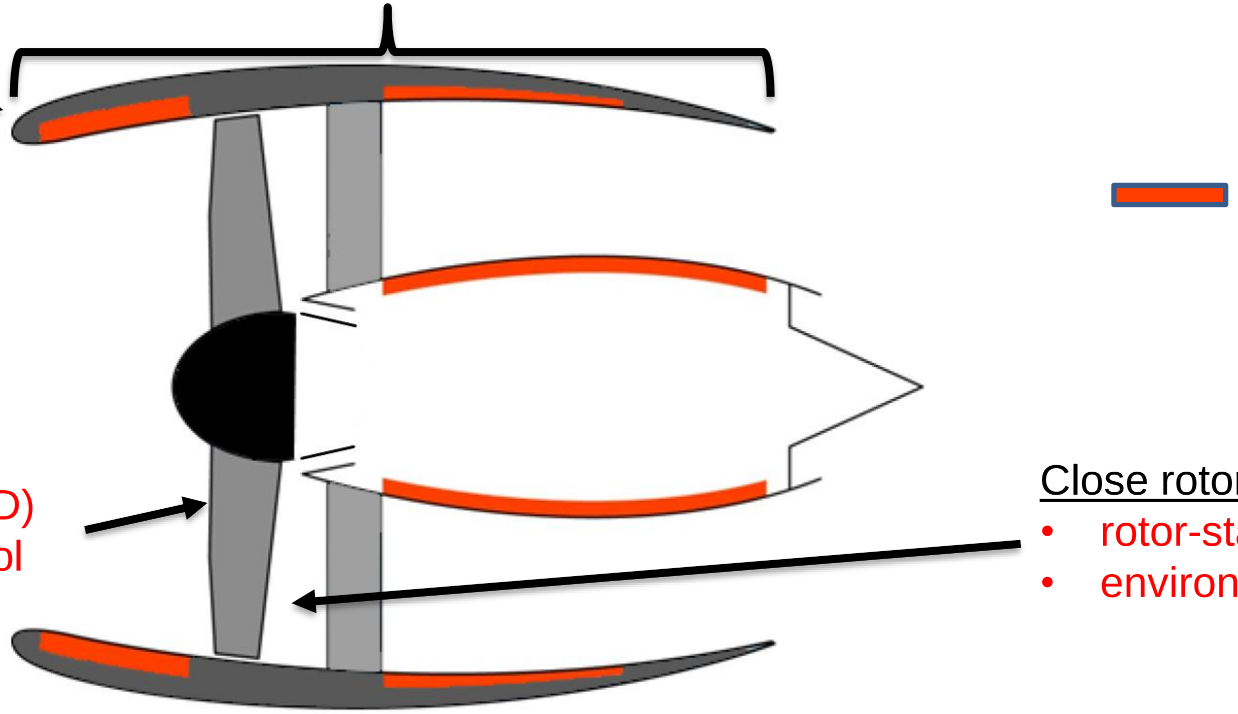
- **Simulation**
  - Source Definition
  - Propagation
  - Liner Modeling
- **Liner Concepts and Applications**
  - Low Pressure Ratio (LPR) Fan
    - Optimized liners for inlet and aft bypass
    - Bifurcation liners
  - Unducted Single Fan (USF)
    - Optimized external core nacelle liner
    - Treated OGVs
    - External airframe liners
- **Evaluation**
  - Liner Technology Facility
  - Planned Static Engine Test
  - 9x15 Tests

NASA/Boeing

Propulsion Noise Challenges with Next-Gen Podded Engines

Slim/low drag nacelle
- potential loss of liner area
- less liner depth (low frequency performance)

Short inlet
- loss of liner area
- inflow distortion at AoA



Large diameter fan
- Reduced attenuation (decreased L/D)
- low frequency noise harder to control
- tone ***and*** broadband noise

Close rotor-OGV spacing
- rotor-stator interaction noise
- environment difficult to model

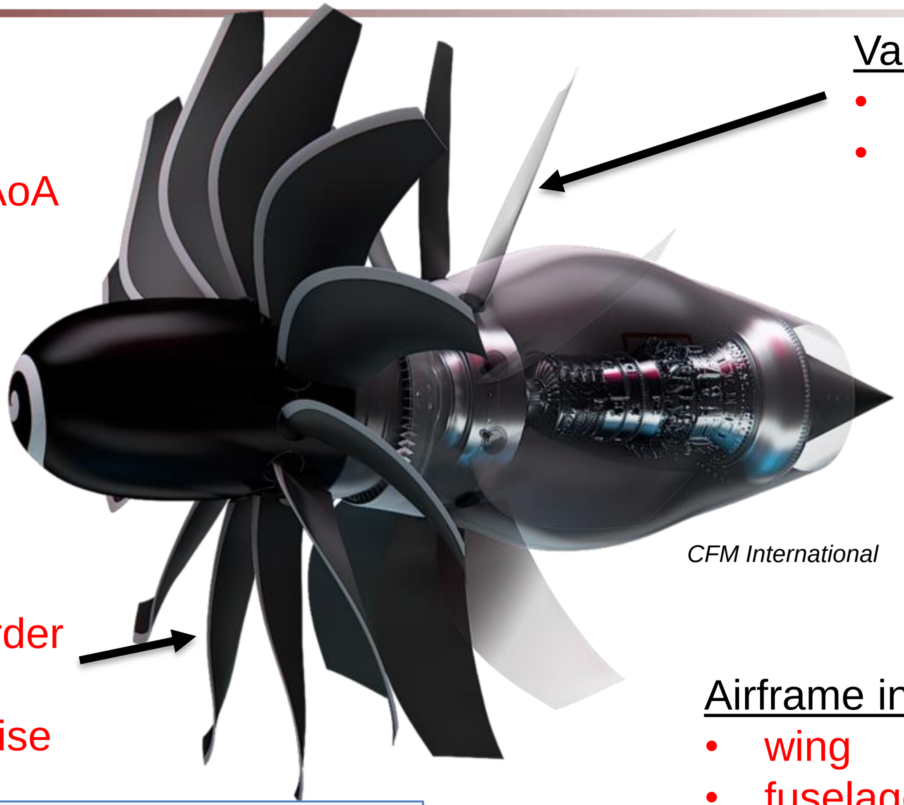
AoA - Angle of Attack
L/D - Length-to-Diameter
OGV - Outlet Guide Vane

New liner concepts and novel applications required to meet acoustic performance goals

Propulsion Noise Challenges with Open Fan Engines

No nacelle
- loss of liner area
- inflow distortion at AoA

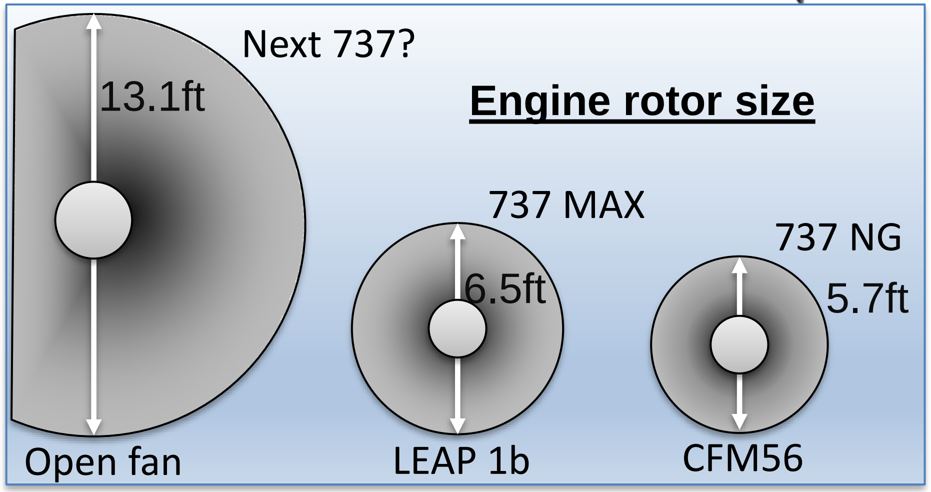
Variable pitch OGV
- source characterization complexity
- more optimization variables


CFM International

Large diameter fan
- low frequency noise harder to control
- tone ***and*** broadband noise

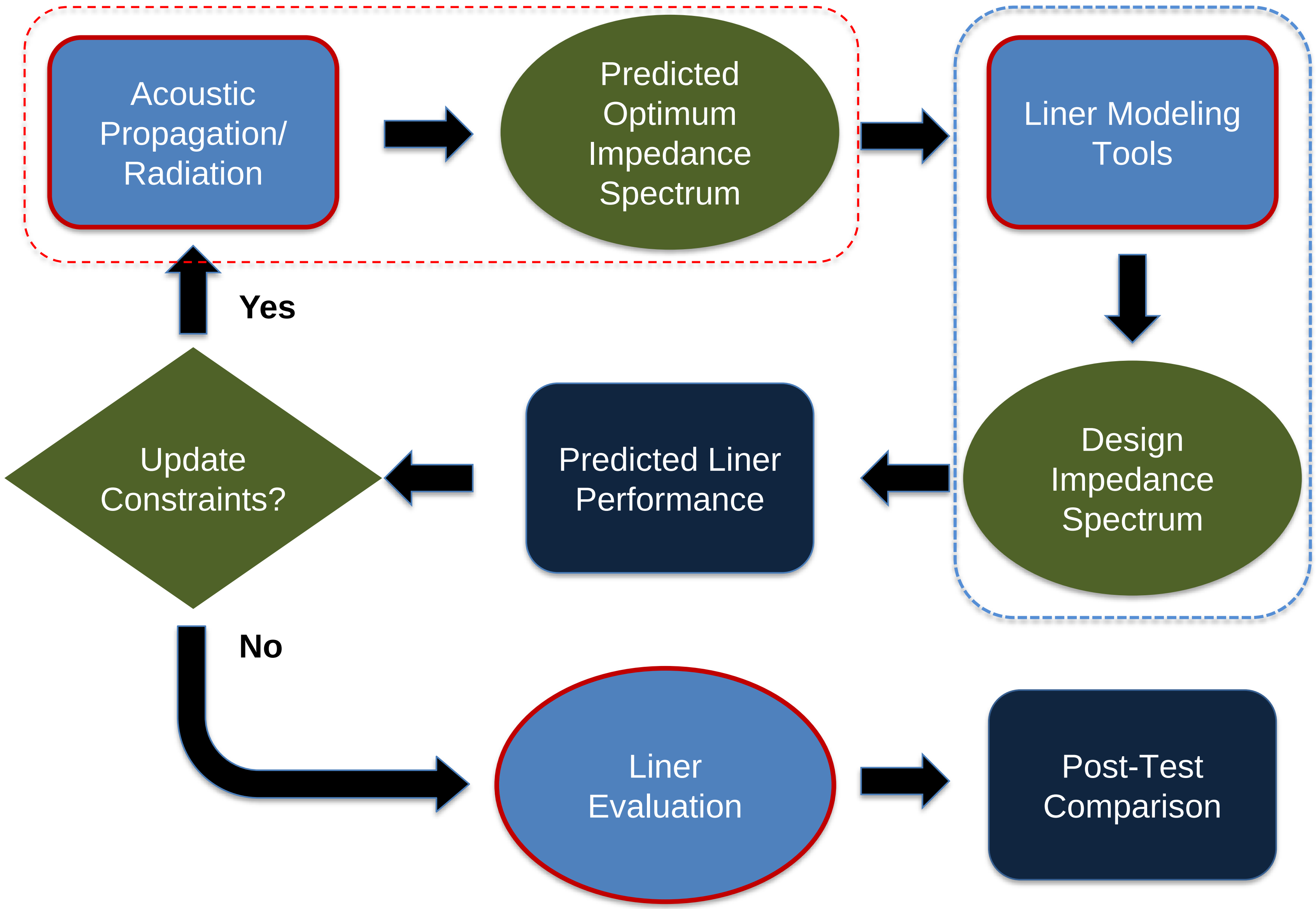
Airframe interactions
- wing
- fuselage
- empennage


NASA/Boeing



Substantial shift in liner concepts, applications and tools for this propulsor configuration

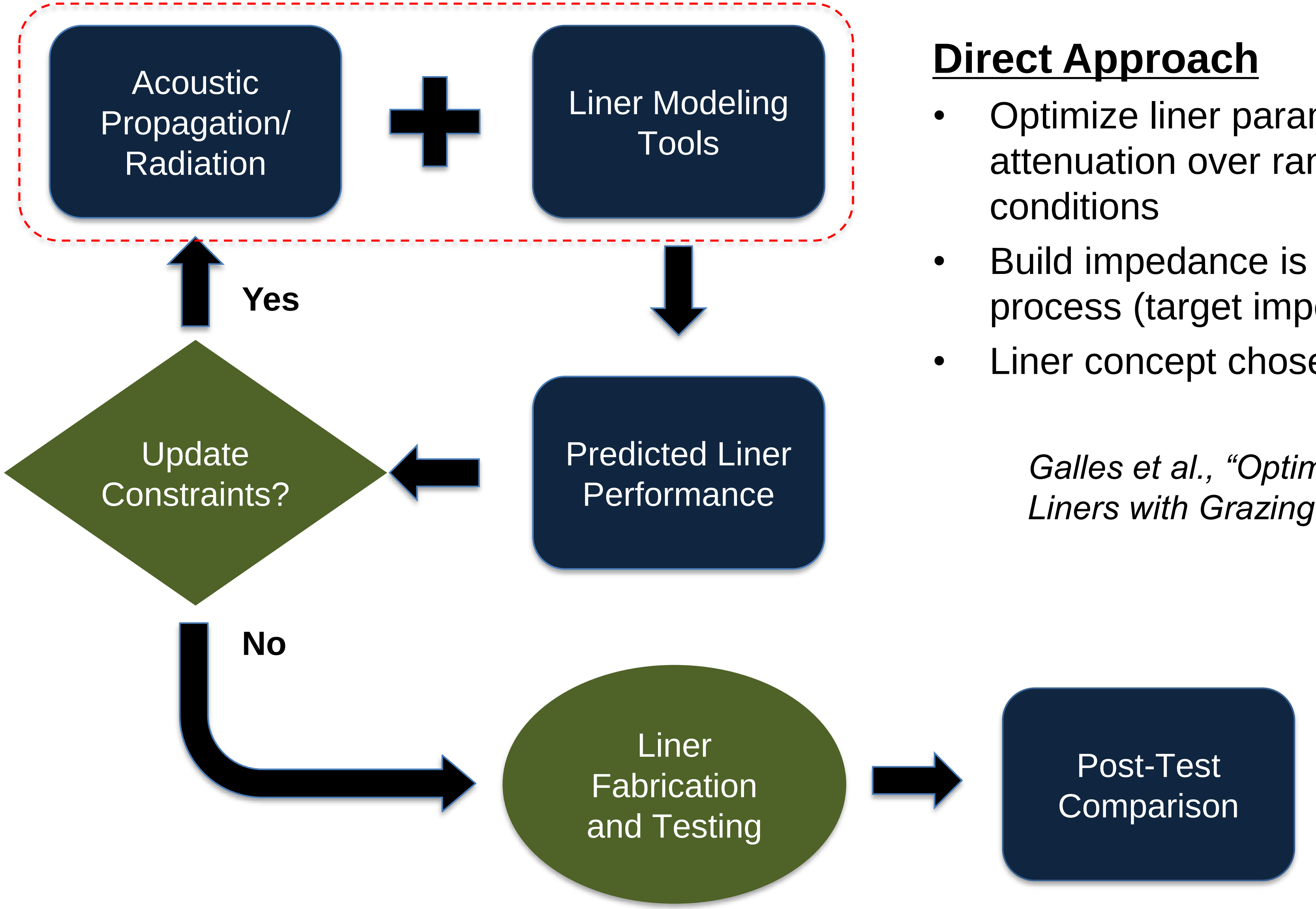
Acoustic Liner Design



Indirect Approach

- **Step 1**: Optimize impedance to achieve maximum attenuation over range of frequencies and flow conditions
- **Step 2**: Optimize liner parameters to match target impedance from Step 1
- Allows multiple liner configurations to be considered as part of Step 2
- Predicted optimum impedance is likely difficult to match, as frequencies and flow conditions are considered independently in Step 1

Acoustic Liner Design



Direct Approach

- Optimize liner parameters to achieve maximum attenuation over range of frequencies and flow conditions
- Build impedance is obtained as part of the optimization process (target impedance is not considered)
- Liner concept chosen at the beginning of process

Galles et al., "Optimization of Variable Depth Acoustic Liners with Grazing Flow," AIAA SciTech 2024

Acoustic Source

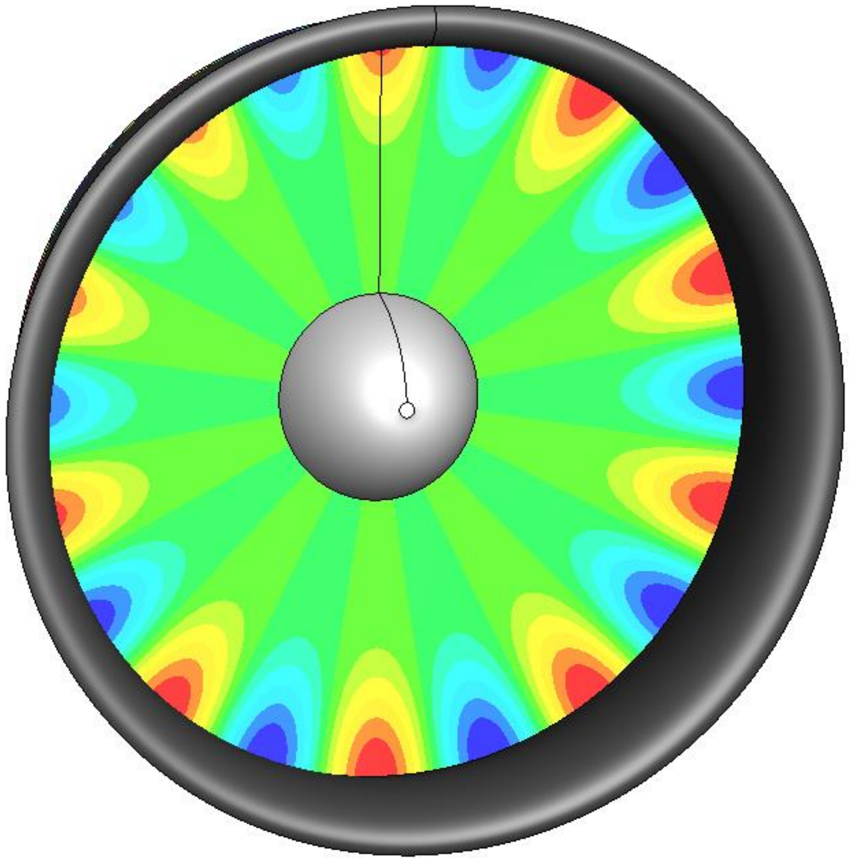
Langley Statistical Approach

- Mean Flow: Assumes 1D Mach-Area
- Acoustic Source: All cut-on modes
  - Random Amplitude/Phase
- Transmitted Acoustic Power: Assumes normally distributed
- Uses Student's *t*-distribution to analyze sample population

Fine/TURBO CAA Calculations (Ed Envia)

- Provides good estimate of relative modal amplitudes
- Results give further confidence in statistical approach

A proven method to generate source pressures in the absence of measured data



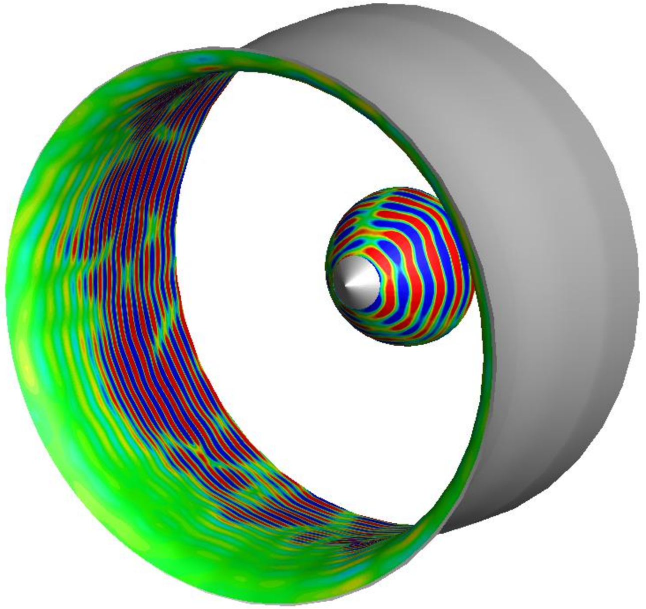
Inlet source acoustic pressure contours derived from statistical approach

Simulation – Propagation/Radiation

CDUCT-LaRC and ACTRAN

- Effect of installed liner impedance with flow
- In-duct and far-field propagation to assess liner impact
- Liner impedance optimization

Acoustic Pressure Contours



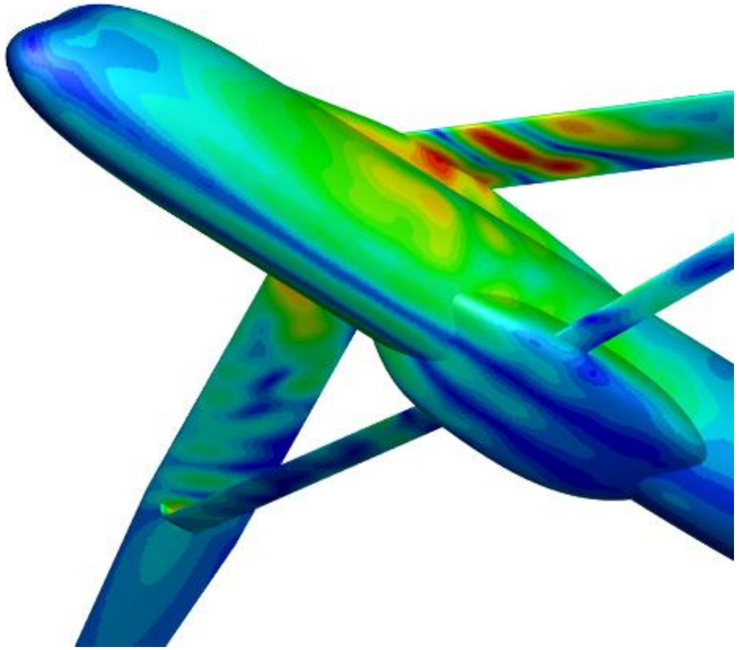
Boeing 737 MAX / GE LEAP 1-B engine inlet

Podded Propulsor

TDFAST (Fang Hu-ODU)

- Time Domain Fast Acoustic Scattering Toolkit
- External and far-field propagation to assess liner impact
- Liner impedance optimization

Acoustic Pressure Contours



TTBW test case with underwing point noise source

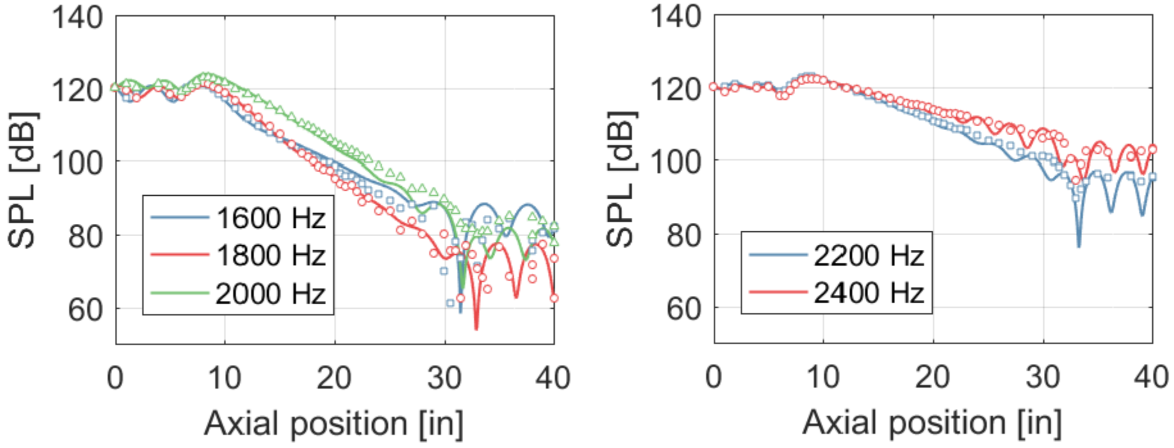
Open Fan

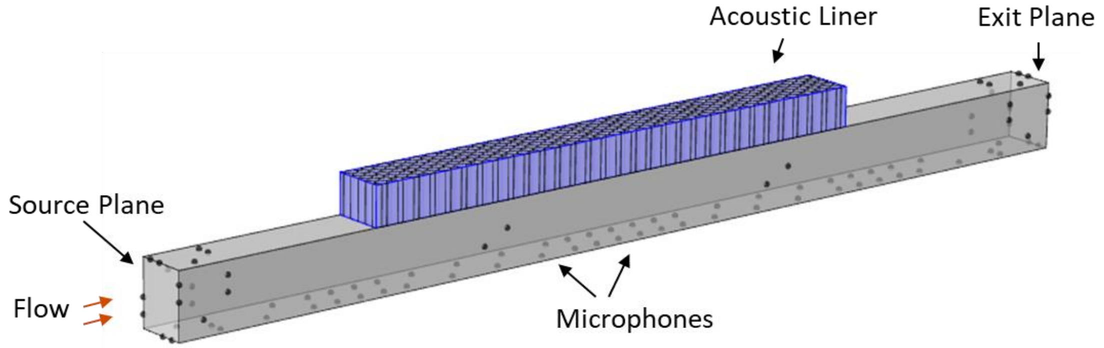
Simulation – Propagation

COMSOL Multiphysics
- Model liner and duct
- Flow effects

GFIT SPL distribution: Measured vs. Predicted

M=0.3

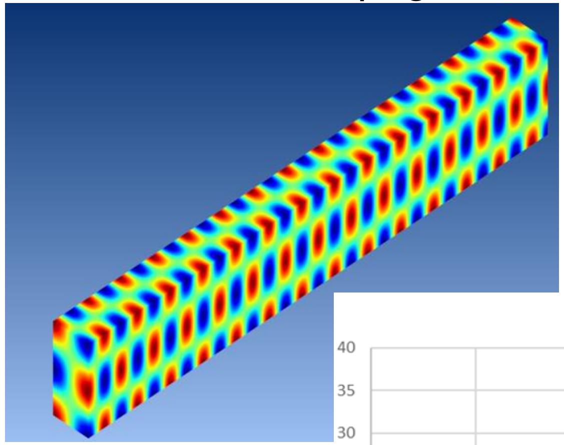


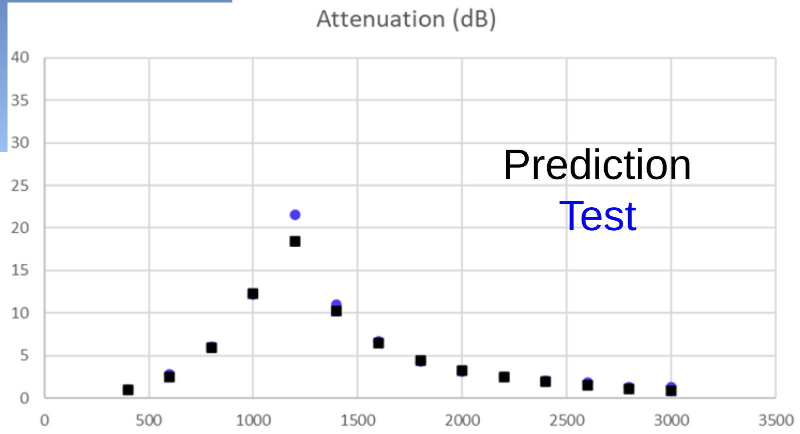


GFIT test section model

ACTRAN
- Liner impedance optimization
- Core design

CDTR Mode Propagation



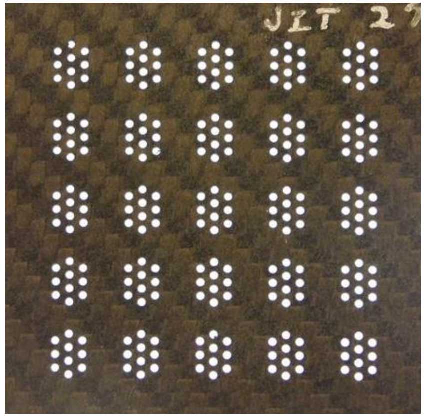


Baseline Liner Attenuation (CDTR)

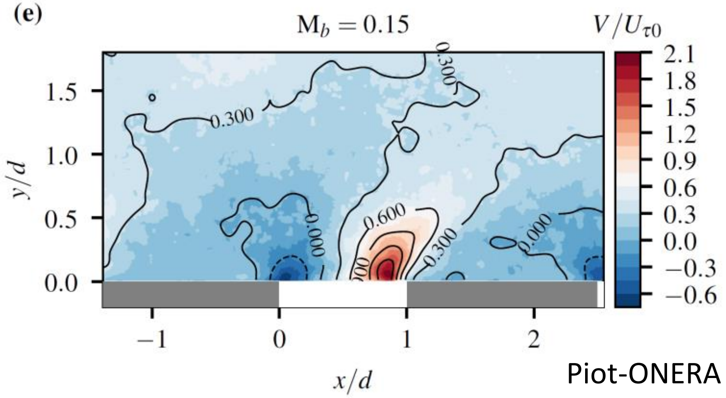
Simulation – Liner Modeling

Goal: Develop physics-based models of acoustic liners to aid in design and evaluation

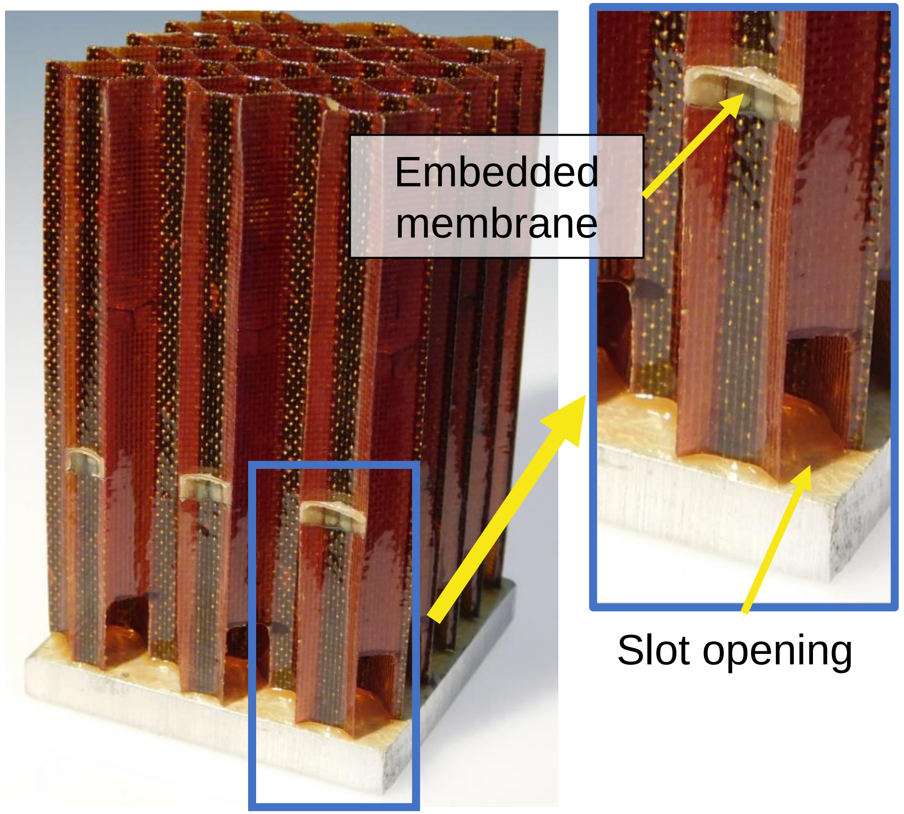
- Low-cost models for optimization studies based on experimental results and theory
- Liner component models to improve fidelity and incorporate new features
- Higher fidelity models to understand the physical effects of liner features



Perforate facesheet

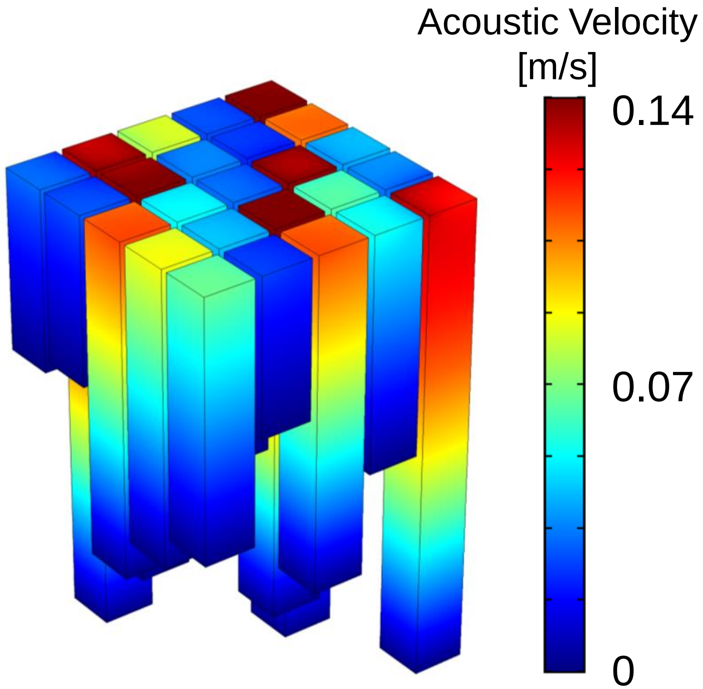


Flowfield around single perforation



Liner core

COMSOL liner simulation

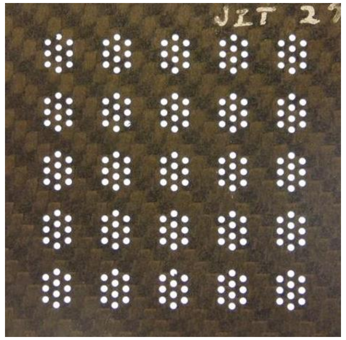


Variable depth liner

Simulation – Liner Modeling

Goal: Develop physics-based models of acoustic liners to aid in design and evaluation

- Low-cost models for optimization studies
  - ZKTL
- Liner component models to improve fidelity and incorporate new features
  - Updated facesheet perforate model

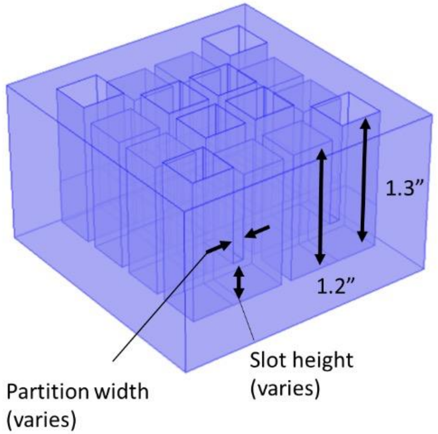


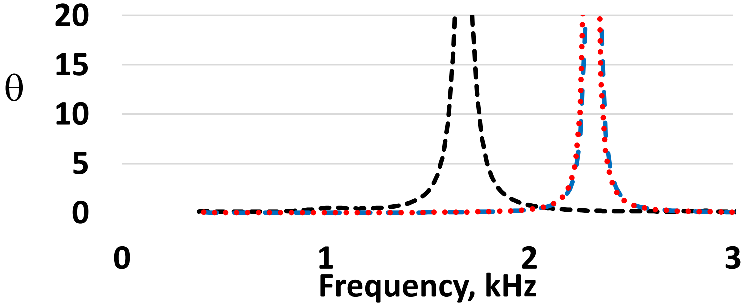
Modified Motsinger and Kraft facesheet perforate model

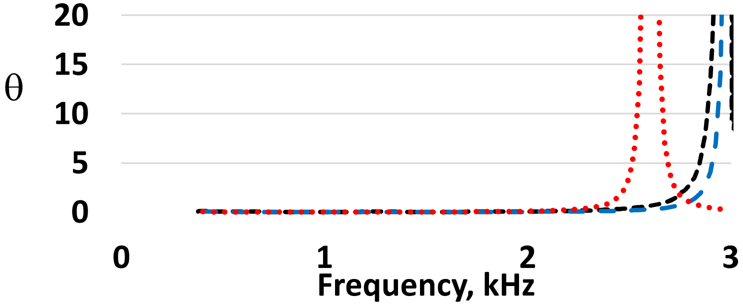
$$\zeta = \frac{a\mu\{\alpha t\}}{2\rho c(\{\gamma\sigma\}C_D)\{\beta d\}^2} + \frac{\kappa_i + \kappa_e}{2c(\{\gamma\sigma\}C_D)} v_{rms} + \frac{M_{C/L}}{\{\gamma\sigma\}\{2 + 1.256(\delta_1/\{\beta d\})\}} + i\left\{\frac{k(\{\alpha t\} + \epsilon\{\beta d\})}{\{\gamma\sigma\}} - \cot(kh)\right\}$$

where $\alpha = 0.73$, $\beta = 0.90$, $\gamma = 0.98$

  - Corrections for bent chambers







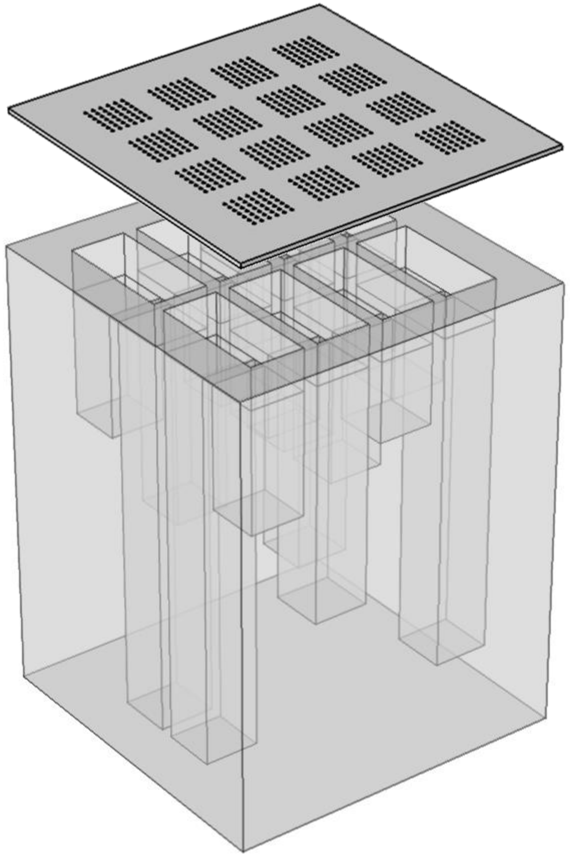
Meas, 120 dB — Pred, L_C
Meas, 140 dB — Pred, L_{Ave}

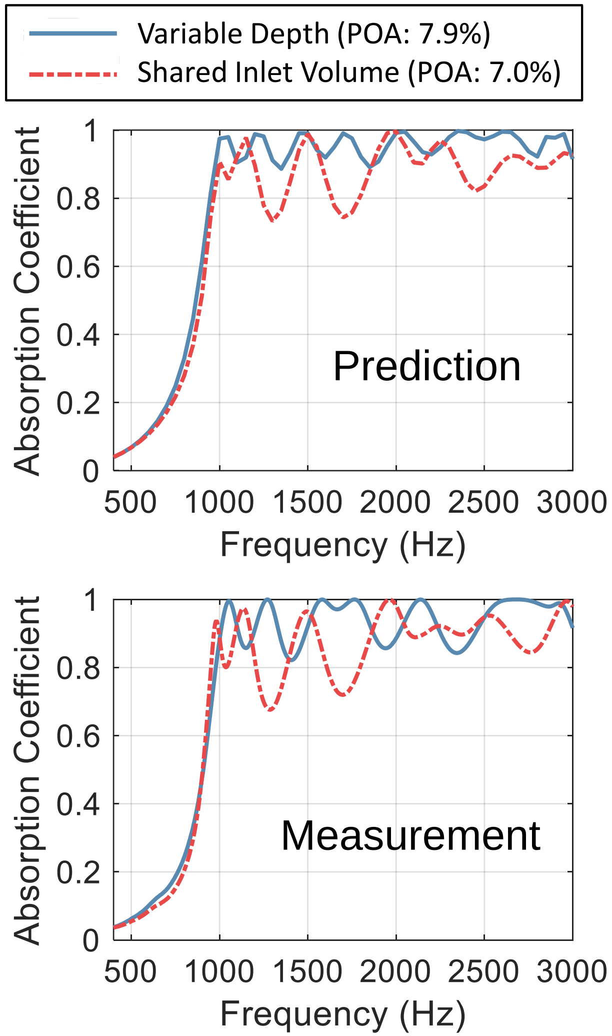
Slot height < cell diameter → poor prediction
Slot height > cell diameter → good prediction

Simulation – Liner Modeling

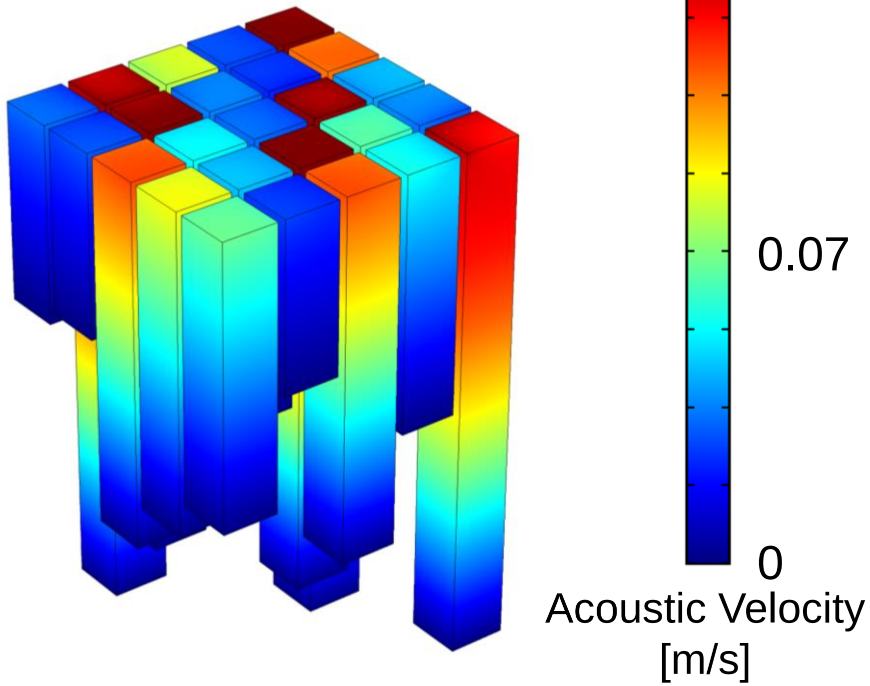
- Simulation using COMSOL/ACTRAN
- High fidelity models provide insight on liner physics

Shared inlet liner



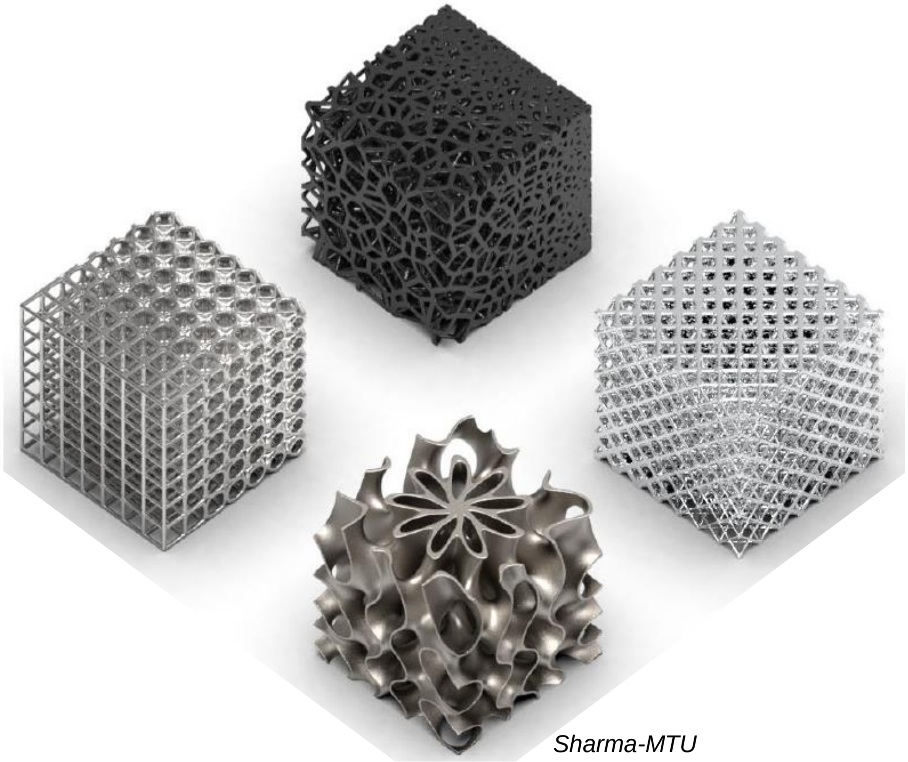


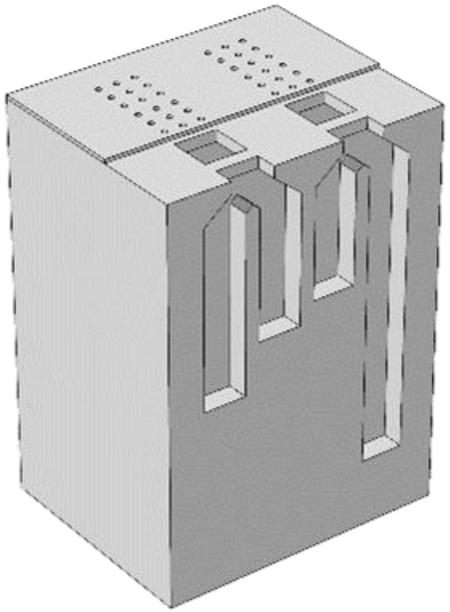
Variable depth liner

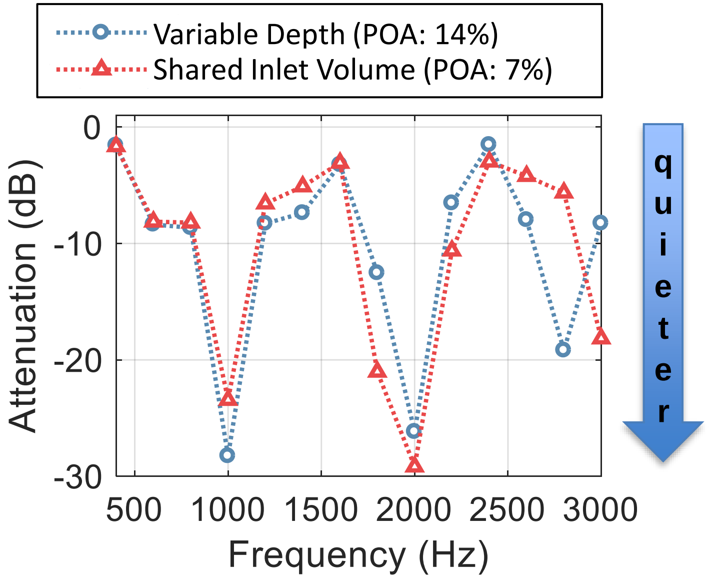


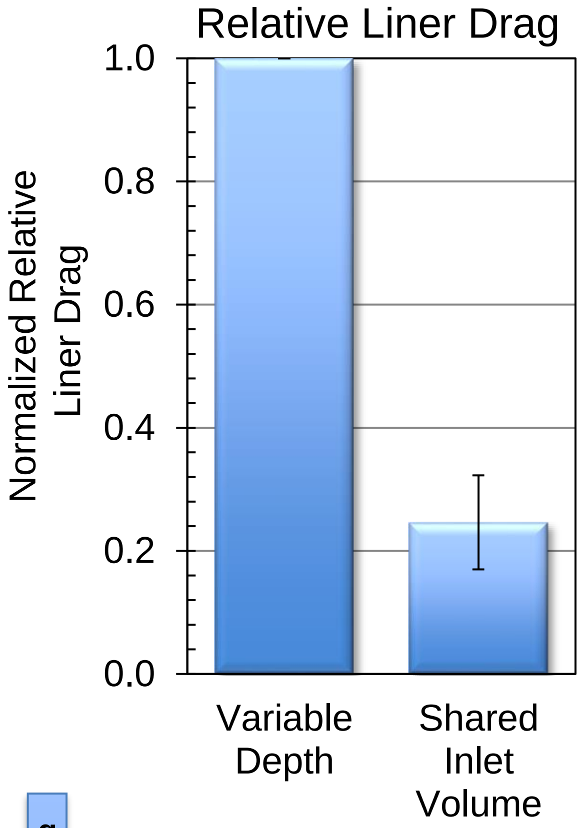
Accurate liner models are *REQUIRED* for design applications and optimization

Liner Concepts: Low TRL









Triply Periodic Minimal Surfaces

- parametric studies to relate properties to impedance
- broadband absorption
- fit into small spaces
- SAA w/ Michigan Technological Univ.

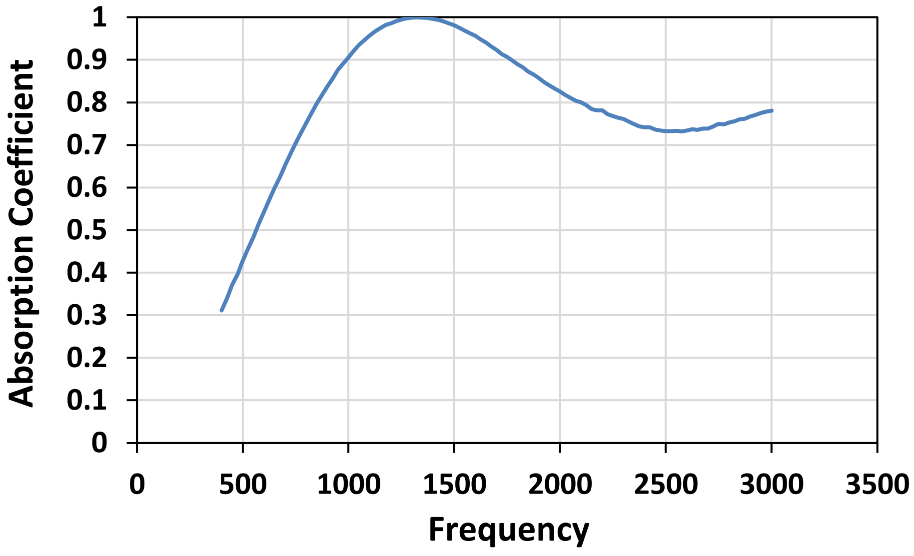
Shared Inlet

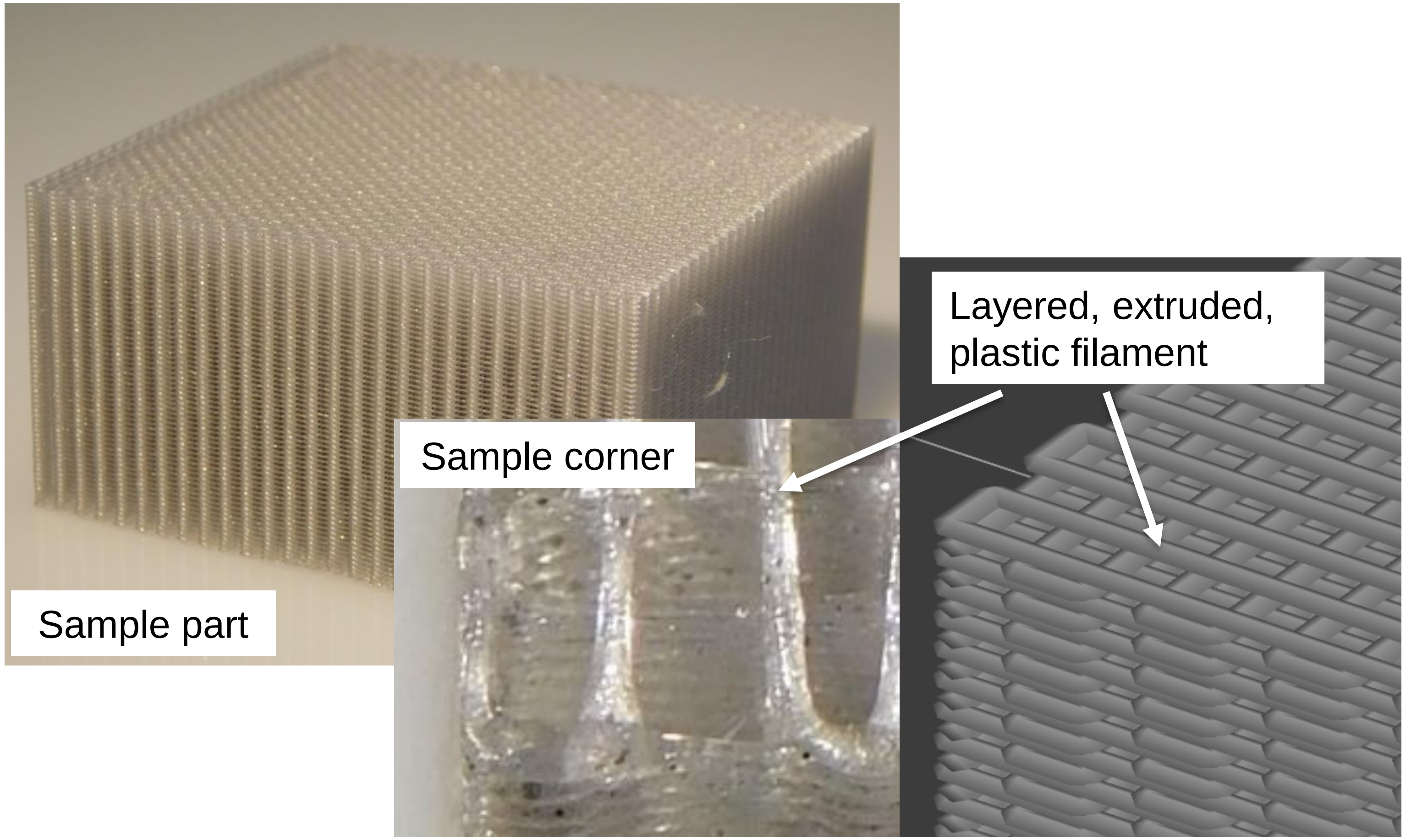
- low drag
- lower cost
- comparable acoustic performance (re:variable)

Liner Concepts: Low TRL – Additive Bulk

Goal: Develop additively-created, bulk absorbers with controllable acoustic properties

- Vary spacing of layer lines in FDM-printed liner samples
- Spacing used to control porosity and tortuosity of material
- More consistent than traditional, fiber-based bulk materials



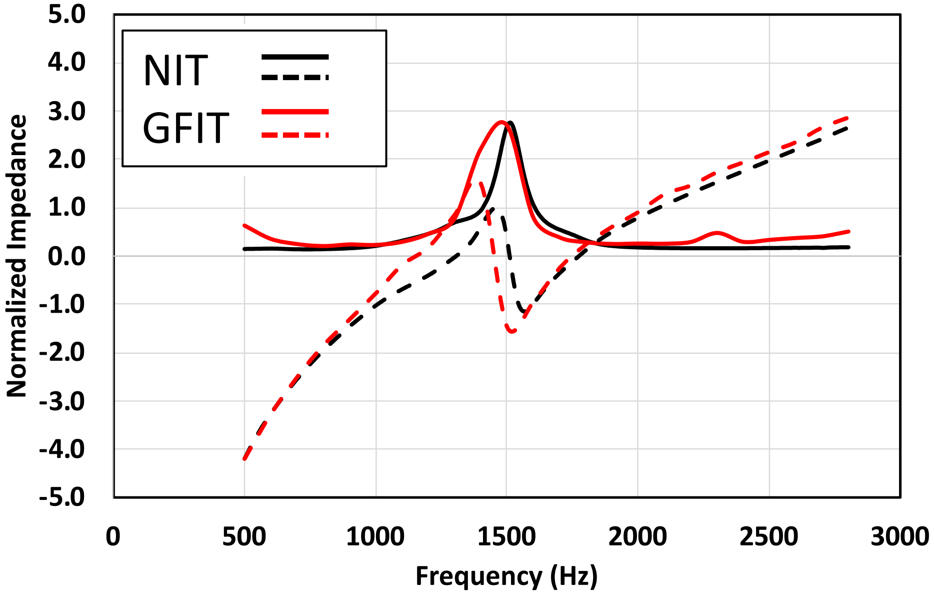


- Initial samples show promise
- Broadband absorption behavior
- Need parametric study to develop impedance model

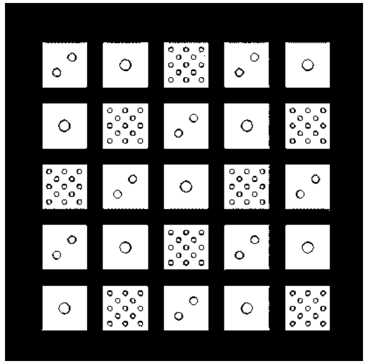
Liner Concepts: Low TRL – Distributed Facesheet

Goal: Accurately modify liner impedance via variation in facesheet porosity

- Variable porosity/perforation over SDOF core
- Tested in the NIT (no flow, normal incidence) and GFIT (w/ flow, grazing incidence)
- Good comparison of measured data and predictions (CHE)
- Brown et al. *AIAA 2021-2243*
- Next step → use optimizer to explore performance limits

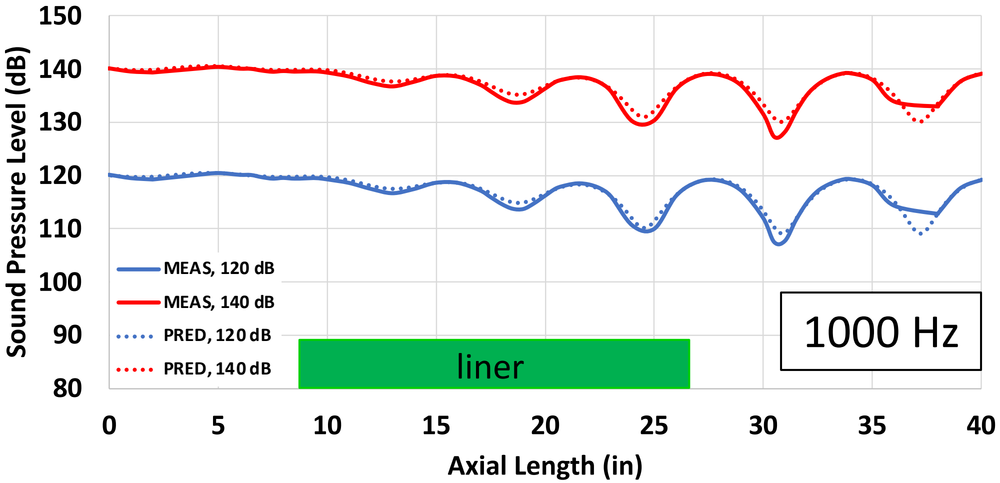


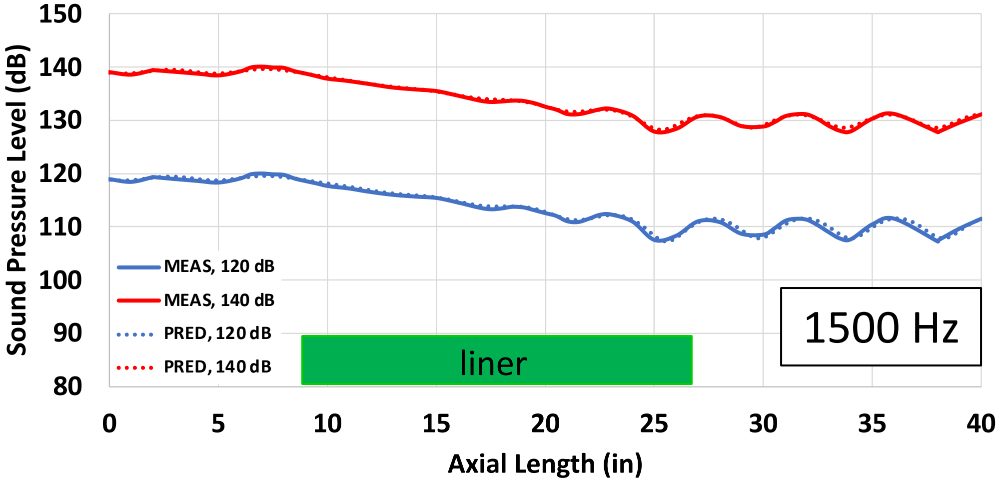
Sample facesheet



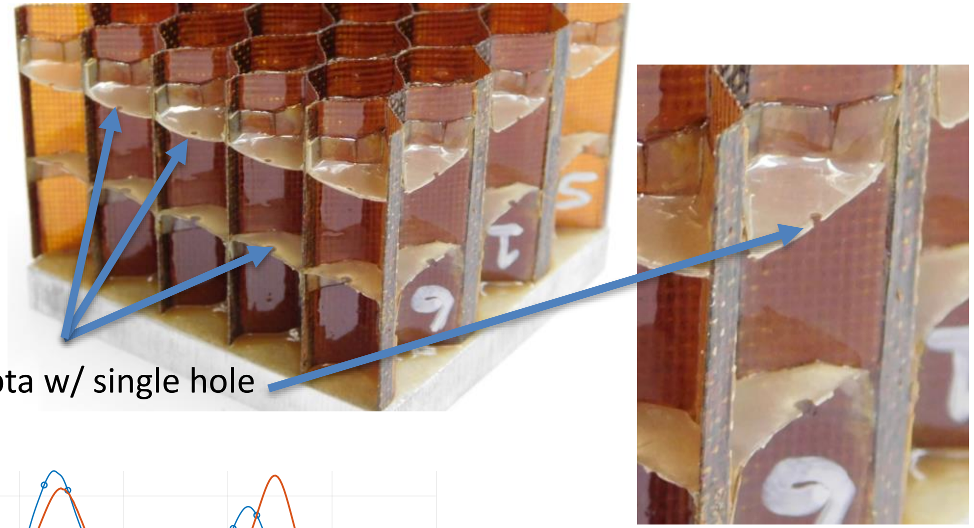
Cell-to-cell variation in porosity, hole size and distribution

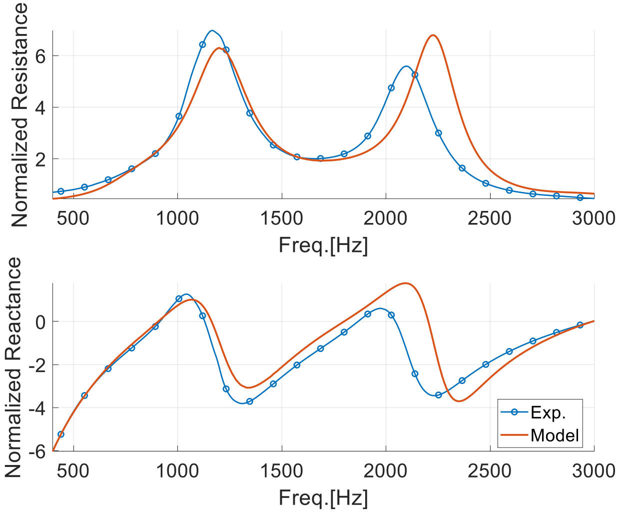
Predicted vs. Measured SPL, M=0.3

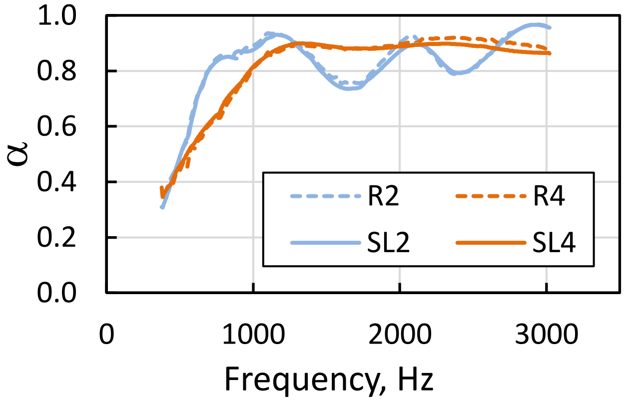


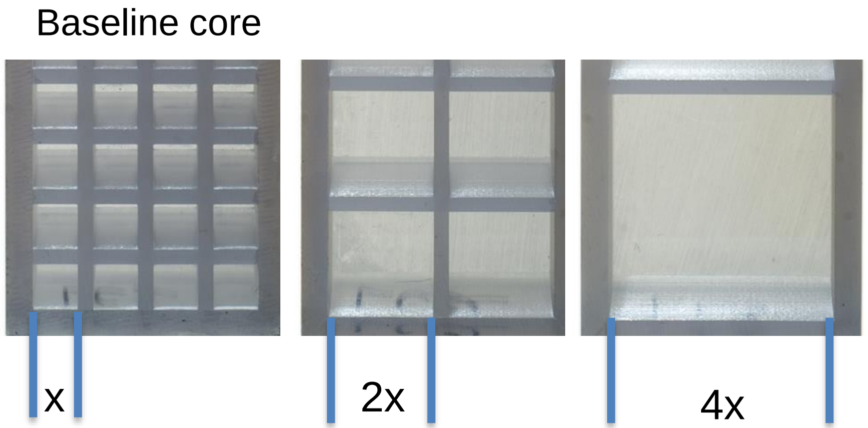


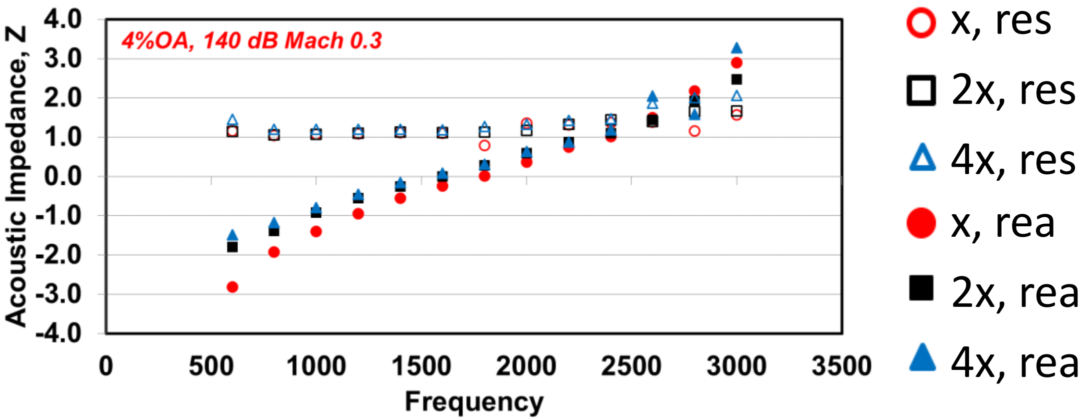
Liner Concepts: Low TRL – Simplified Septa and Large Core











Simplified Septa

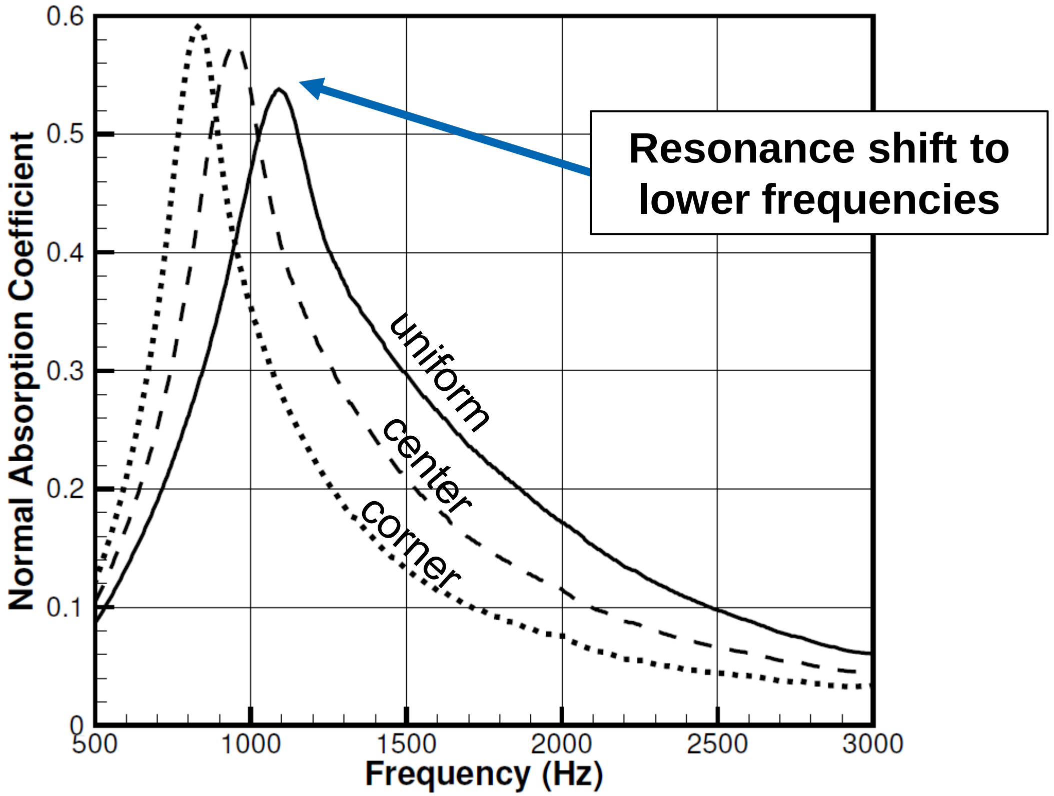
- extend bandwidth
- reduce complexity
- low frequency absorption

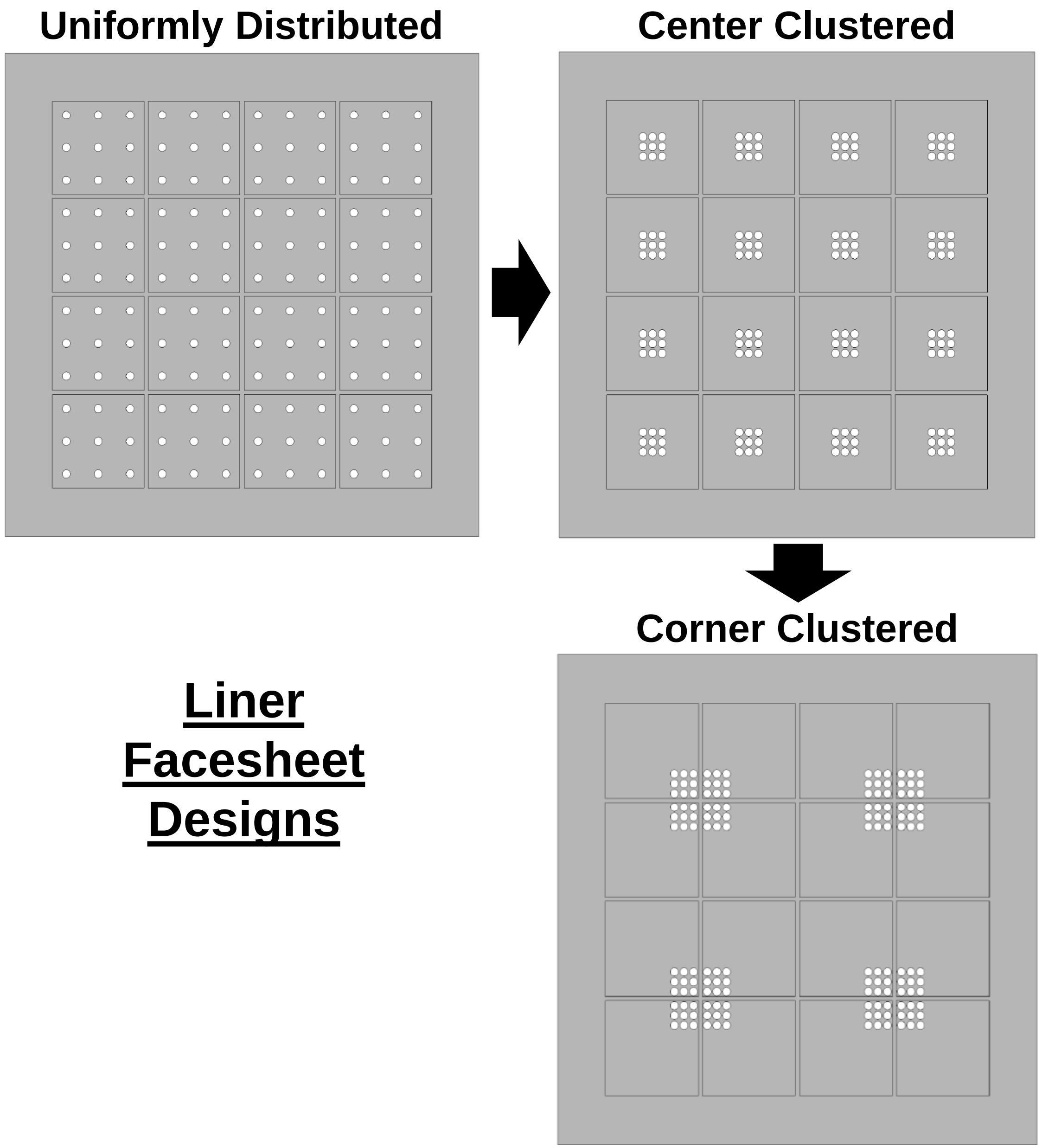
Large Core

- reduce weight/cost
- minimal acoustic impact

Liner Concepts: Low TRL – Hole-Clustered Facesheet

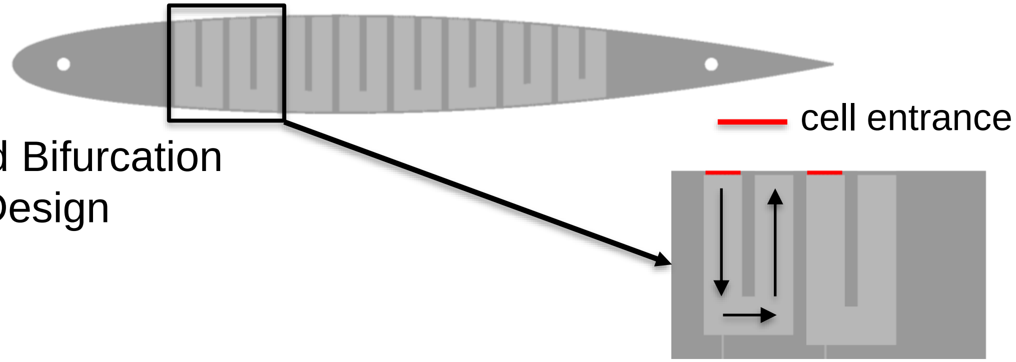
- Hole clustering *lowers* resonant frequency through mutual radiation effects
- Clustering near common chamber corners further *lowers* resonance
- Reactance control at minimal expense to resistance
- Testing shows 300+ Hz reduction in resonant frequency





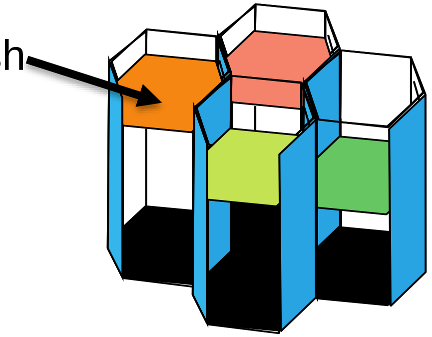
Liner Facesheet Designs

Liner Concepts: Mid TRL



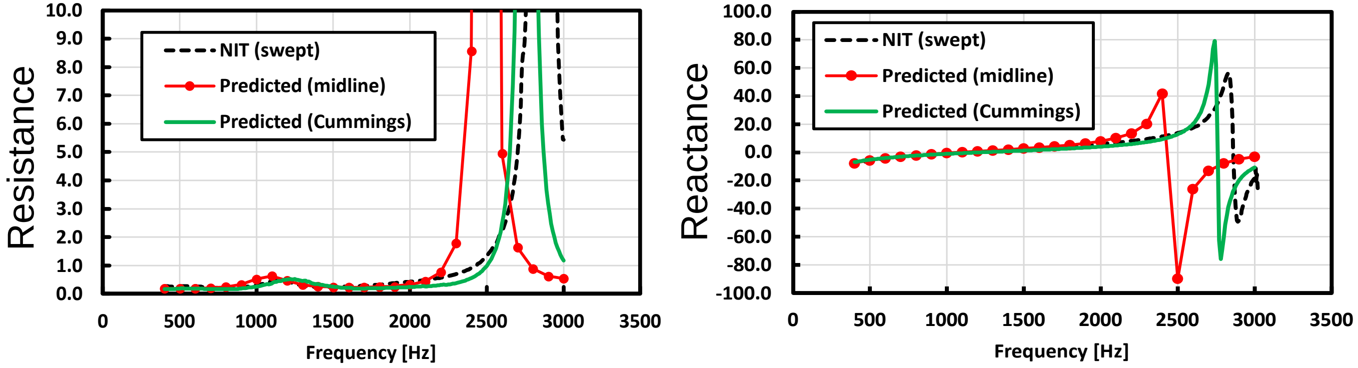
Treated Bifurcation Design

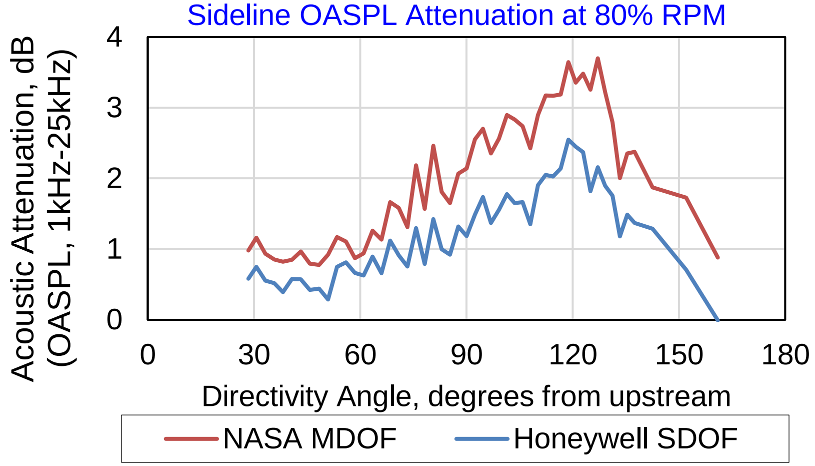
test sample



Mesh Cap MDOF core

Normal Incidence Tube Results – 140dB tones





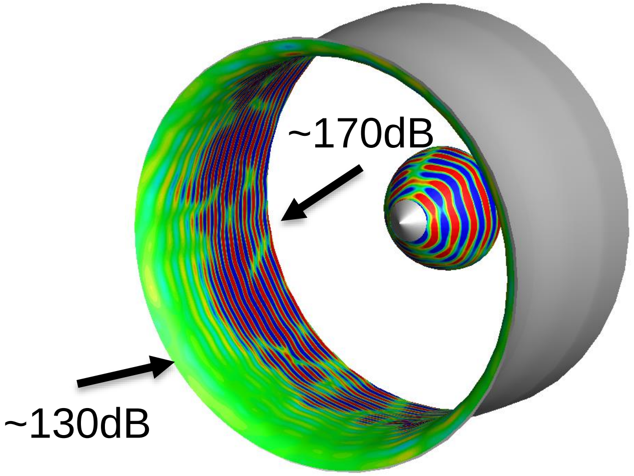
Bent Chambers

- low frequency/broadband
- compact packaging
- modeling issues

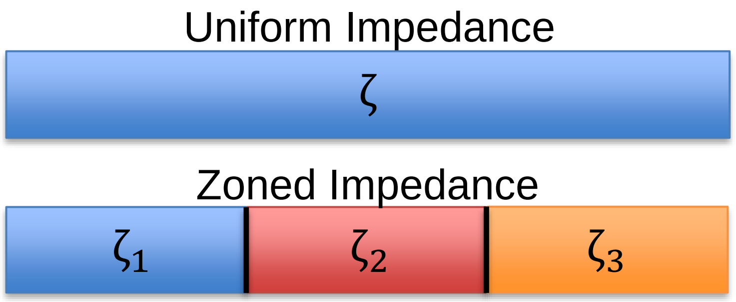
Mesh Cap MDOF

- broadband absorption
- flightworthy construction
- increased cost (rel: 2-3DOF)

Liner Concepts: High TRL



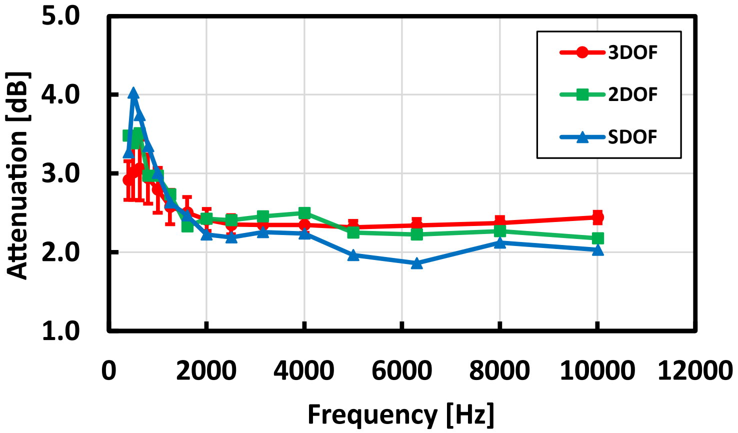
Issue: Axial variation in optimal impedance due to changing SPL



Zone Liner

- account for varying SPL in engine
- lower cost rel: 2–3DOF?

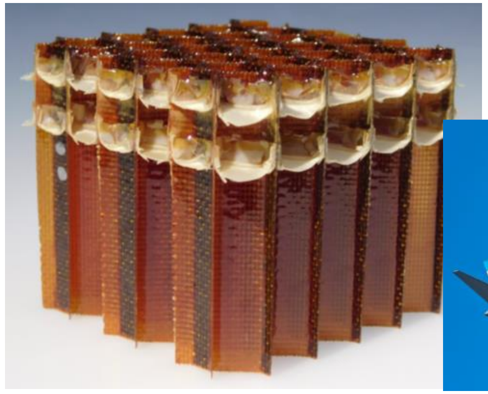
2DOF Liner Core



Optimized Mesh Cap 2DOF

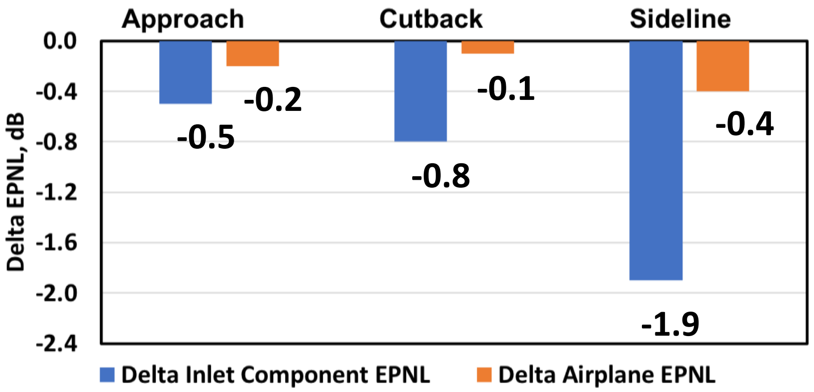
- can be similar to 3DOF
- lower cost
- flight ready

3DOF Liner Core



NASA/Boeing

3DOF Liner Performance: B737 Max

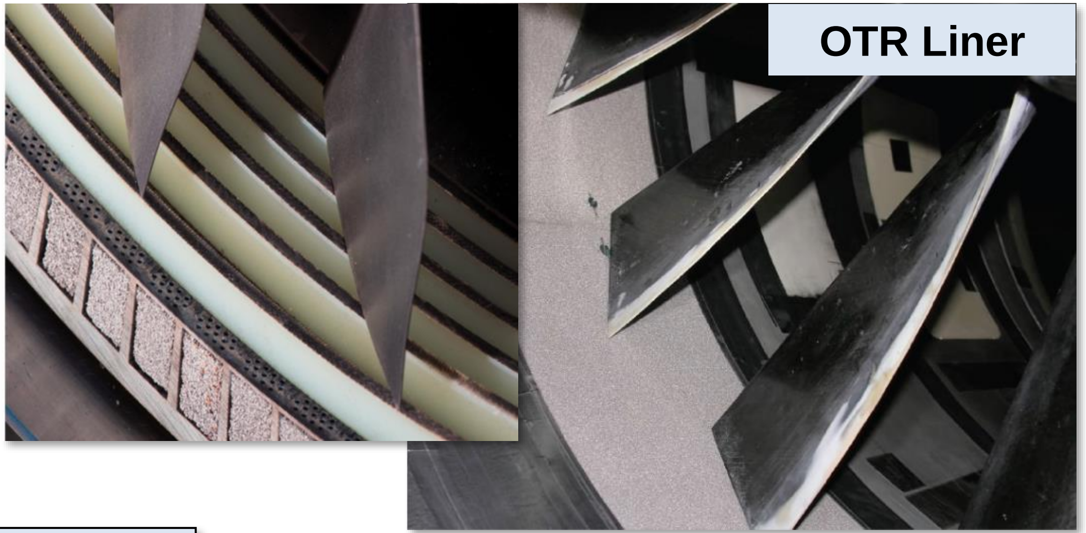


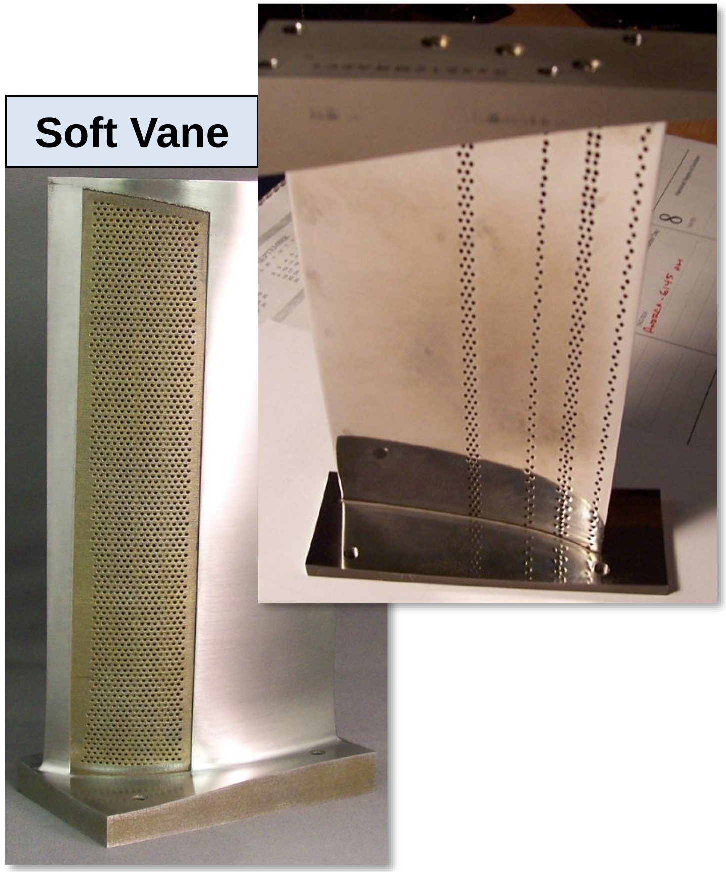
Optimized Mesh Cap 3DOF

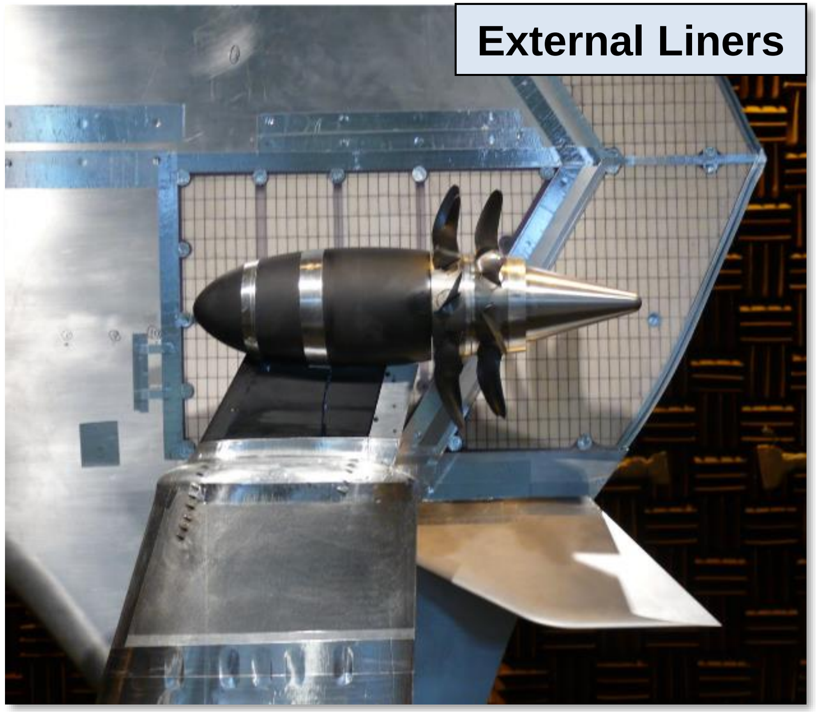
- broadband absorption
- flight ready

Liner Concepts: Advanced Applications

- Over-the-rotor (OTR) liner
- Treated bifurcations
- Soft vane
- External liners







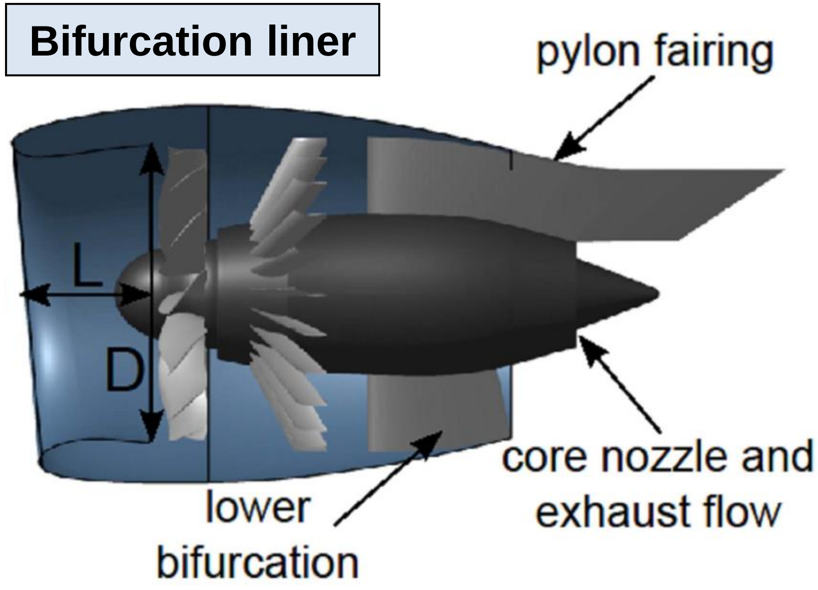


Photo credits: NASA GRC and Boeing

Liner Concepts: Low-Drag Facesheets

Goal: Minimize liner drag to reduce treatment impact on fuel burn

- Measurements to get relative drag

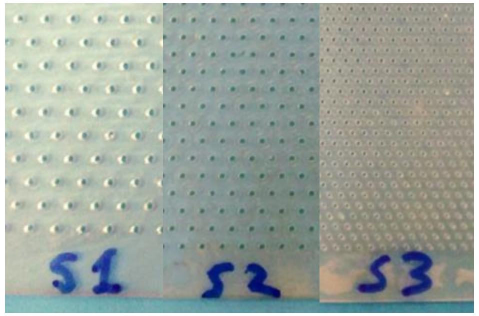
Resistance Factor: $$\lambda = \frac{dp}{dx}\frac{d_h}{q}$$

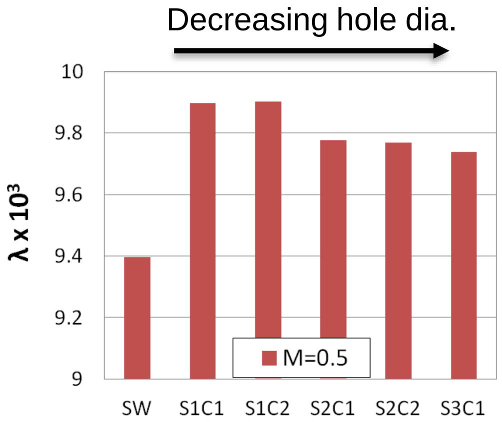
- Perforate effects

Factors for drag reduction:

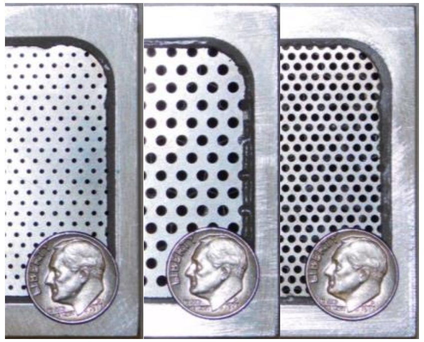
Smaller holes

Percent Open Area (POA) = 8%

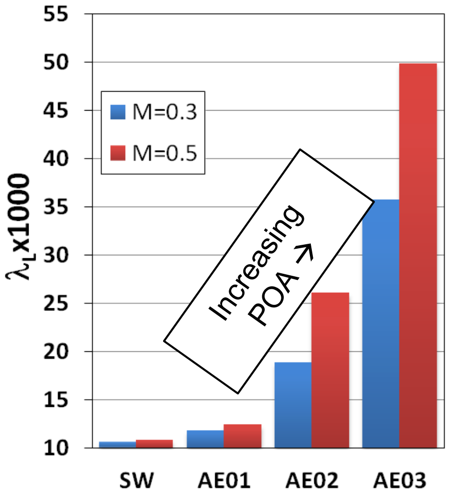




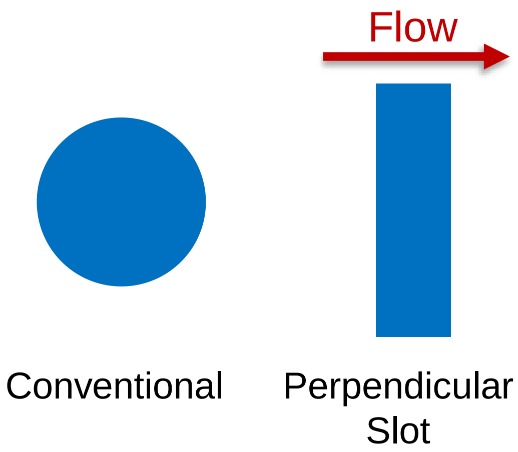
Reduce POA

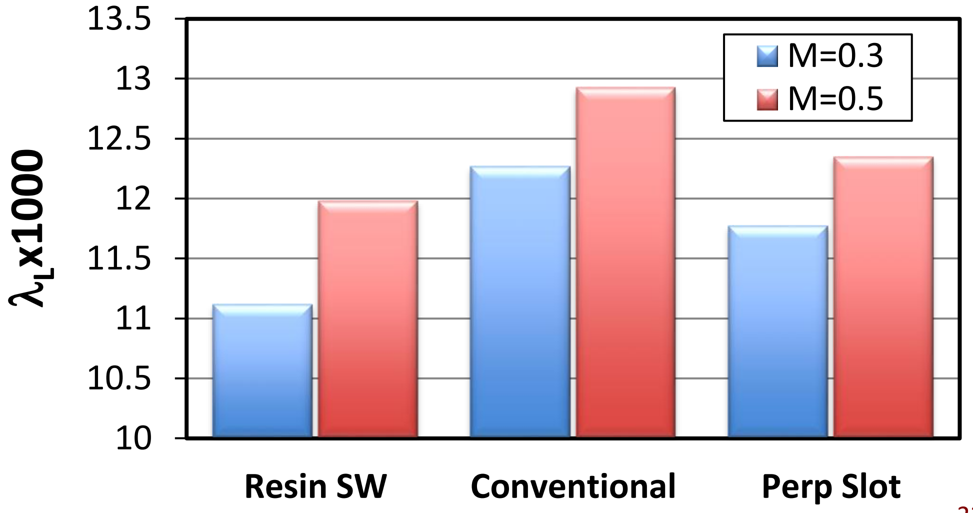


AE01 AE02 AE03



Modify perforate shape

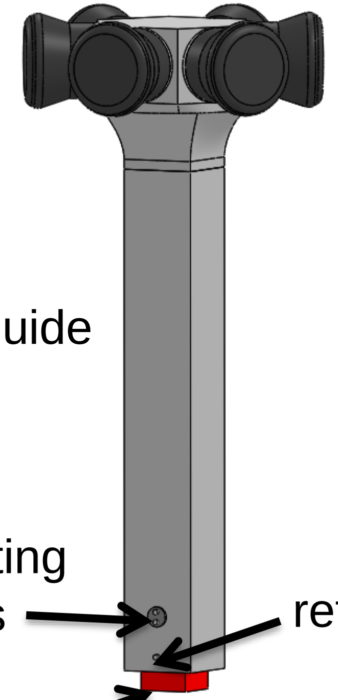




Evaluation – LTF Rigs, No Flow

Normal Incidence Tube (NIT)

TRL 2

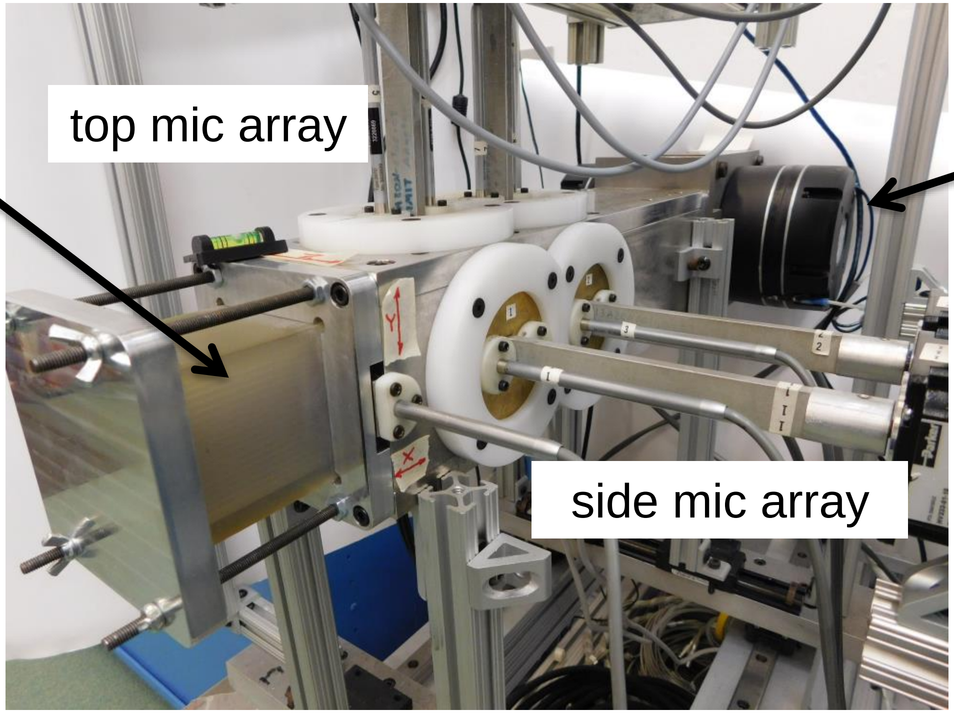


Capabilities: 160dB, 400<f<3000Hz, acoustic measurements

- Verify liner design models
- Evaluate new concepts

High Intensity Modal Impedance Tube (HIMIT)

TRL 2.5



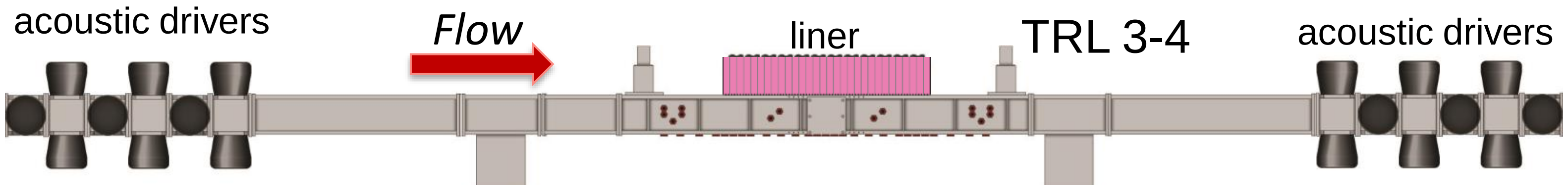
Capabilities: 165dB, 400<f<6000Hz, acoustic measurements

- Higher SPL/Freq (more realistic)
- Acoustic modes present

LINER TECHNOLOGY FACILITY

Evaluation – LTF Rigs, With Flow

Grazing Flow Impedance Tube (GFIT)



Capabilities: 0<M<0.6, 160dB, 400<f<3000Hz, acoustics and drag measurements

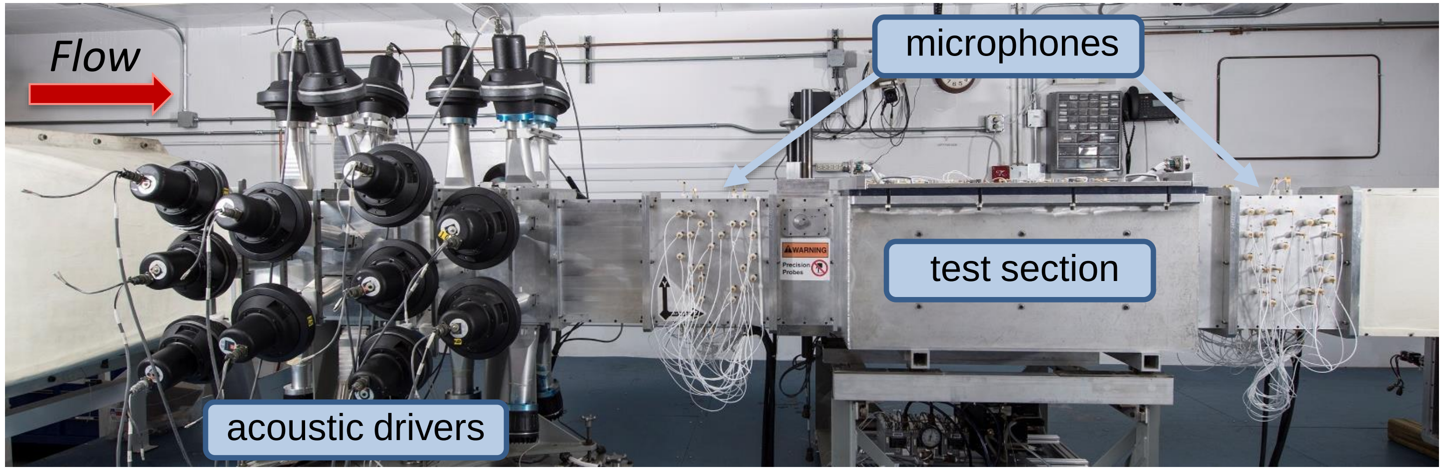
- Liner impedance characterization
- Drag performance of liners

LINER TECHNOLOGY FACILITY

TRL 4

- Evaluate configuration effects
- Complex acoustic environment
- Larger scale (~1/3 to 1/5) of FS engine
- Acoustic mode effects

Curved Duct Test Rig (CDTR)

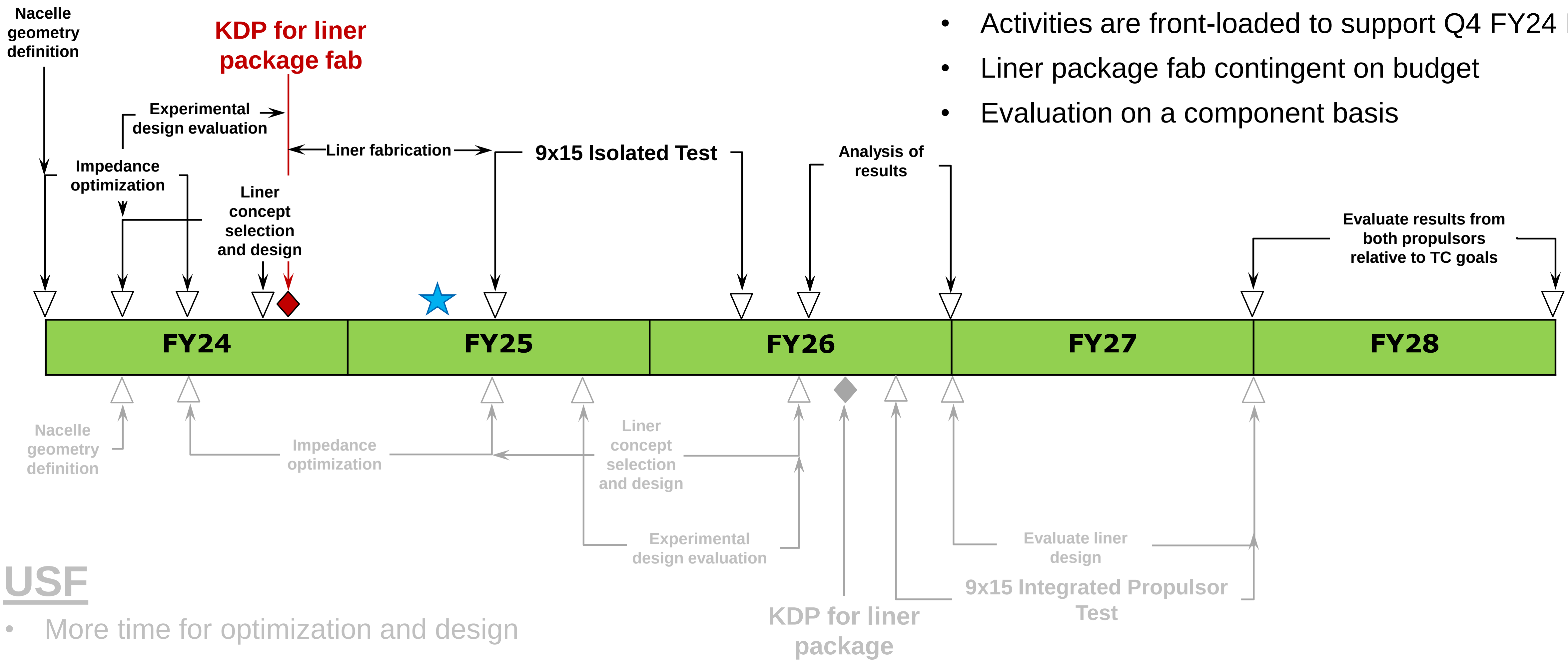


Capabilities: 0<M<0.5, 145dB, 400<f<2600Hz, acoustic measurements

Tech Challenge Activity Schedule

LPR

- Activities are front-loaded to support Q4 FY24 KDP
- Liner package fab contingent on budget
- Evaluation on a component basis



USF

- More time for optimization and design
- Currently planning 'virtual' liner design test
- Challenge to evaluate component benefit

★ Tentative static engine test for risk reduction and tool validation

Tech Challenge Activity Schedule

LPR

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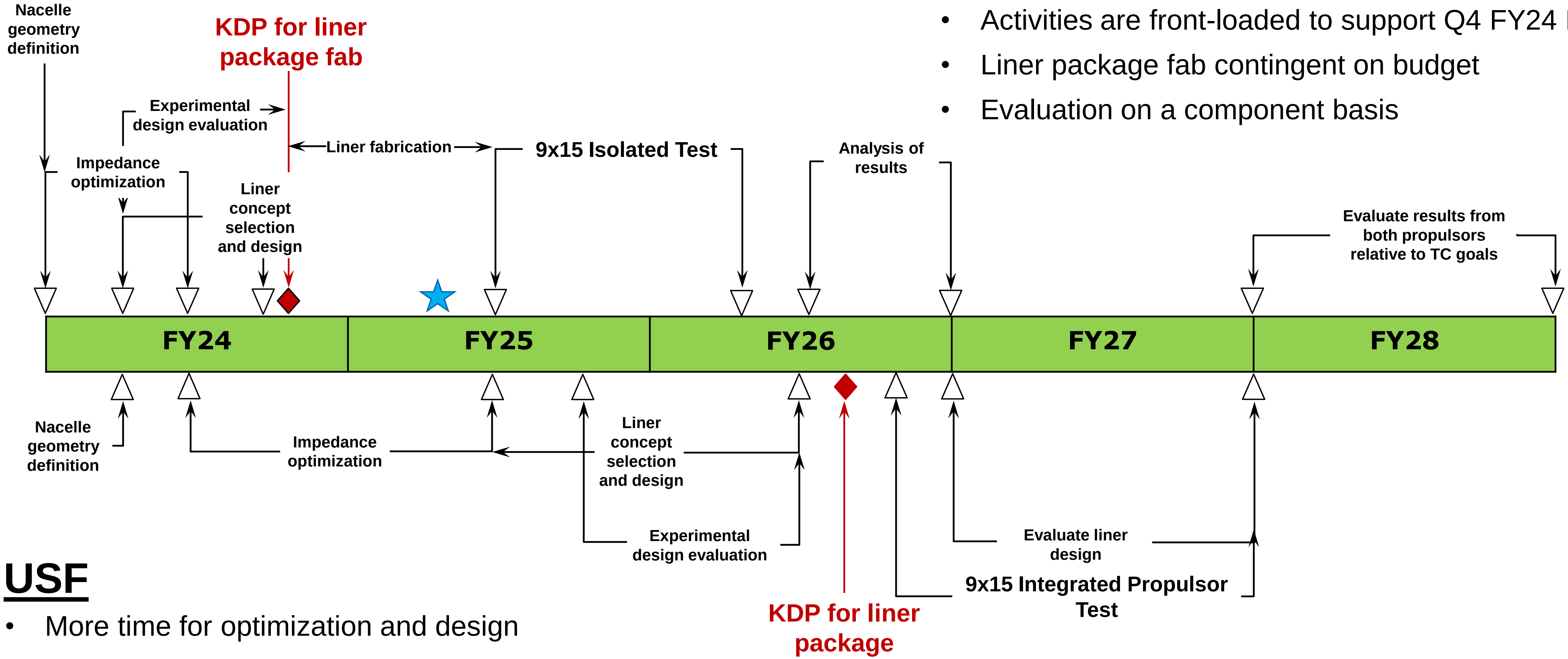


USF

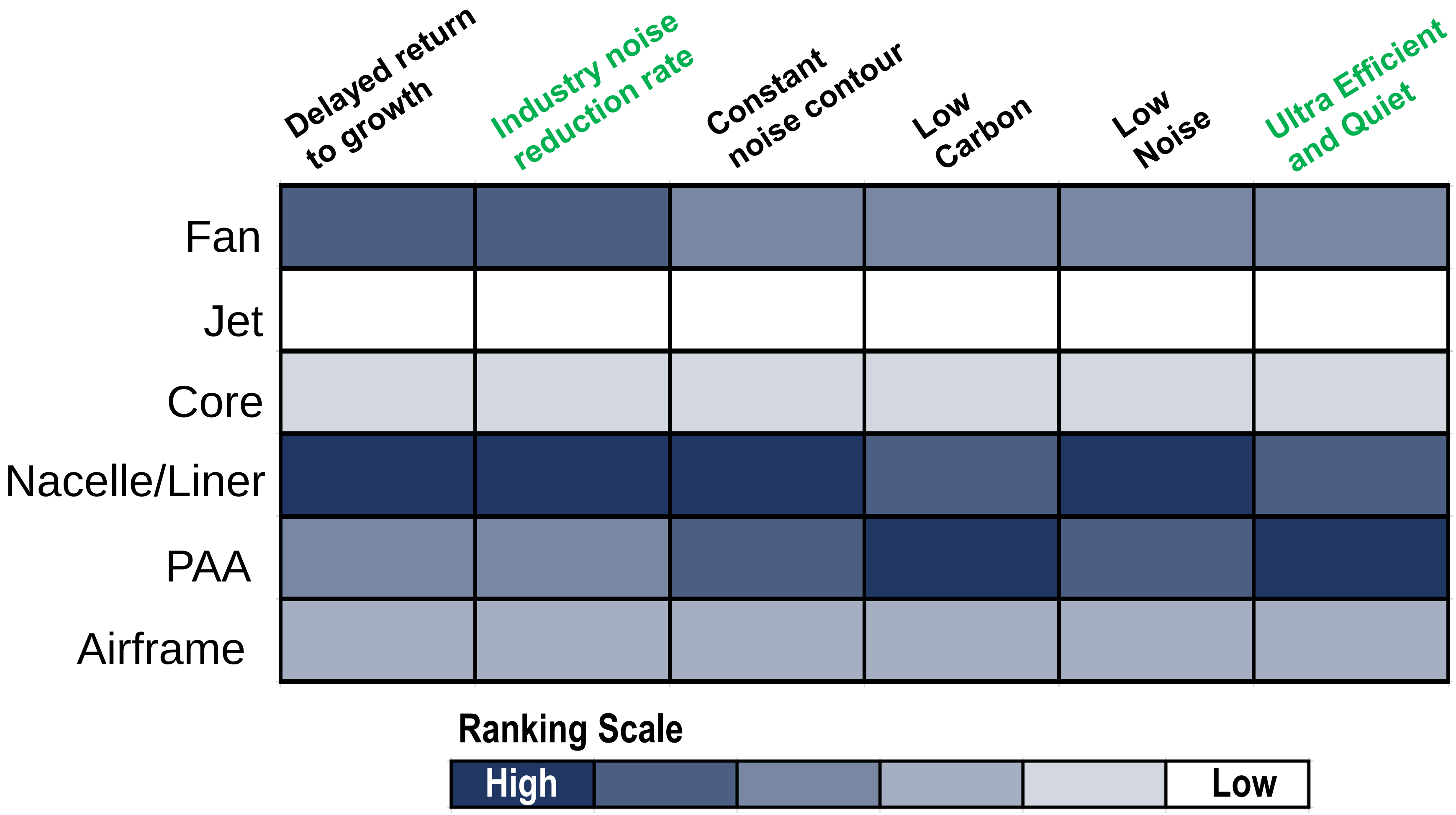
- More time for optimization and design
- Currently planning ‘virtual’ liner design test
- Challenge to evaluate component benefit

★ Tentative static engine test for risk reduction and tool validation

NASA

Backup Material

AOA Study: Investment Area Rankings



- High rankings for importance of nacelle/liner and fan work
- Open fan configurations pose new challenges to meet noise requirements
- Propulsor design trends generally hinder noise reduction efforts

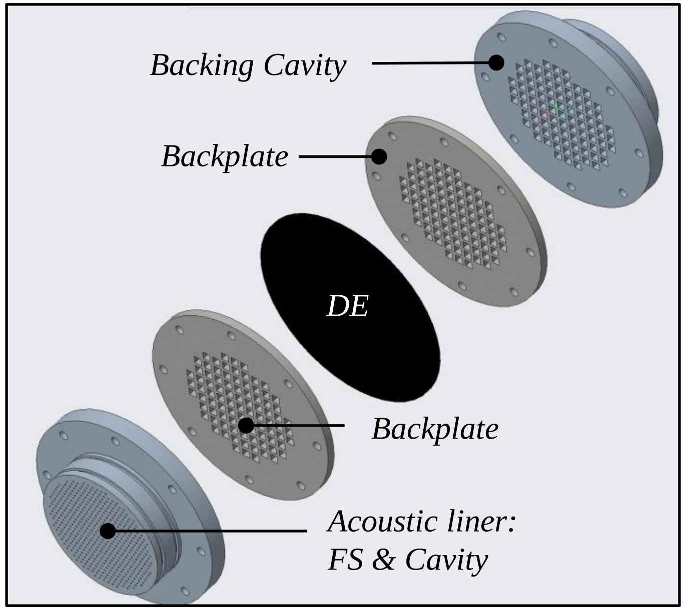
Further effort required to advance technologies for continued noise reduction

Liner Concepts: Low TRL-DEAL

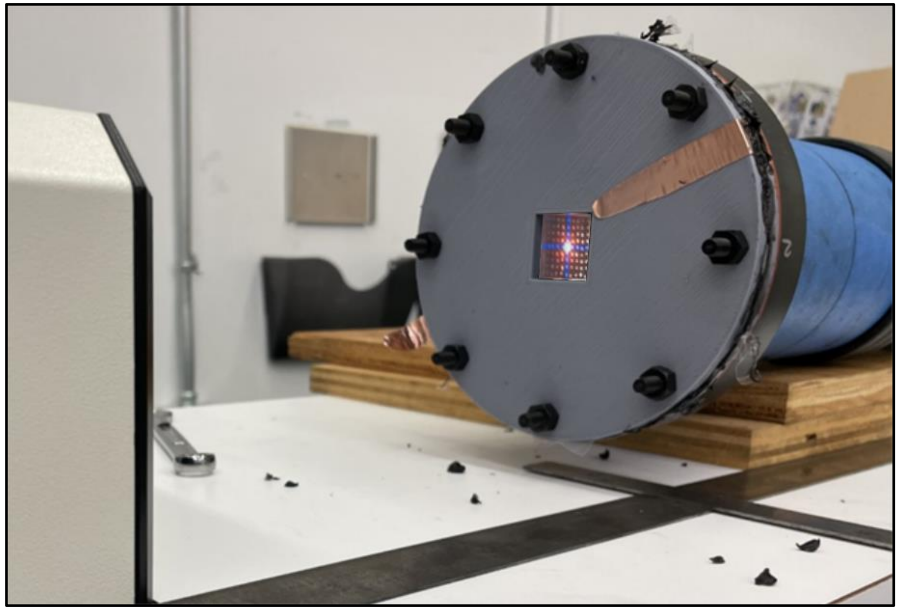
Goal: Investigate Dielectric Elastomer Acoustic Liner (DEAL) concept to actively vary liner impedance

- Dielectric elastomer (DE) embedded septa
- Impedance variation by changing elastomer compliance via voltage
- Laser vibrometer tests to characterize elastomer response
- Next Step → validate DE response model for DEAL optimization

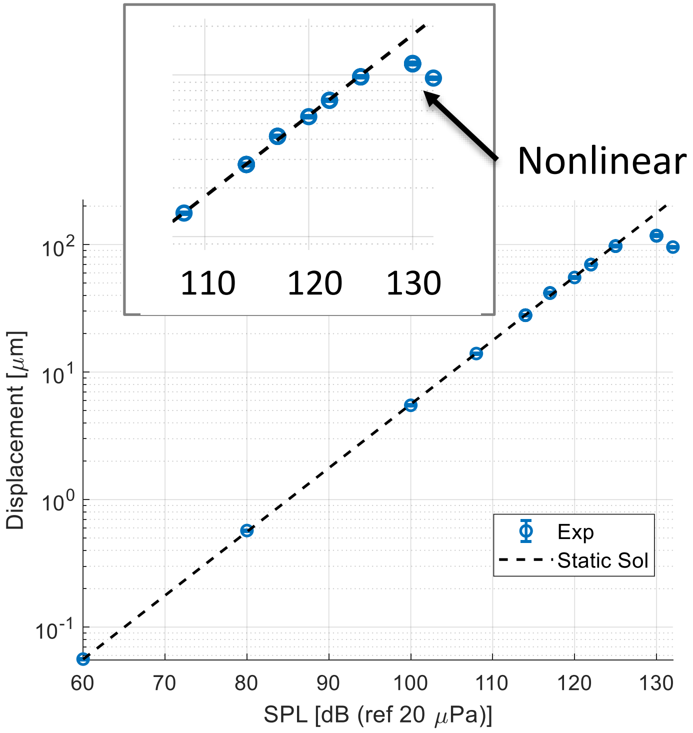
Embedded Dielectric Elastomer



Laser Vibrometer Testing



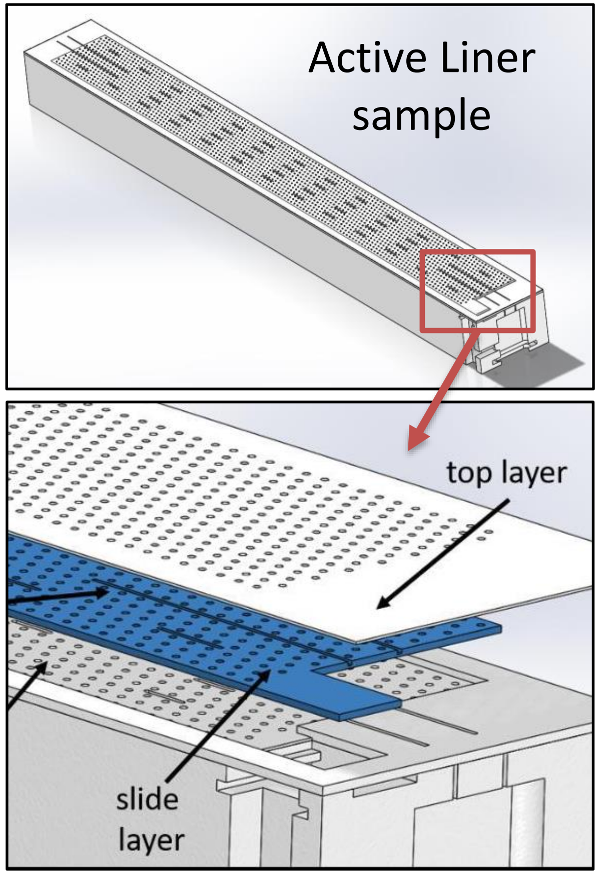
Elastomer Displacement vs. SPL



Liner Concepts: Low TRL-Active Liner

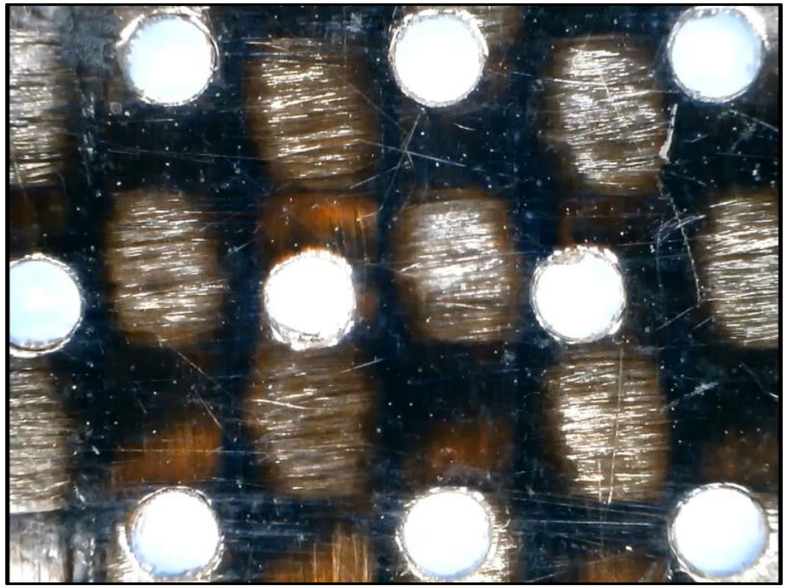
Goal: Evaluate active liner to control impedance/reduce drag

- Controlled, variable-porosity facesheet, ~10% POA
- Shape Memory Alloy (SMA) activated
- Follow-on work looking at gap effects between FS layers

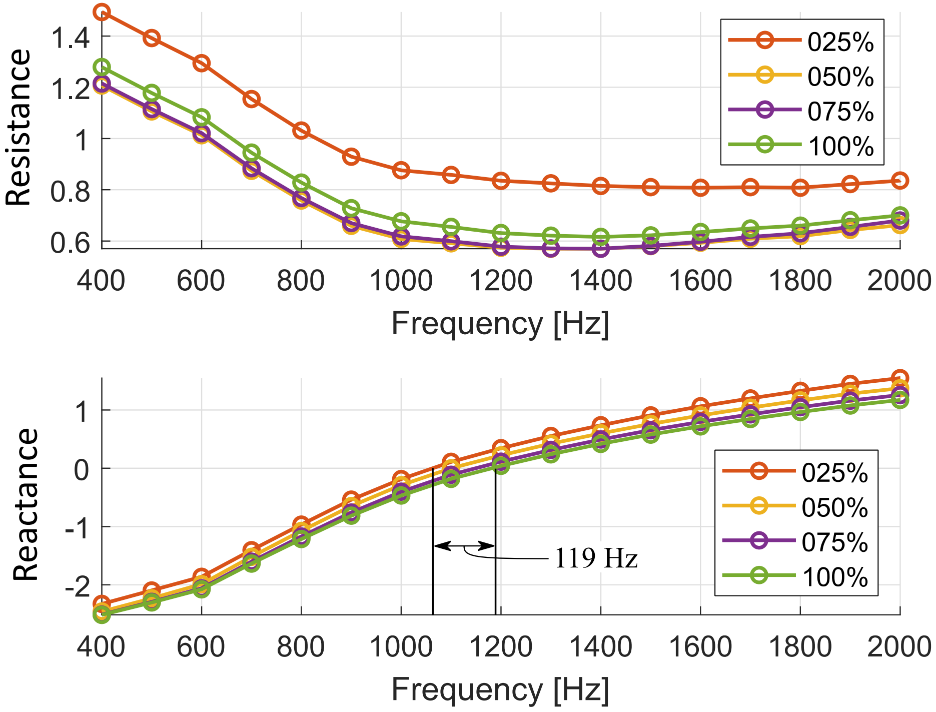


Preliminary result: Measurable effect on impedance, minimal effect on drag (no sound)

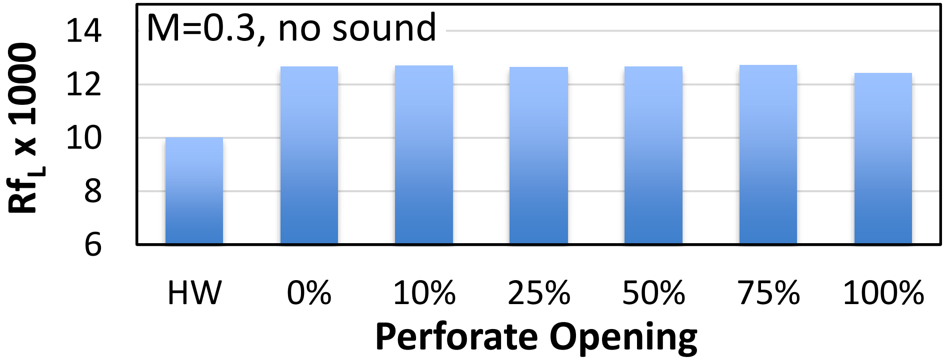
Magnification of FS perforation



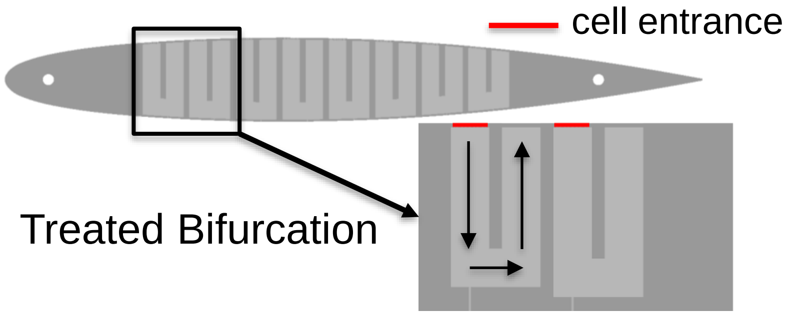
Impedance variation w/ Perforate opening

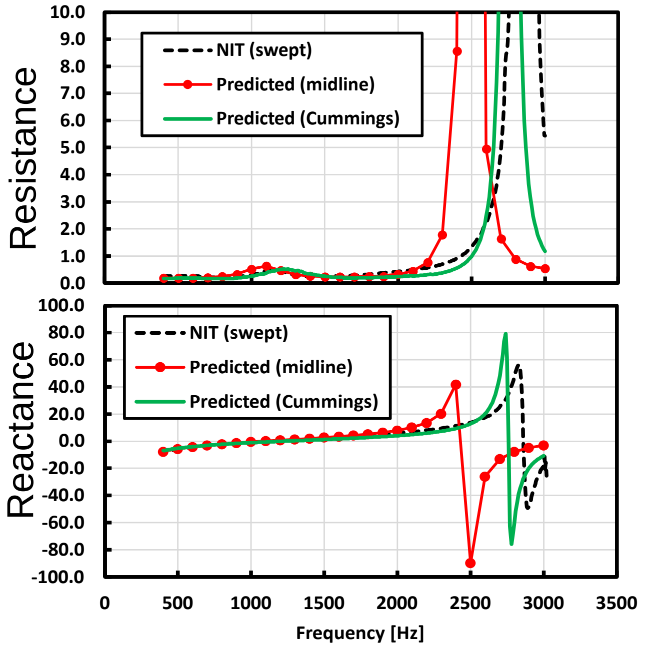


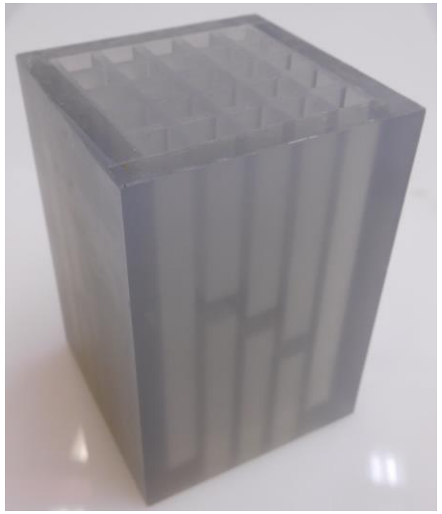
Resistance Factor vs. Perforate Opening



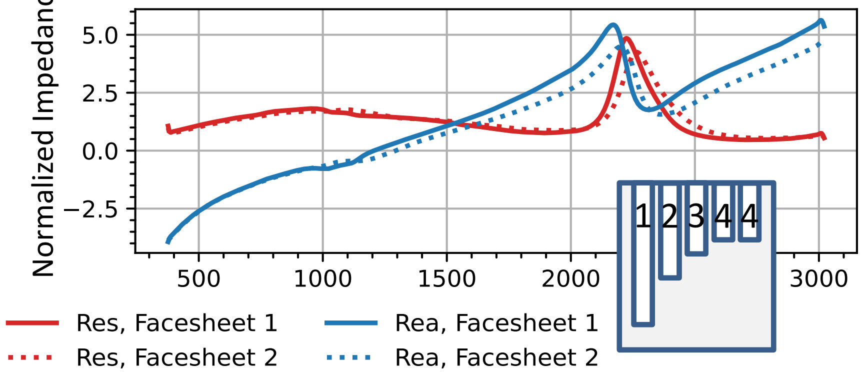
Liner Concepts – Mid TRL

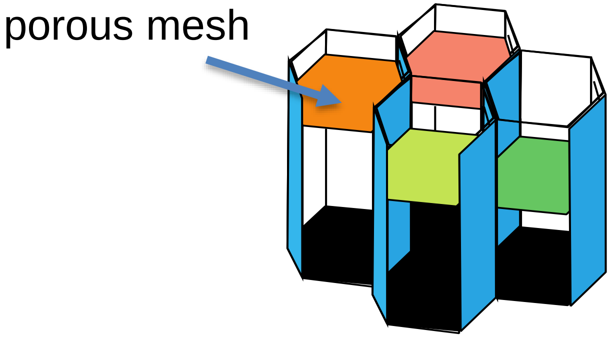




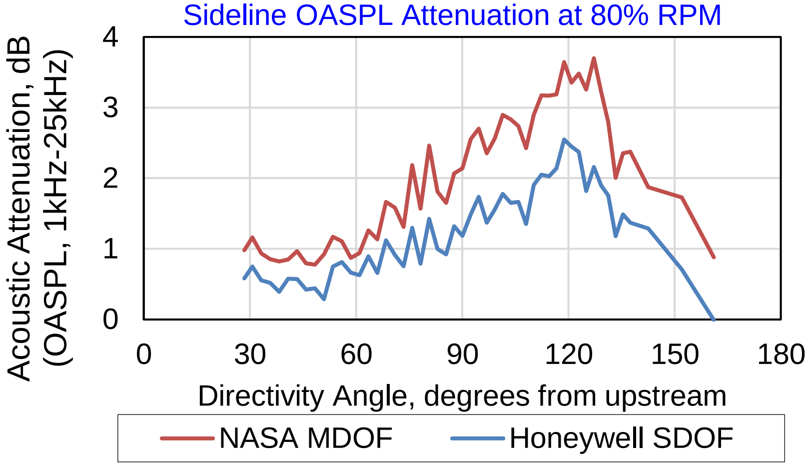


Variable Depth





Mesh Cap MDOF core



Bent Chambers

- low frequency/broadband
- compact packaging
- modeling issues

Variable Depth

- greater freq. tuning
- wide applicability

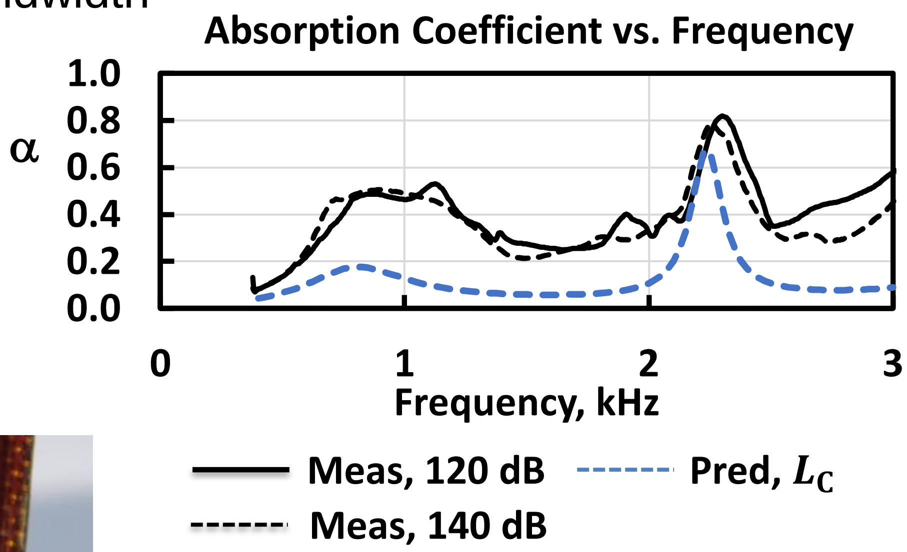
Mesh Cap MDOF

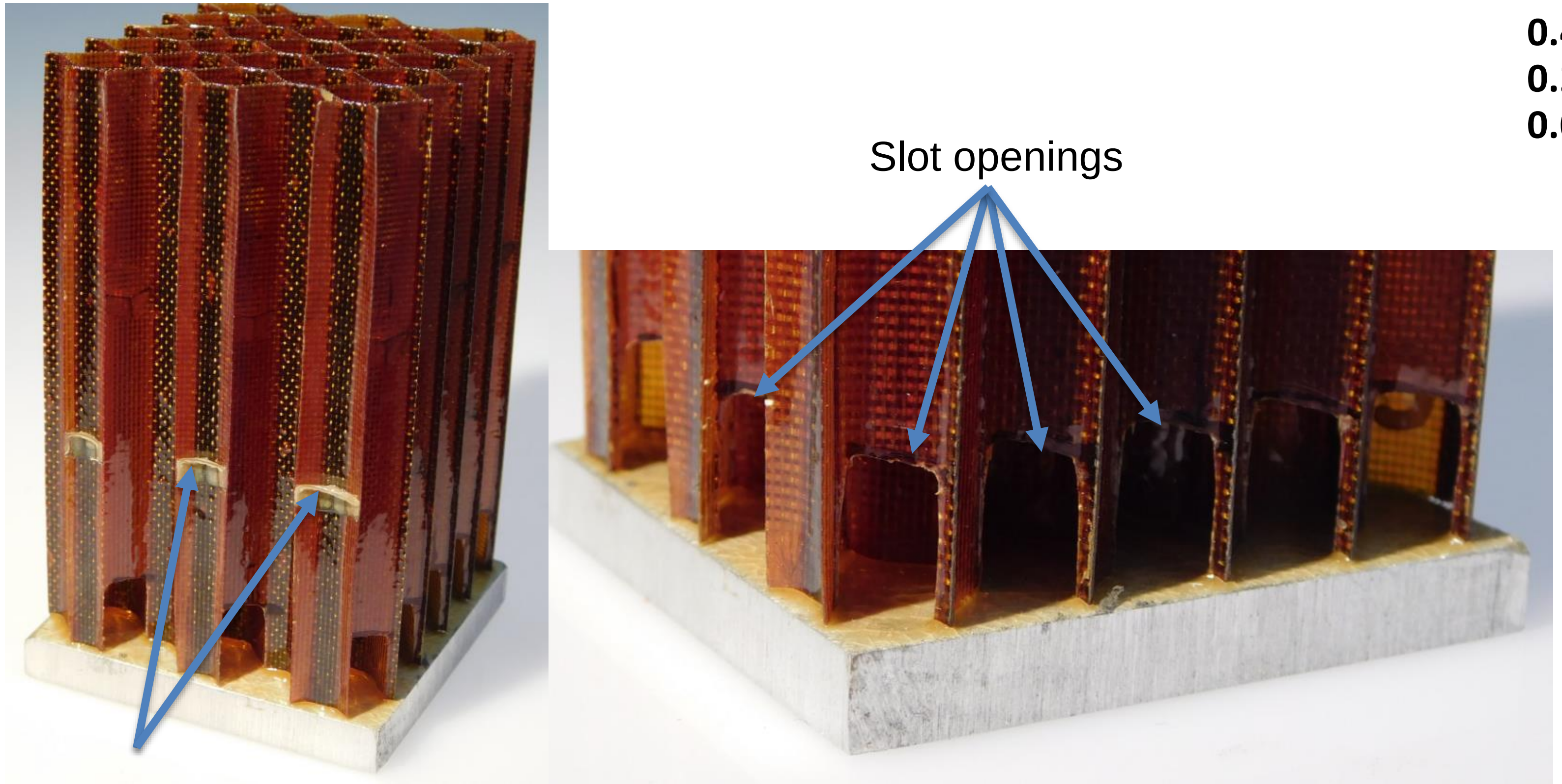
- broadband absorption
- flightworthy construction
- increased cost (rel: 2–3DOF)

Liner Concepts: Low TRL-Slotted Core

Goal: Enable bent chamber variable depth liners using flight-ready methods

- Openings cut between adjacent cells of liner core
- Embedded partitions used to create variable depth for extended bandwidth and low frequency absorption
- Allows for more efficient packaging of deep liners





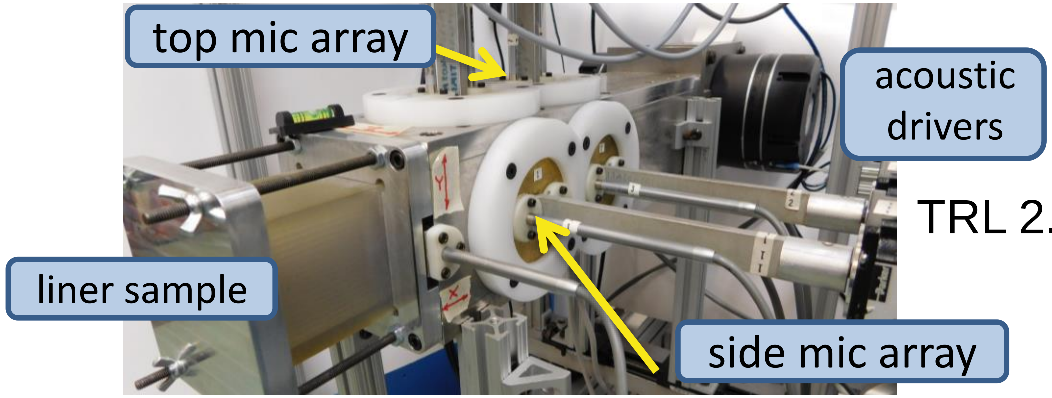
Embedded partitions

Evaluation - Liner Technology Facility

- Commissioned in 2009
- ~$10M investment
- ~20 tests/year
- ~$200k/year reimbursable work
- TRL 0 → 4
- Critical facility for US industry

LINER TECHNOLOGY FACILITY

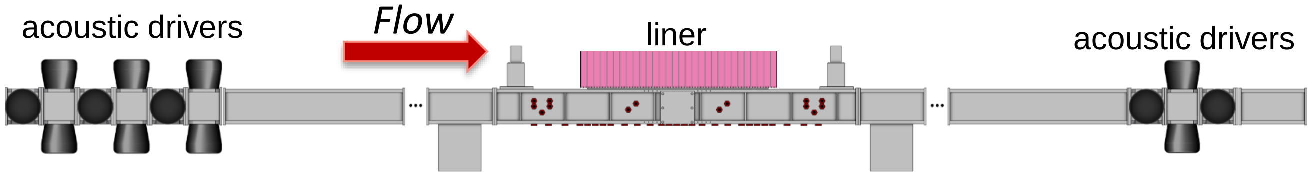
High Intensity Modal Impedance Tube (HIMIT)



TRL 2.5

- Higher SPL/Freq (more realistic)
- Acoustic mode effects

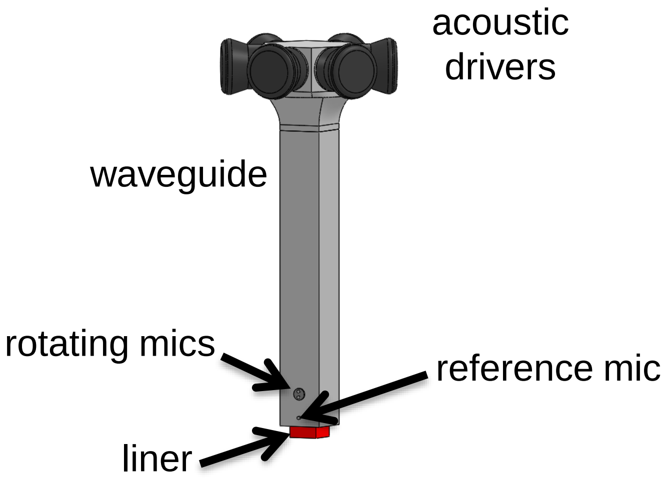
Grazing Flow Impedance Tube (GFIT)



TRL 3

- Simulates the flow and noise inside the engine
- Characterize the acoustic and drag performance of liners

Normal Incidence Tube (NIT)



- Verify liner design models
- Evaluate new concepts

Curved Duct Test Rig (CDTR)

- Evaluate configuration effects
- Complex acoustic environment
- Larger scale (~1/3 to 1/5) of FS engine
- Acoustic mode effects

TRL 4