Experimental Characterization of Acoustic Liners

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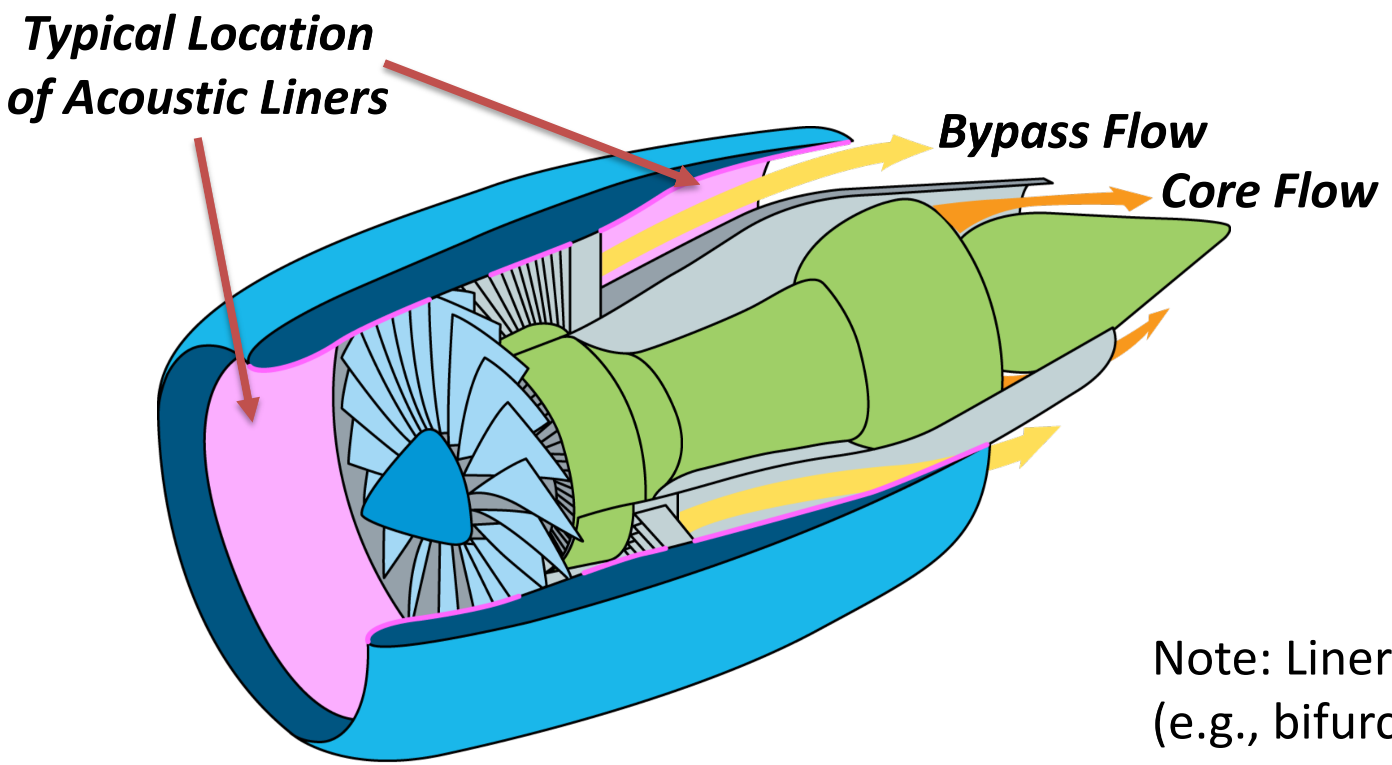
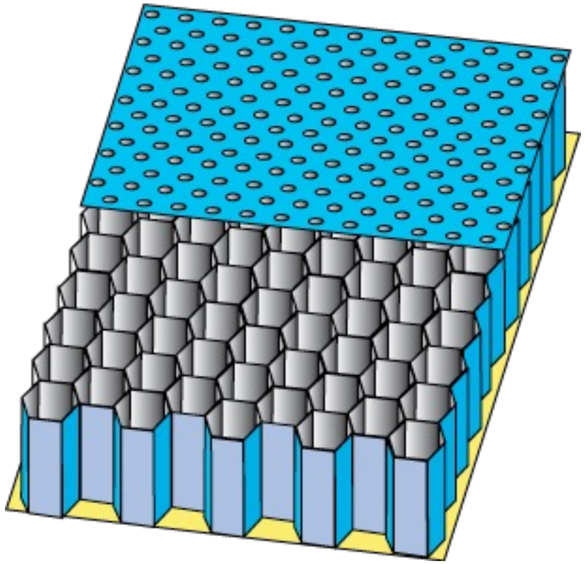
Acoustic Liners





Single Layer Liner

Note: Liners can be placed in other locations (e.g., bifurcation, fan exit guide vanes, landing gear door, wing, fuselage)

A liner is typically "defined" by its acoustic impedance, $\zeta = \theta + i\chi$

Outline

- Acoustic impedance, $\zeta = \theta + i\chi$

  What is it? Why should I care? What is a good impedance?
- Acoustic Liners
- Impedance eduction (NASA progression)
  - $\theta(0\ \mathrm{Hz})$: raylometer
  - $\zeta(f, \mathrm{SPL}; \mathrm{plane\ waves})$: normal incidence tube, NIT
  - $\zeta(f, \mathrm{SPL}; \mathrm{modes})$: high intensity modal impedance tube, HIMIT
  - $\zeta(f, \mathrm{SPL}, M)$: grazing flow impedance tube, GFIT
  - Verify via application in different environment: curved duct test rig, CDTR

Presented from a NASA perspective,

using NASA test rigs as supporting material

Acoustic Impedance

What is it?

- Liner impedance, ζ, is function of
  - Frequency, SPL
  - Liner geometry
  - Aeroacoustic environment

- Definition: $\zeta = \frac{p}{u_n} = \theta + i\,\chi$ { acoustic pressure, p; acoustic particle velocity, u_n

- Resistance, θ: A measure of the forces (e.g., viscous scrubbing losses) that dissipate energy
- Reactance, χ: "Gate" that determines frequencies where energy conversion process is optimized

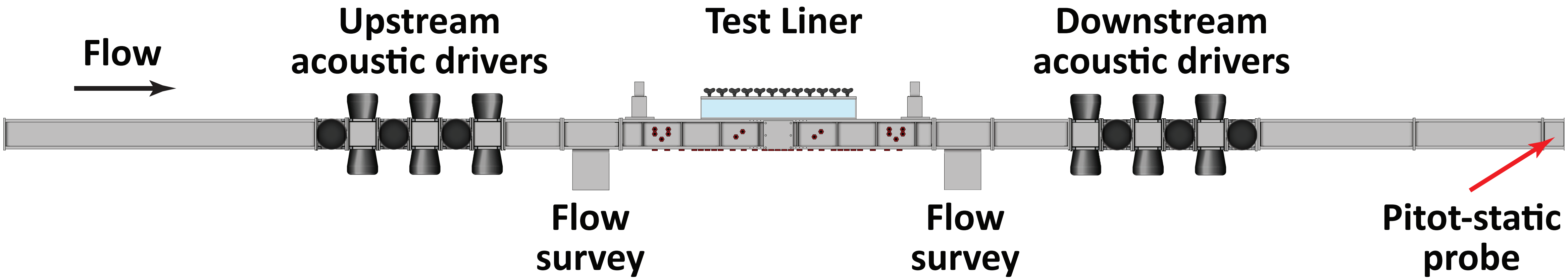
1. *"Aeroacoustics of Flight Vehicles: Theory and Practice. Volume 2: Noise Control," H. Hubbard: editor, NASA RP-1258, 1991*

Acoustic Impedance

What makes impedance so special?

- Intrinsic property of acoustic liner (Tester, Myers, Parrott)
- Independent of duct geometry (unlike attenuation or transmission loss)
  - Detailed study in controlled environment (e.g., GFIT)
  - Suitable for predictions in aircraft engine nacelles

NASA Grazing Flow Impedance Tube (GFIT)



- Propagation codes predict sound transmission through a duct
- Acoustic liners represented as impedance boundary condition

Acoustic Impedance

What is a good impedance?

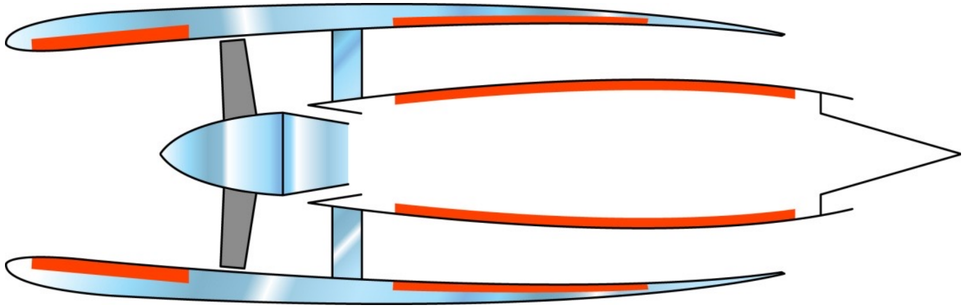
Function of

- Duct geometry
- Aeroacoustic environment

~1970

Low bypass ratio (~4)

Tone dominated (blade passage frequency, BPF)

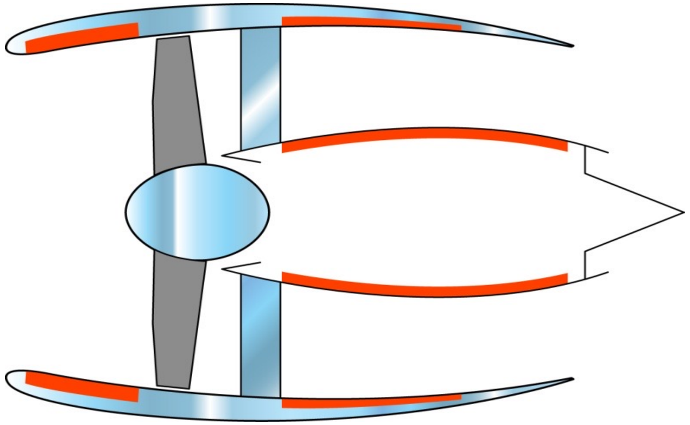


Present

Higher bypass ratio (>11) – more broadband

Larger fan diameter – lower BPF

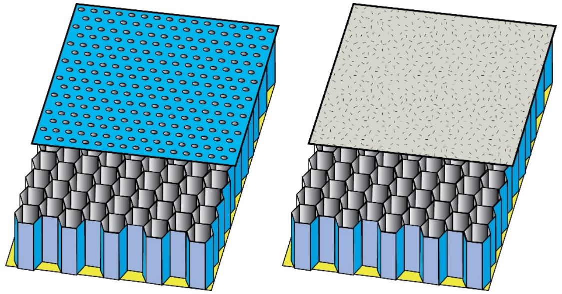
Shorter nacelle – liner optimization needed



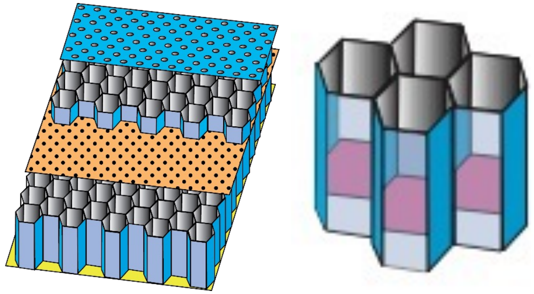
Acoustic Liners (a few concepts of interest)

Conventional

Start with SDOF configurations; perforate or mesh facesheet

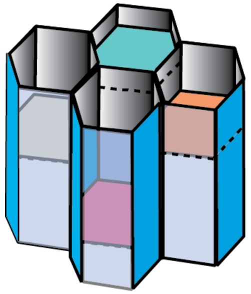


2DOF: Add second layer

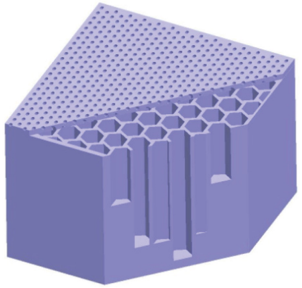


Novel

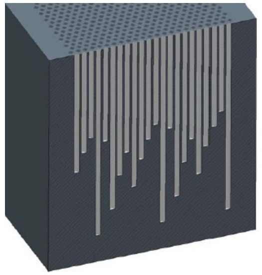
Increase # DOF with variable depths and resistances



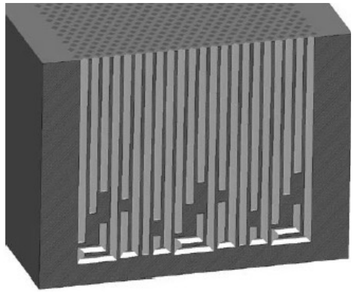
Change to variable-depth core



Reduce chamber diameter, eliminate facesheet



Employ bent chambers



[Source: NASA]

Conventional Local-Reacting Liner

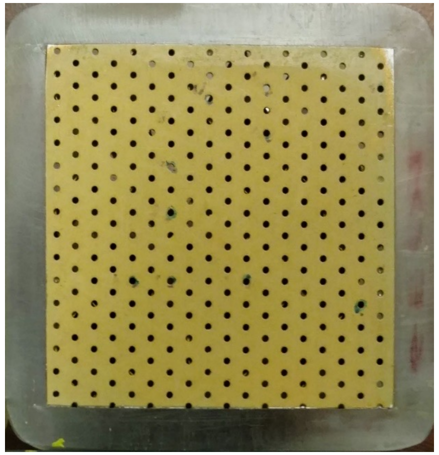
"Thin" resistive facesheet + blocked lateral wave

- Spatially concentrated absorption
- Enhanced fluid pumping

Salient features

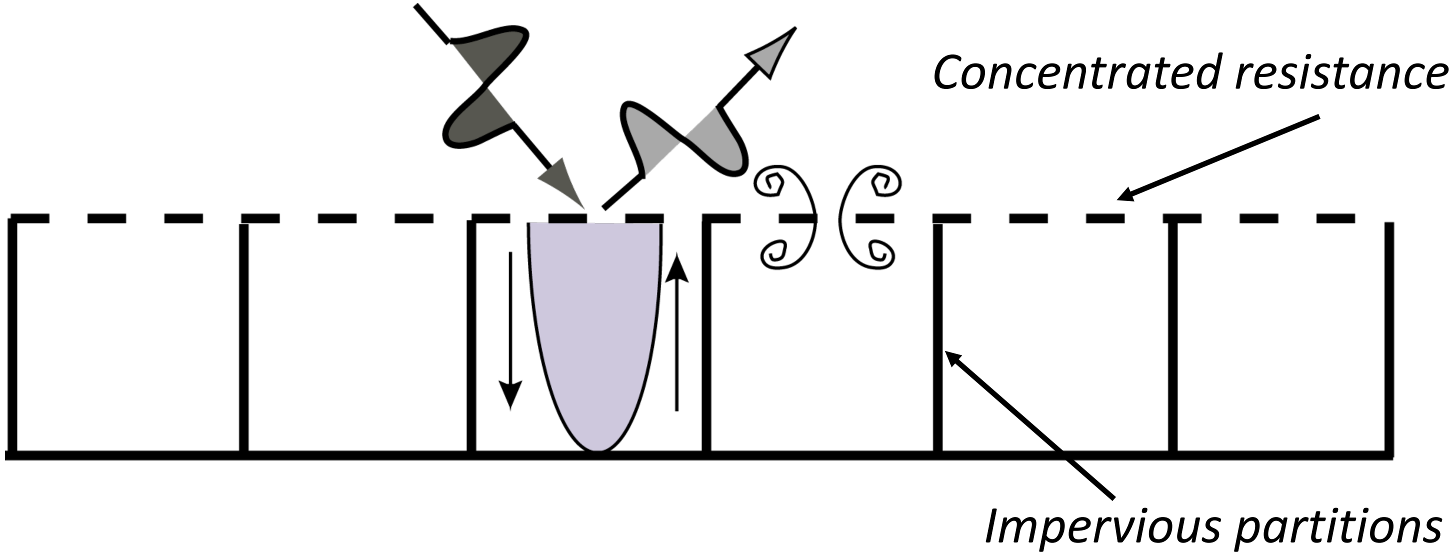
- Strong resonance
- Bandwidth limited absorption
- Very good for tones

Top View



Bottom View

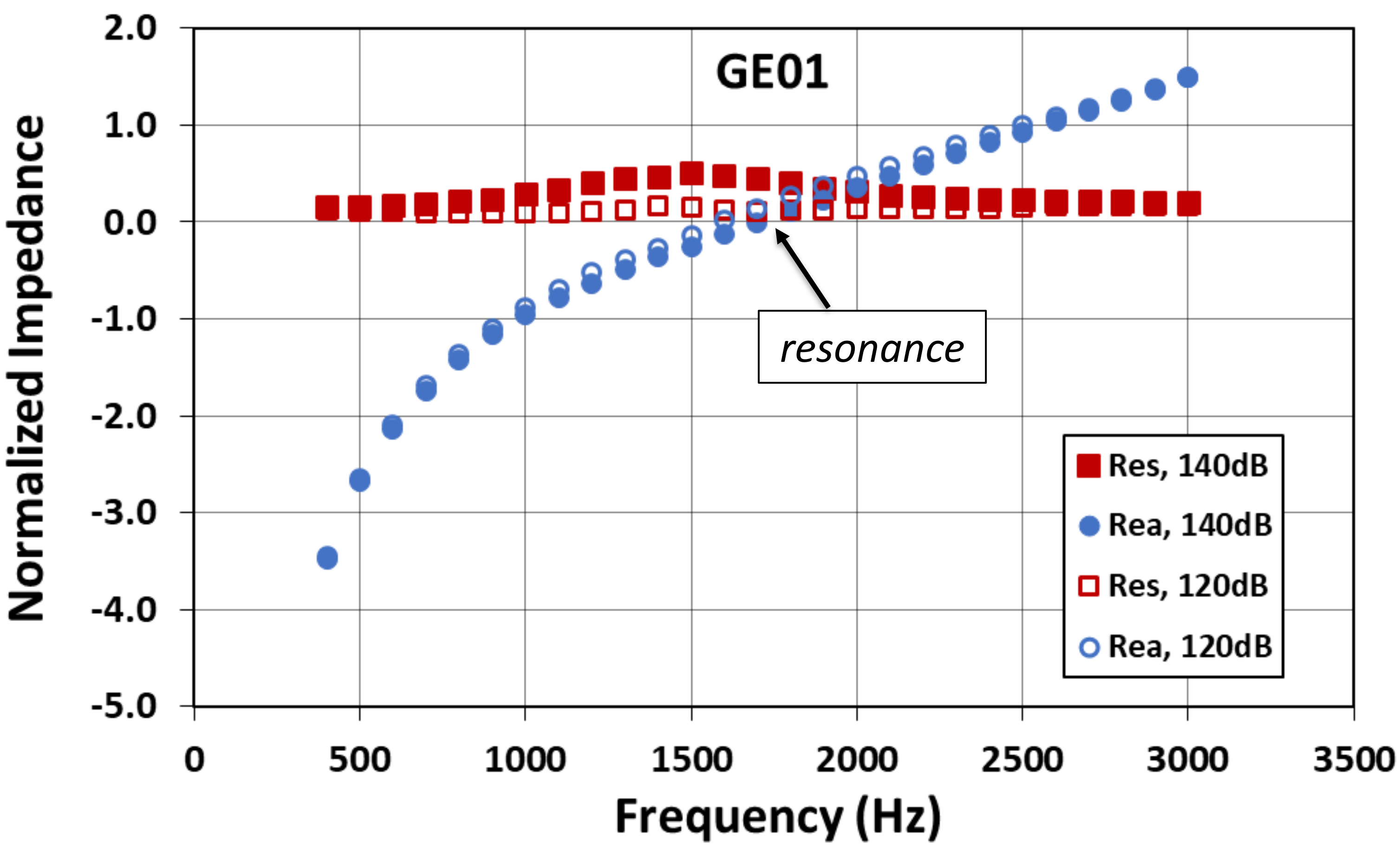
[Source: NASA]

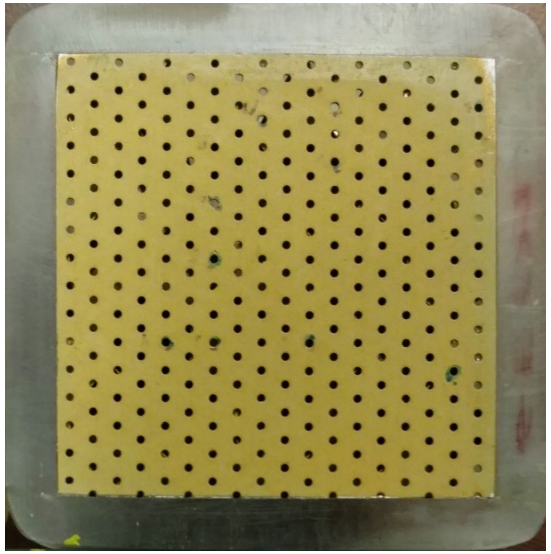


Conventional Local-Reacting Liner

Typical Liner (GE01)

- 8% POA, 1.5” deep (38.1mm)
- Locally reacting with honeycomb core





[Source: NASA]

NASA LaRC Liner Technology Facility

[Source: NASA]

Purpose:

- Perform acoustic measurements under a variety of conditions to characterize the response of liners (determine their effective impedance).

NASA LaRC Liner Technology Facility

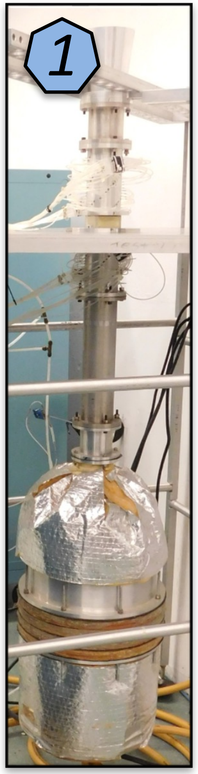
[1] *Raylometer*
- *$U = 0.2$ to 500 cm/sec*

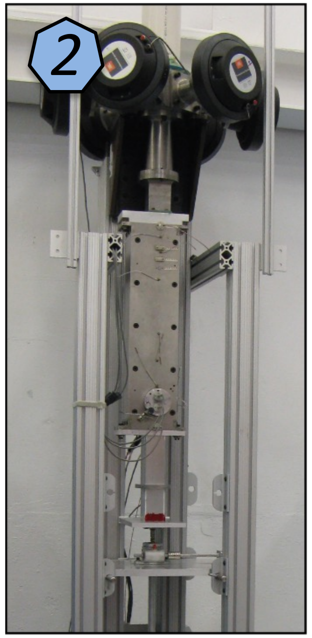
[2] *Normal Incidence Tube (NIT)*
- *Mach 0.0, SPL $\leq$ 155 dB, Freq $\leq$ 3 kHz*
- *Tone, multitone, and broadband sources*

[3] *High Intensity Modal Impedance Tube (HIMIT)*
- *Mach 0.0, SPL $\leq$ 170 dB, Freq $\leq$ 6 kHz*
- *Tone source*

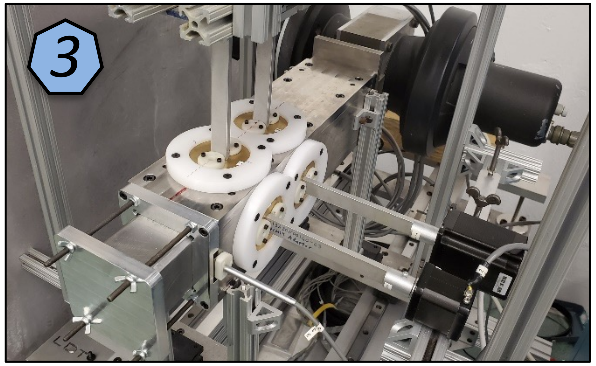
[4] *Grazing Flow Impedance Tube (GFIT)*
- *Mach $\leq$ 0.6, SPL $\leq$ 155 dB, Freq $\leq$ 3 kHz*
- *Tone source*

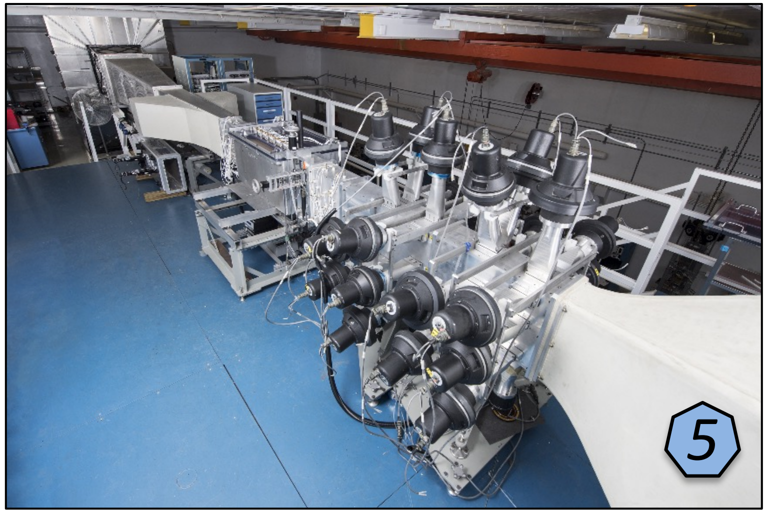
[5] *Curved Duct Test Rig (CDTR)*
- *Mach $\leq$ 0.5, SPL $\leq$ 140 dB, Freq $\leq$ 3 kHz*
- *Controlled mode tonal and broadband sources*

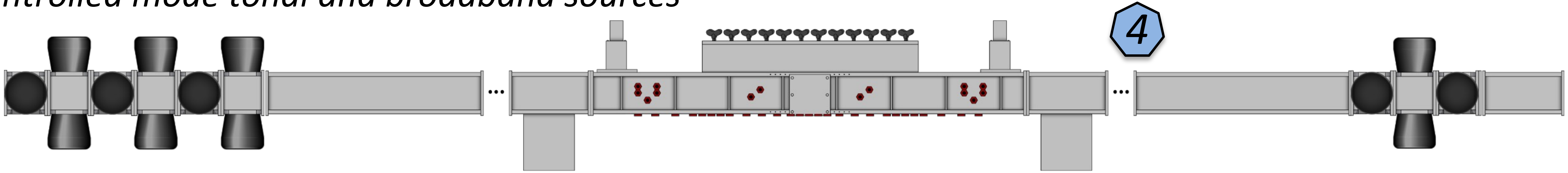




[Source: NASA]







$R_f \rightarrow \theta$ at 0 Hz [NASA Raylometer]

$$\frac{R_f}{\rho c} = \frac{\Delta P_s}{\rho c U} \rightarrow \theta(0\ \mathrm{Hz})$$

ΔP_s = static pressure drop across sample (facesheet)

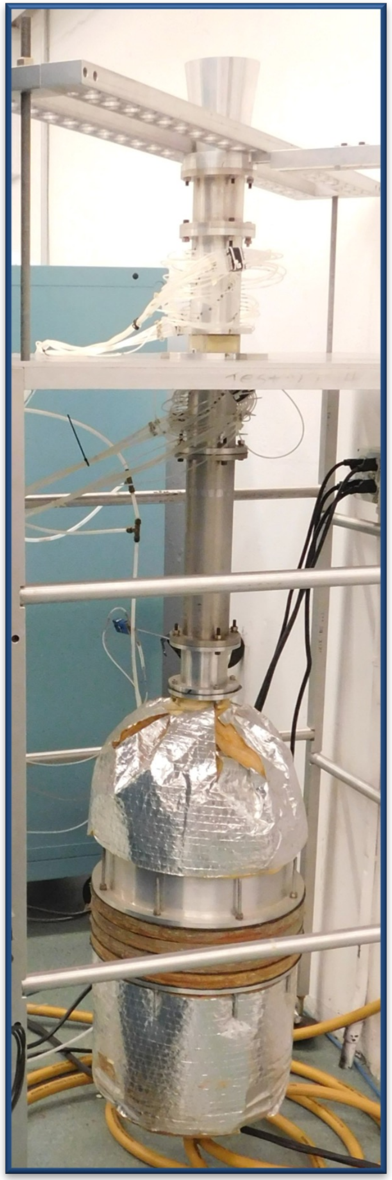
U = incident velocity entering the sample

ρc = characteristic impedance of air

Features:

- Automated (sets to predetermined velocities)
- Velocity range: $U = 0.2 - 500$ cm/s
- Spiral arrays correct for sample nonuniformities
- Auto-compensates for P_{atm} changes
- Dynamic averaging to minimize settling time
- Test small samples or sheets

1. *Brown, et al: "Flow Resistance Comparative Study," NASA TM-2017-217743, November 2017*

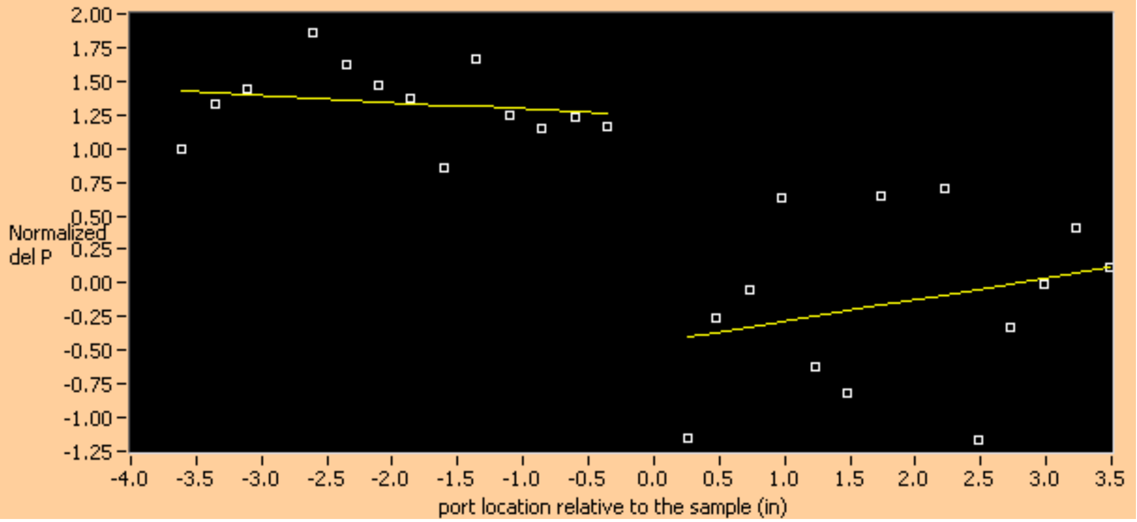


[Source: NASA]

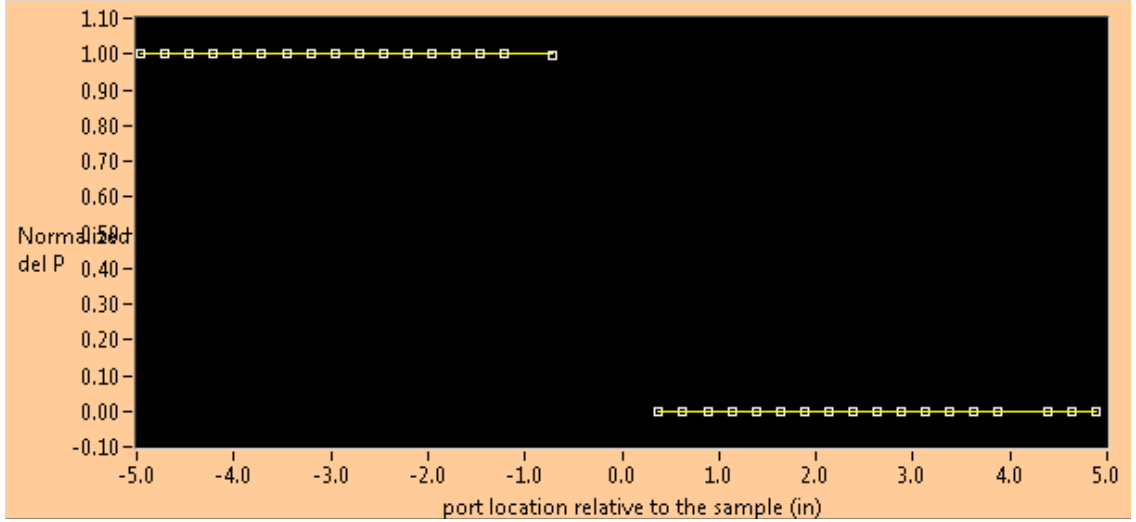
$R_f \rightarrow \theta$ at 0 Hz [NASA Raylometer]

Notes:

- Most raylometers use one static pressure port on each side of the facesheet
- Need to ensure that static pressure ports are not too close to the sample; proper distance is larger for nonuniform test samples
- At very low velocities, results affected by changes in atmospheric pressure (fluctuations ~0.5 Pa)



Low velocity, low resistance



Higher velocity, higher resistance

1. *Syed, Yu, Kwan, Chien: "The Steady Flow Resistance of Perforated Sheet Materials in High Speed Grazing Flows,"* NASA CR-2002-211749, July 2002

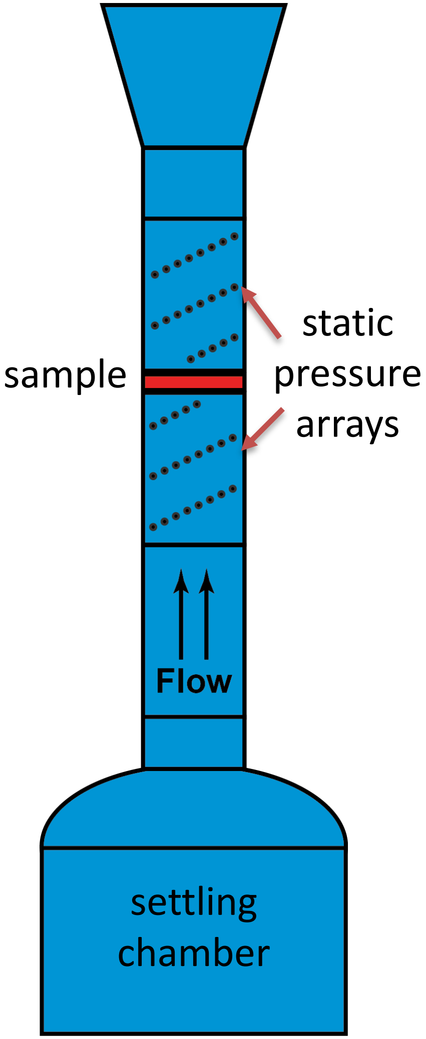
$R_f \rightarrow \theta$ at 0 Hz [NASA Raylometer]

- Typically measured at U of 20, 105, 200 cm/s

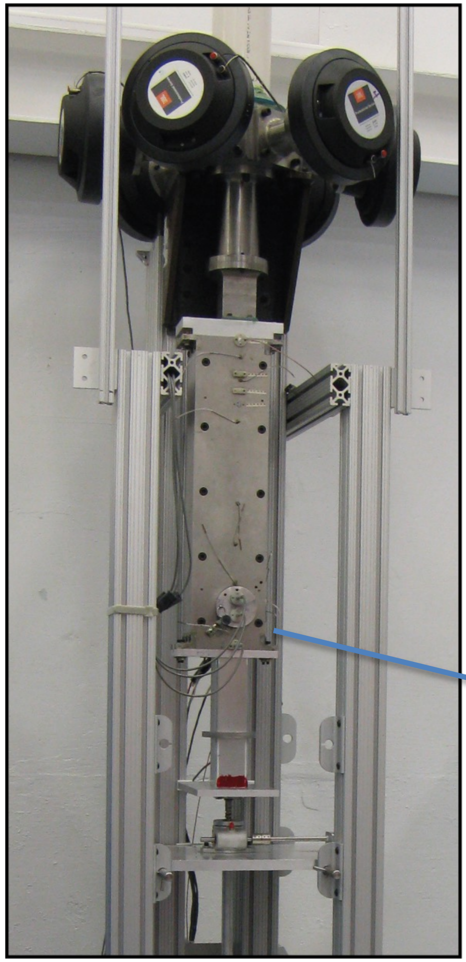
  R_f typically quoted at 105 cm/s
- Nonlinearity Factor (NLF)

$$\mathrm{NLF} = \frac{R_f(200\ \mathrm{cm/s})}{R_f(20\ \mathrm{cm/s})}$$

  - Wire mesh: $\mathrm{NLF} \gtrsim 2$
  - Conventional perforates: $\mathrm{NLF} \approx O(10)$
- Measure average P_s at each axial plane
- Linear fit results and extrapolate to sample surface to compute ΔP_s



$\zeta(f, \mathrm{SPL})$ at M=0 [NASA NIT]

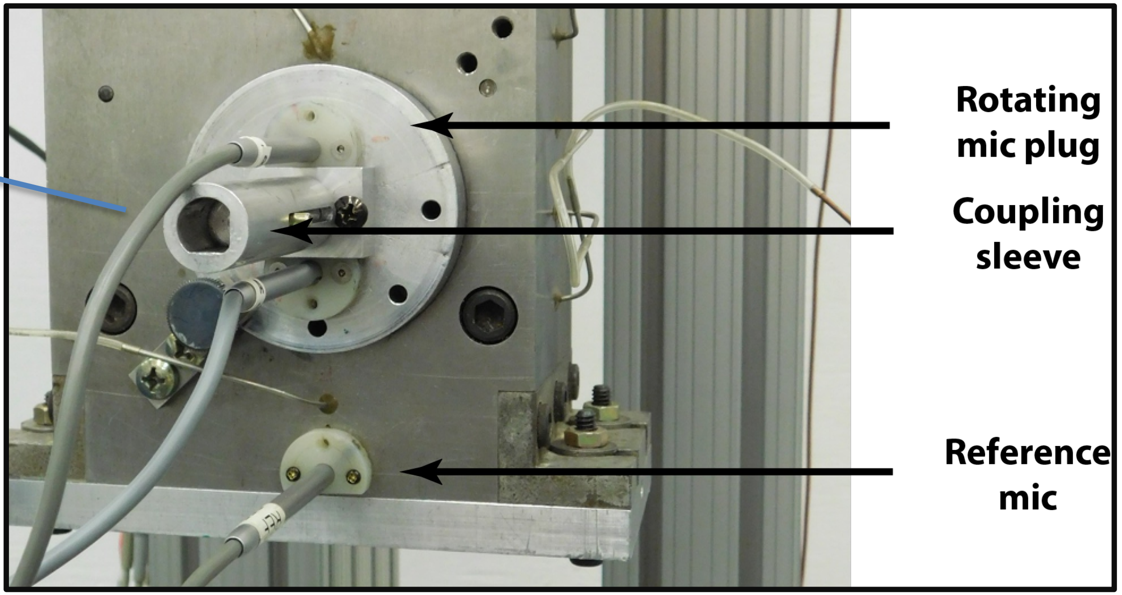


[Source: NASA]

Features:

- Dimensions: 2.0”x2.0” (51mm x 51mm)
- Frequencies (kHz): 0.4 – 3.0
- Plane waves over frequency range
- Automated rotating plug for two mics
- Fully automated acquisition and reporting

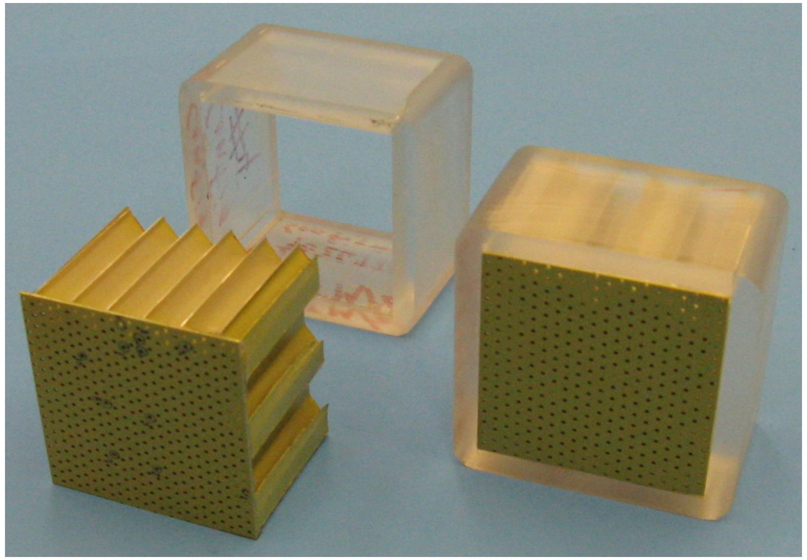
- Four source types (typical ranges)
  - Stepped sine (Max ~ 155 dB)
  - Swept sine (Max ~ 145 dB)
  - Multitone (Max ~ 140 dB)
  - Broadband (OASPLs: 120, 140 dB)



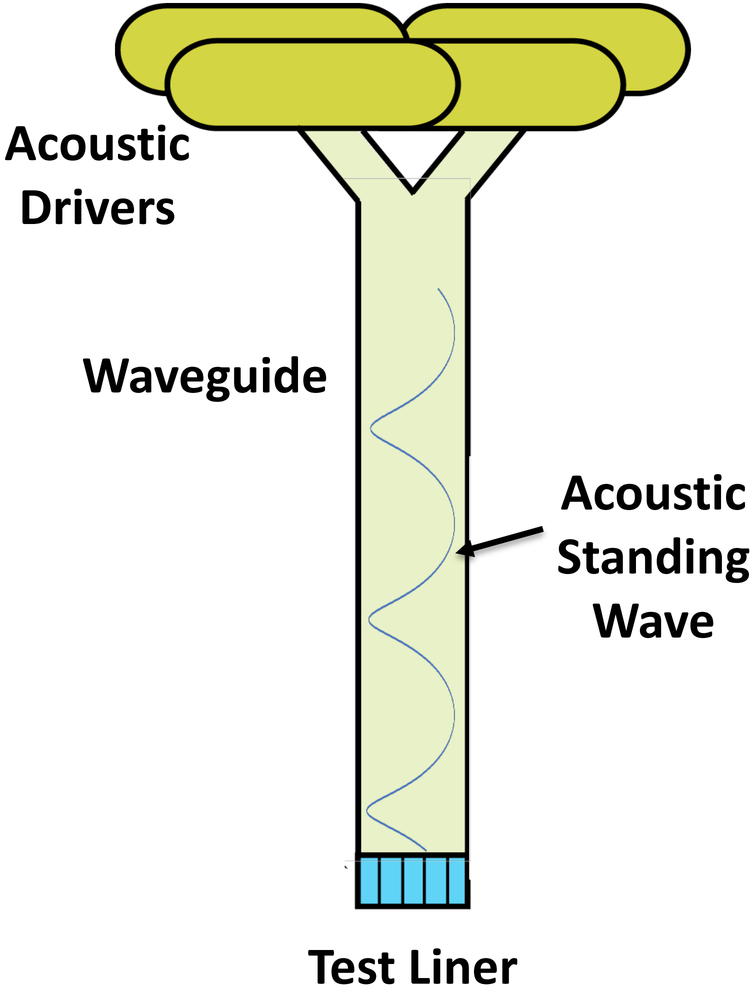
Impedance Measurement Methods - NIT

Measurement Methods:

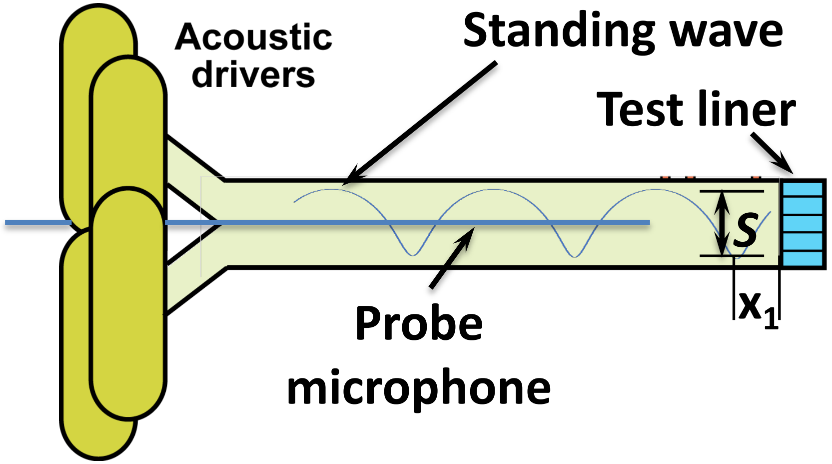
- In situ (Dean's) Method
- Standing Wave Method
- Multipoint Method
- Two Microphone Method



[Source: NASA]



Standing Wave Method - NIT



$$\frac{B}{A} = \frac{10^{S/20} - 1}{10^{S/20} + 1} e^{i\phi}$$

$$\phi = -\pi - 2kx_1$$

$$\zeta = \frac{(A + B)\rho c}{(A - B)}$$

Acoustic pressure amplitude:

$p = A\cos(\omega t - kx) + B\cos(\omega t + kx)$

x_1: distance to first null

S: standing wave ratio (in dB)

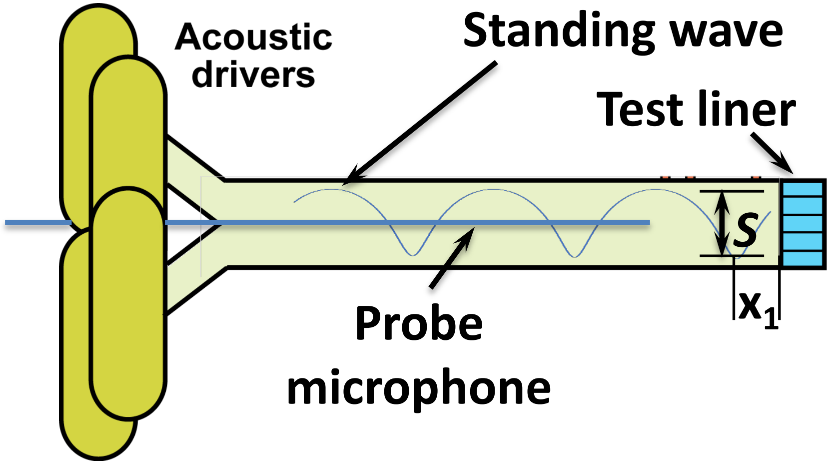
$k = \omega/c$: freespace wavenumber

Notes:

- Inexpensive (can use ruler and voltmeter)
- Time consuming
- Requires precise positioning
- Difficult to accurately determine null levels

1. *Parrott and Smith: "Random and Systematic Measurement Errors in Acoustic Impedance as Determined by the Transmission Line Method," NASA TN D-8520, Dec 1977*
2. *Kinsler and Frey: Fundamentals of Acoustics, John Wiley & Sons, Second Edition, 1962*

Multipoint Method - NIT



$$p_j = \left[p_i e^{-i\Gamma x_j} + p_r e^{i\Gamma x_j}\right] e^{i\omega t}$$

$$R = \frac{p_r}{p_i} \rightarrow \zeta = \frac{1+R}{1-R}$$

$$\Gamma = k + i\beta_v$$

Procedure:

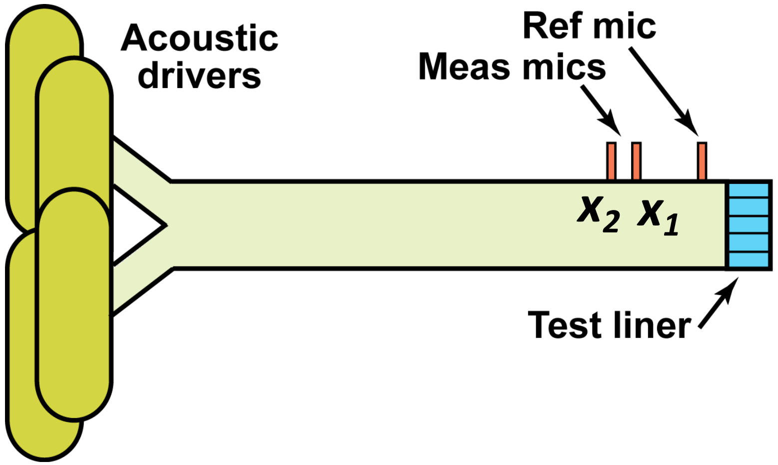
- Measure acoustic pressure at multiple axial locations, x_j (6 pts within first $\lambda/2$ is ideal)
- Employ a complex propagation constant, Γ, that accounts for viscothermal losses at the wall of the NIT (β_v)
- Apply least-squares fit to determine p_i and p_r; compute R; compute ζ

Notes:

- Assumes plane waves, but frequency range can be extended via use of a specialized probe
- Time consuming
- Ideal measurement spacing is frequency-dependent
- No concerns regarding microphone calibration, since the same microphone is used throughout

1. *Jones and Stiede: "Comparison of methods for determining specific acoustic impedance," JASA 101(5), May 1997*

Two Microphone Method - NIT



$$p_j = \left[p_i e^{-i\Gamma x_j} + p_r e^{i\Gamma x_j}\right] e^{i\omega t}$$

$$R = \frac{p_r}{p_i} \rightarrow \zeta = \frac{1+R}{1-R}$$

$$\Gamma = k + i\beta_v$$

Procedure:

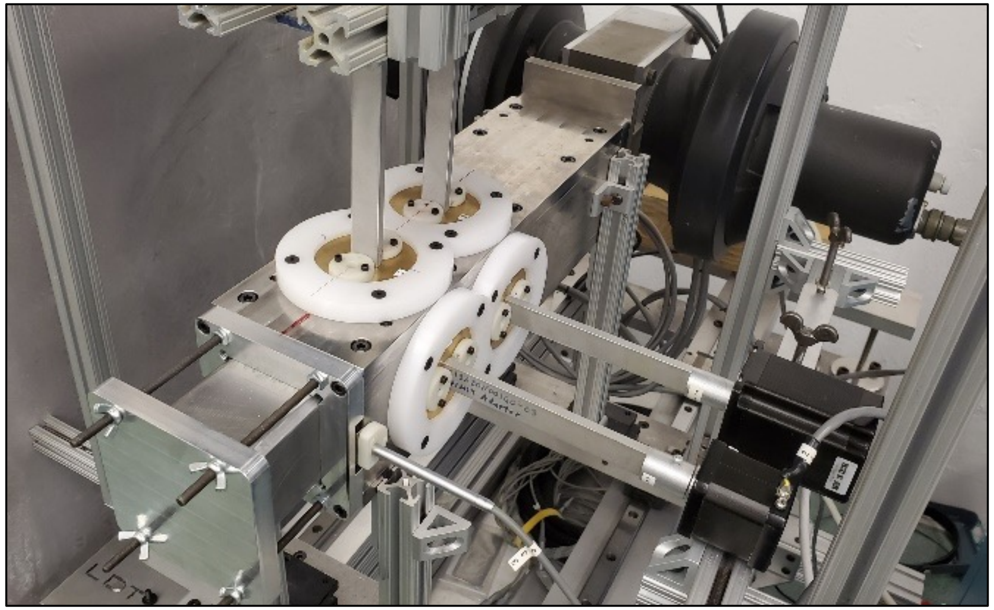
- Set source level using feedback from reference microphone
- Measure p_1 and p_2 at axial locations x_1 and x_2
- Solve for p_i and p_r
- Compute R → ζ

Notes:

- More efficient
- Difficulties for frequencies where microphones are half-wavelength apart
- No need to precisely calibrate the switching mics (errors are cancelled in the equations); need two measurements per frequency

1. *Jones and Stiede: "Comparison of methods for determining specific acoustic impedance," JASA 101(5), May 1997*
2. *ASTM E1050-12, "Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System", ASTM International, West Conshohocken, PA, 2012*

$\zeta(f, \mathrm{SPL})$ at M=0 [NASA HIMIT]



[Source: NASA]

Features:

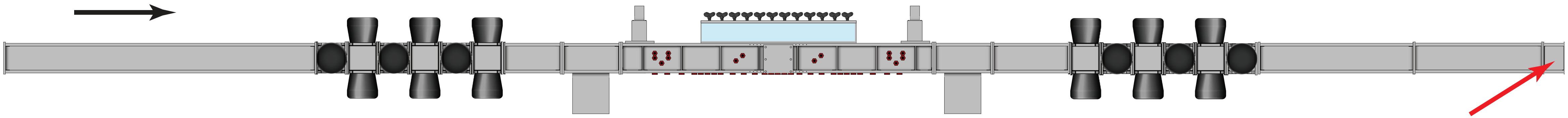
- 2.0”x2.0” (51mm x 51mm) cross-section
- Two sources
  - Compression drivers (Max ~ 160 dB); stepped sine
  - Hartmann Generator (Max ~ 170 dB); multitone
- Frequencies (kHz): 0.4 – 6.0
- Higher order modes present above 3.3 kHz
- Four rotating plugs for eight microphones
- Fully automated acquisition and reporting
- Howerton presentation

Current Process:

- A reference microphone near the sample surface is used to set the desired SPL for plane wave frequencies (< 3.3 kHz); development of an acceptable method to “set a level” for frequencies above 3.3 kHz (higher order modes are cut on) is a work in progress
- Acquire data with 8 microphones positioned to enable mode decomposition up to 6 kHz
- Use axial wavenumber for mode with most power (typically the plane wave) to estimate surface impedance of liner

1. *Jones, et al.: “Implementation of the NASA High Intensity Modal Impedance Tube,” NASA TM 2022-0017773, Dec 2022*
2. *Solano, et al. : “High Intensity Modal Impedance Tube Development at NASA Langley,” NASA TM 2023-0000292, Feb 2023*

$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT]



Flow

Upstream acoustic drivers

Test Liner

Downstream acoustic drivers

Flow survey

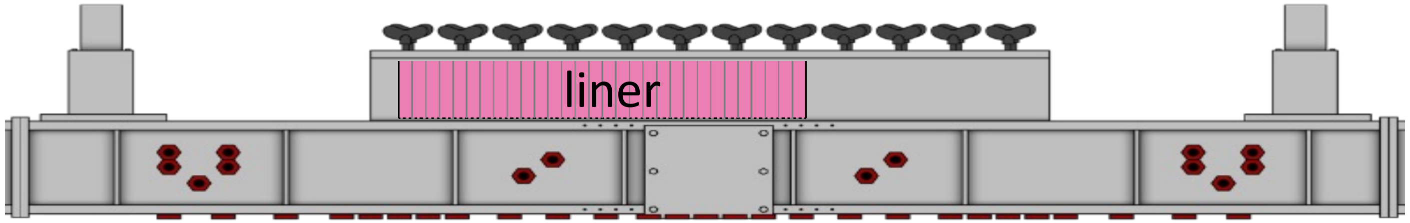
Flow survey

Pitot-static probe

Features:

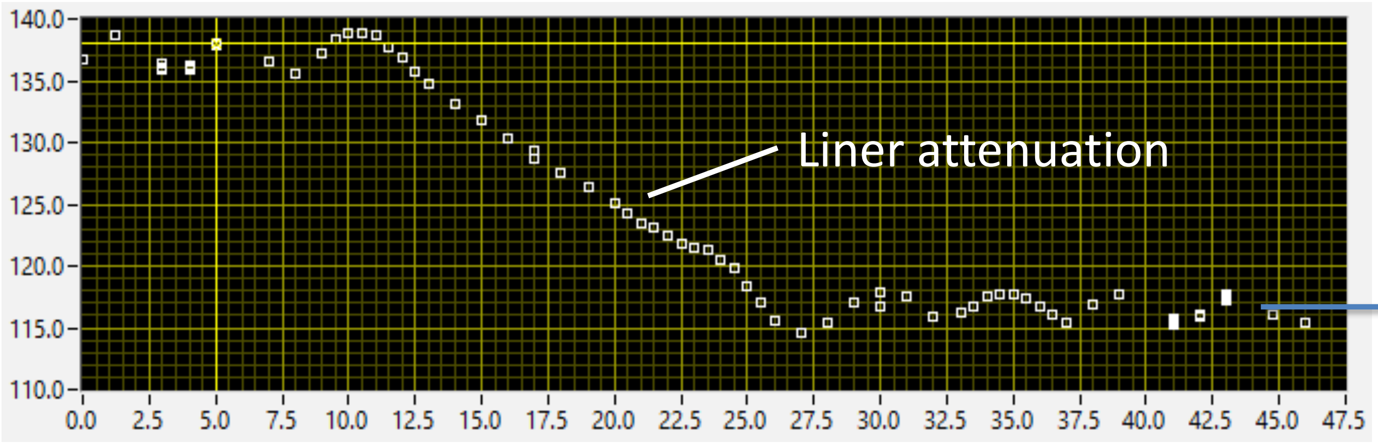
- 2.0”x2.5” (51mm x 63mm) cross-section
- Liners up to 24” (610 mm)
- 95 microphones distributed on four walls
- Two source types (typical ranges)
  - Stepped sine (Max ~ 155 dB)
  - Swept sine (Max ~ 145 dB)
- Sources at each end of duct (exhaust/inlet modes)
- Mach #: 0.0 – 0.6
- Frequencies (kHz): 0.4 - 3.0 (plan to increase to 6.0 soon)

$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT]



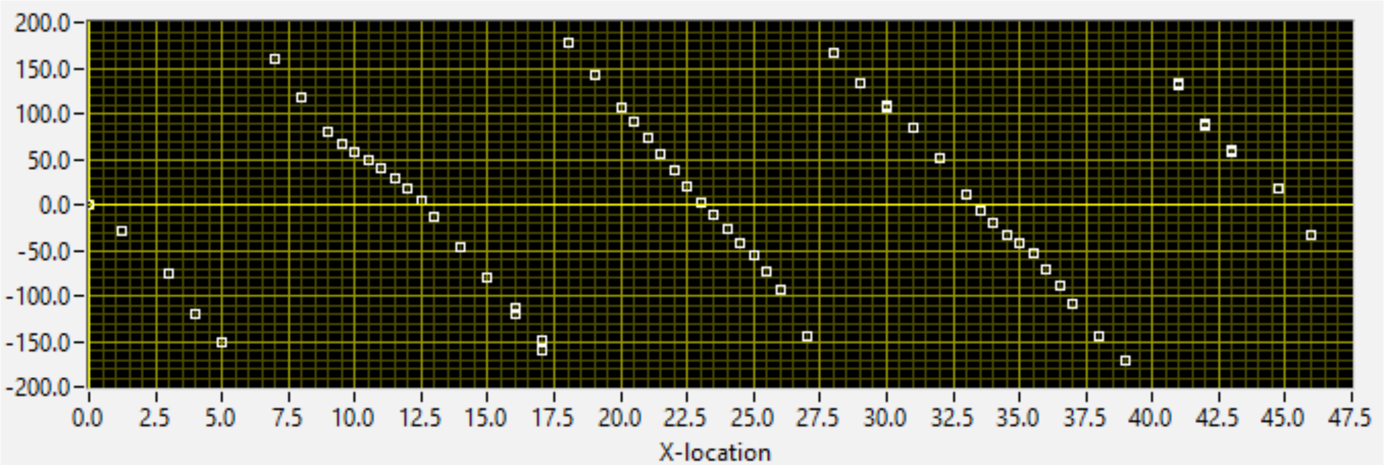
Representative Dataset

SPL(x)

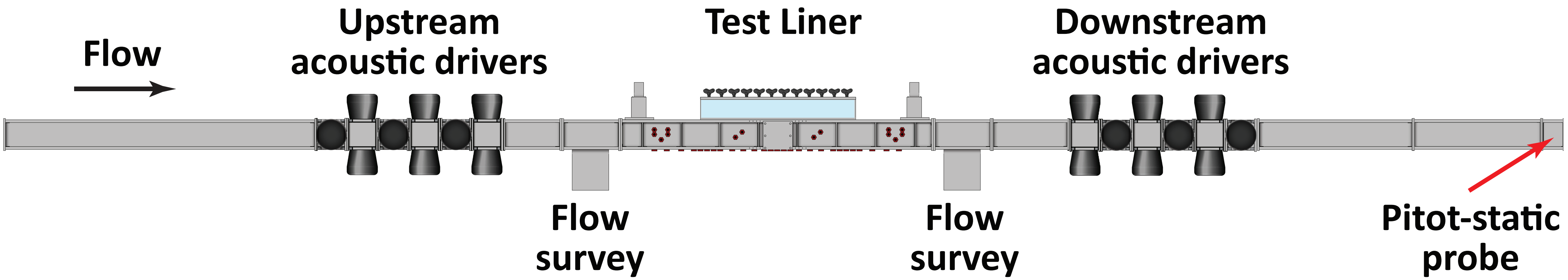


Standing wave (reflection from termination)

Phase(x)



$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT]



Impedance Eduction Methods:

Indirect

- Convected Helmholtz equation (CHE) solver
- Linearized Euler equations (LEE) solver

Direct

- Single Mode Method (SMM)
- Prony Method (PM)
- Pridmore-Brown equation (PBE)

Based on the convected Helmholtz equation

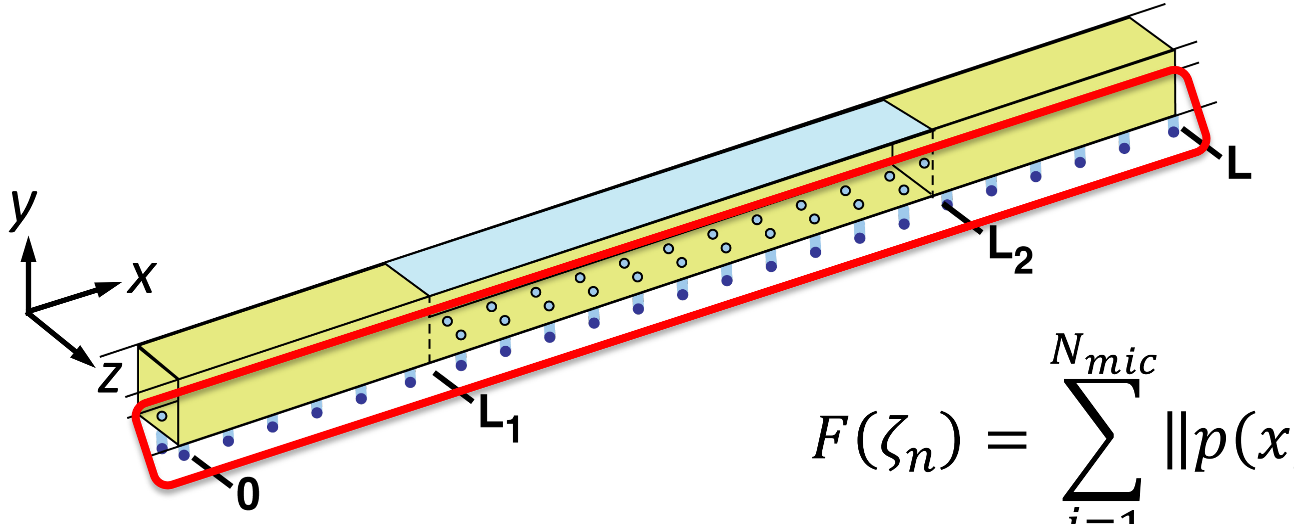
Others

- In Situ Method
- Hybrid Method (combination of PM and CHE)

$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT] – Indirect Methods

Indirect Impedance Eduction Methods

- Solve equations using finite element method, for which impedance, ζ, is a boundary condition
- Use optimizer to find ζ that causes p_{num} (predicted acoustic pressures over the length of the test section) and p_{meas} (corresponding measured acoustic pressures) to converge within an acceptable tolerance



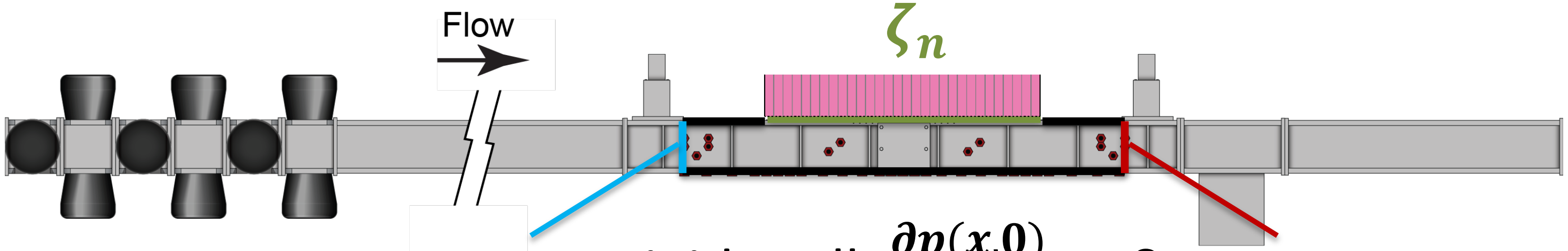
$$F(\zeta_n) = \sum_{i=1}^{N_{mic}} \| p(x_i, 0)_{\mathrm{num}} - p(x_i, 0)_{\mathrm{meas}} \|$$

- Two indirect methods have been used at NASA
  - CHE (based on the convected Helmholtz equation)
  - LEE (based on the linearized Euler equations)

$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT] – CHE Method

Convected Helmholtz Equation

$$(1 - M_0^2)\frac{\partial^2 p(x,y)}{\partial x^2} + \frac{\partial^2 p(x,y)}{\partial y^2} - 2ikM_0\frac{\partial p(x,y)}{\partial x} + k^2 p(x,y) = 0$$



Source: $\boldsymbol{p_s(0,y)}$

Rigid Wall: $\boldsymbol{\frac{\partial p(x,0)}{\partial y} = 0}$

Exit

Boundary Conditions

Liner (Ingard-Myers): $-\frac{\partial p(x,H)}{\partial y} = ik\left(\frac{p(x,H)}{\zeta_n}\right) + 2M_0\frac{\partial}{\partial x}\left(\frac{p(x,H)}{\zeta_n}\right) + \frac{M_0^2}{ik}\frac{\partial^2}{\partial x^2}\left(\frac{p(x,H)}{\zeta_n}\right)$

Exit Plane: $p(L,y) = p(L,0)$

Assumptions:

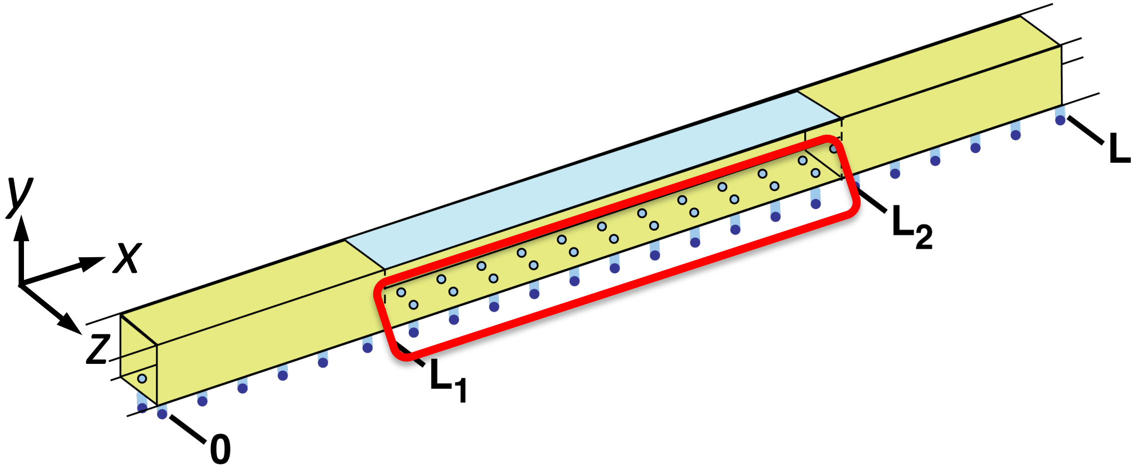
- Uniform flow (**not realistic!**)
- Only plane waves exist at source and exit planes

1. *Myers, M. K., "On the Acoustic Boundary Condition in the Presence of Flow," J. of Sound and Vibration, Vol. 71(3), 1980*

$\zeta(f, \mathrm{SPL}, M)$ [NASA GFIT] – Direct Methods

Direct Impedance Eduction Methods

- Determine axial wavenumber, K_n, from acoustic pressures, p_{meas}, measured in wall opposite liner



- Three direct methods have been used at NASA
  - SMM (single mode dominant) and PM (account for multiple modes) are both based on the convected Helmholtz equation)
  - PBE (based on the Pridmore-Brown equation; account for 1D shear)
- These methods assume infinite-length duct with one wall fully treated

Modal Solution to CHE

Procedure:

- Expand acoustic pressure as series of normal duct modes:

$$p(x,y) = \sum_{n=1}^{R} A_n P_n(y) e^{-K_n x}$$

where

$$P_n(y) = \cos(\lambda_n y)$$

and

$$\lambda_n^2 = (k - K_n M_0)^2 - K_n^2$$

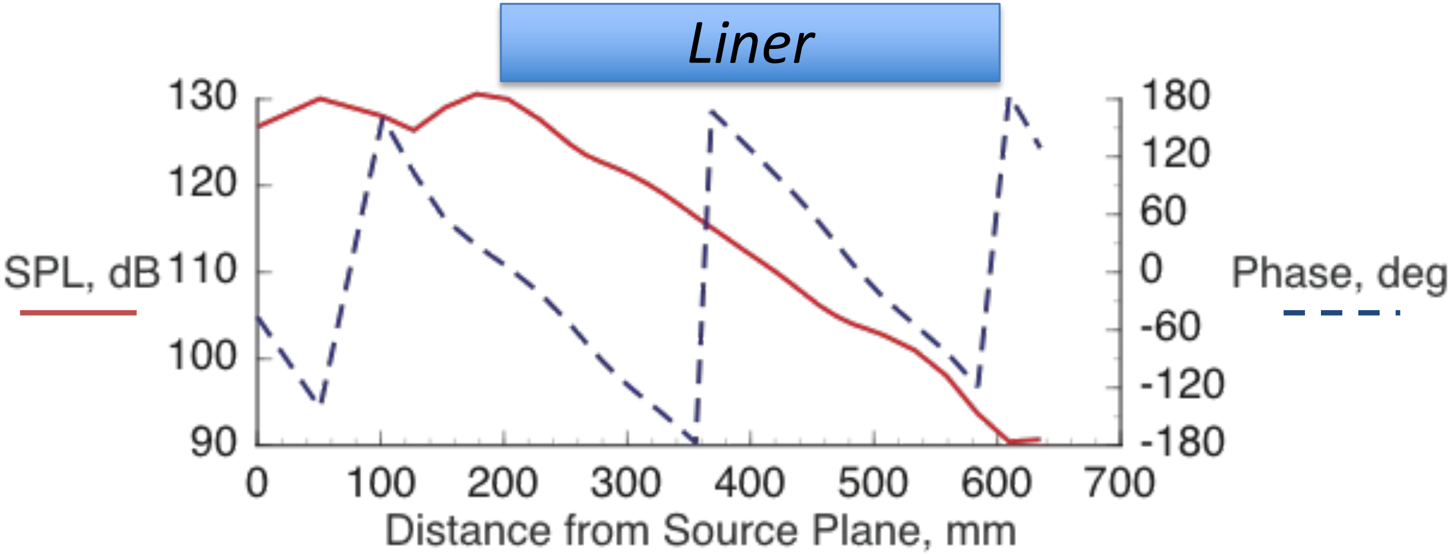
- Determine K_n (axial wavenumber)
- Substitute mode solution into wall impedance BC

$$\boxed{\zeta = \frac{ik}{\lambda_n}\left(1 - \frac{K_n M_0}{k}\right)^2 \cot(\lambda_n H)}$$

$\zeta(f, \mathrm{SPL}, M)$ [Single Mode Method, SMM]

- **<u>If single mode is dominant</u>**, SPL and phase decay will be nearly linear over length of liner
- Determine axial wavenumber, K_n, from acoustic pressures measured with mics on wall opposite the liner (or liner segment)

Apply linear fit to find $\frac{d\phi(x)}{dx}$ and $\frac{d\mathrm{SPL}(x)}{dx}$ → $K_n = \left|\frac{d\phi(x)}{dx}\right| + \frac{i}{20\log_{10} e}\left|\frac{d\mathrm{SPL}(x)}{dx}\right|$



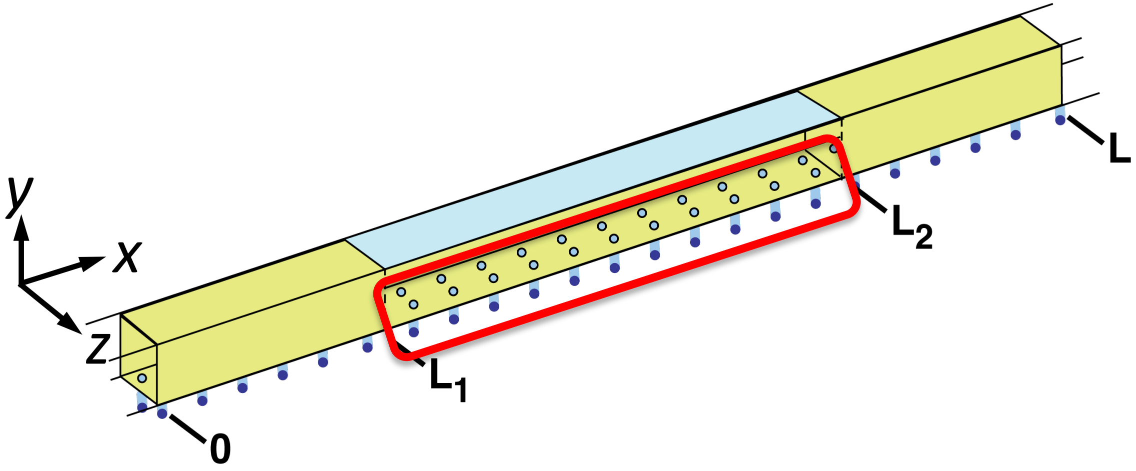
A change in slope (flatter) indicates another mode has become dominant.

- Use K_n with Ingard-Myers BC to determine ζ

1. *Armstrong: "Acoustic Grazing Flow Impedance Using Waveguide Principles," NASA CR-120848, December 1971*

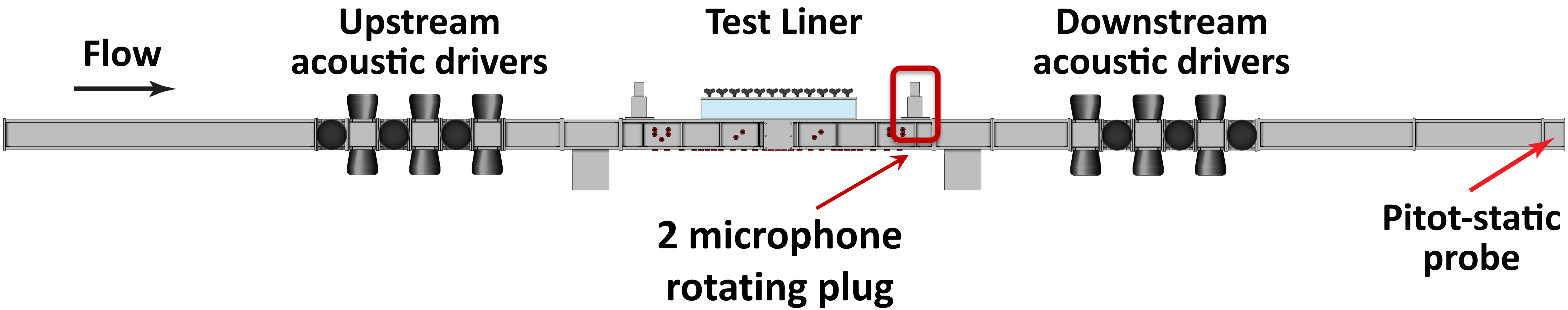
$\zeta(f, \mathrm{SPL}, M)$ [Prony Method, SMM]

- **If single mode is not dominant**, apply Prony method[1] to determine K_n from acoustic pressures measured with microphones on wall opposite the liner, for *N* (we use 6) modes
- Kumaresan and Tufts algorithm[2] provides a mechanism for separating out spurious modes (caution!)
- Use K_n with Ingard-Myers BC to determine ζ



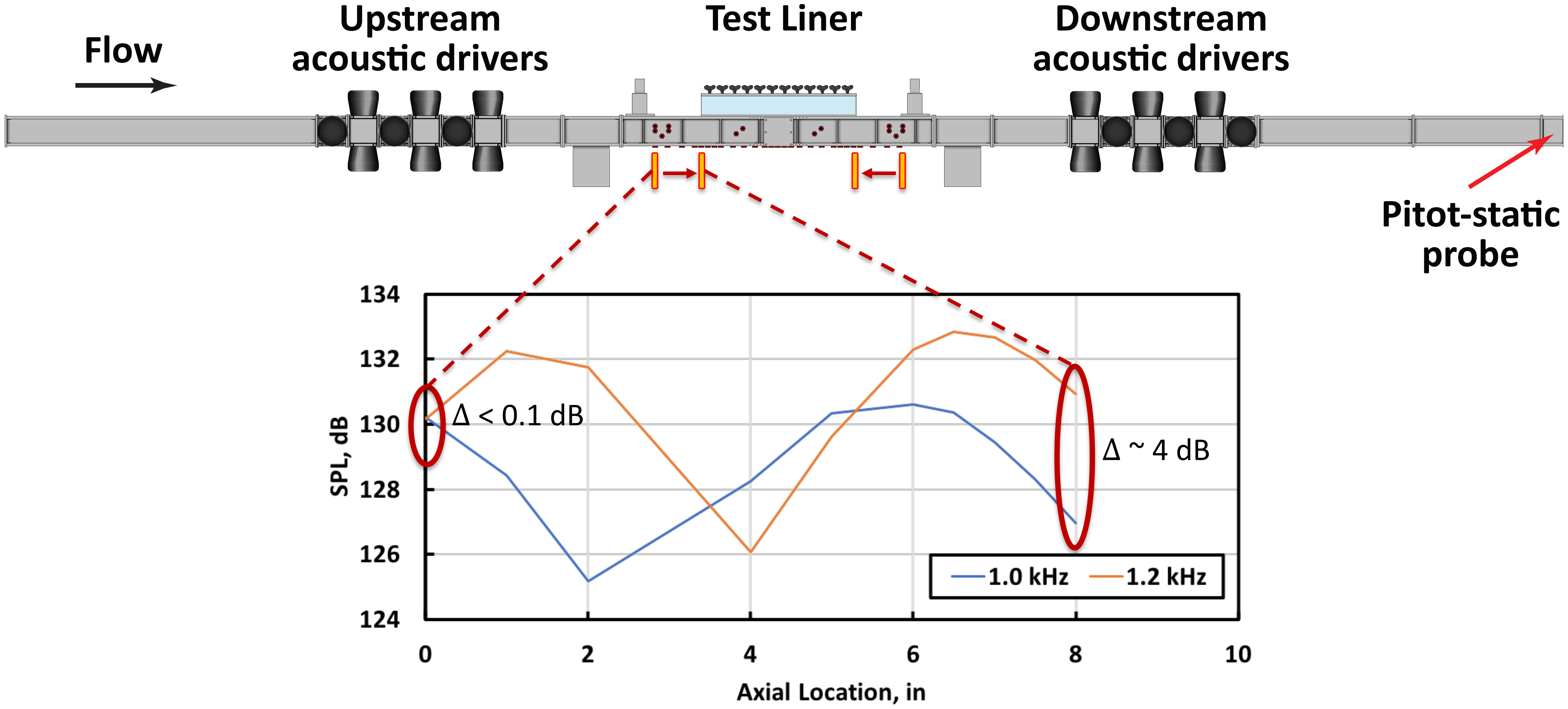
1. *Jing, Peng, Sun: "A straightforward method for wall impedance eduction in a flow duct," Journal of the Acoustical Society of America, Vol. 124(1), July 2008*
2. *Watson, Carpenter, Jones: "Performance of Kumaresan and Tufts Algorithm in Liner Impedance Eduction with Flow," AIAA Journal, Vol. 53(4), April 2015*

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Microphone Calibration]



1. Replace liner with hardwall insert
2. Engage single-tone source at frequency f_1 and 120 dB (at calibrated reference microphone location) for Mach=0.0 condition
3. Use rotating plug (Two-Microphone Method) to determine the impedance of the duct plus termination and the resultant standing wave pattern
4. Use standing wave pattern to compute the correct SPL and phase at each microphone location
5. Apply calibration corrections to each microphone
6. Repeat steps 2 – 4 for a second frequency to confirm calibration corrections are valid
7. Confirm that the microphones are measuring the predicted SPL and phase to within an acceptable tolerance (comparison to last calibration)

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Setting Source Level]



Flow

Upstream acoustic drivers

Test Liner

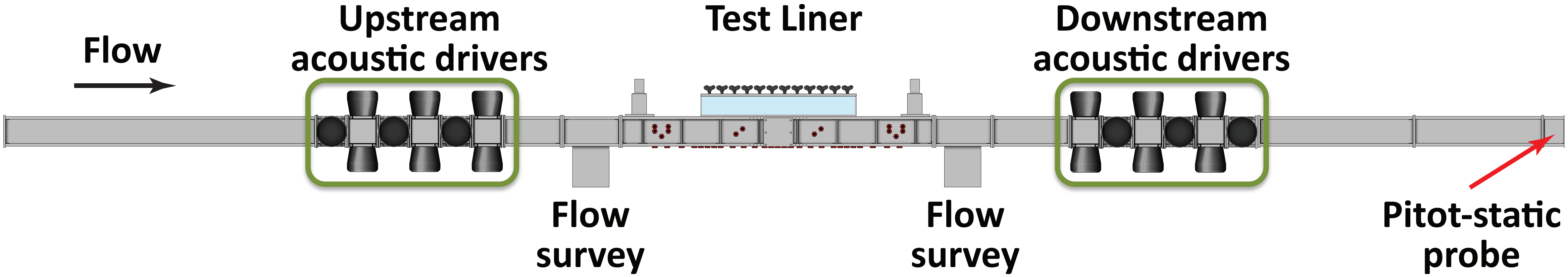
Downstream acoustic drivers

Pitot-static probe

Note: For nonlinear liners, results are dependent on source SPL.

Currently set source total SPL at LE of liner → ensures liner experiences same level for each test frequency

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Inlet/Aft Mode Impedance Eduction]


Flow

Upstream acoustic drivers

Test Liner

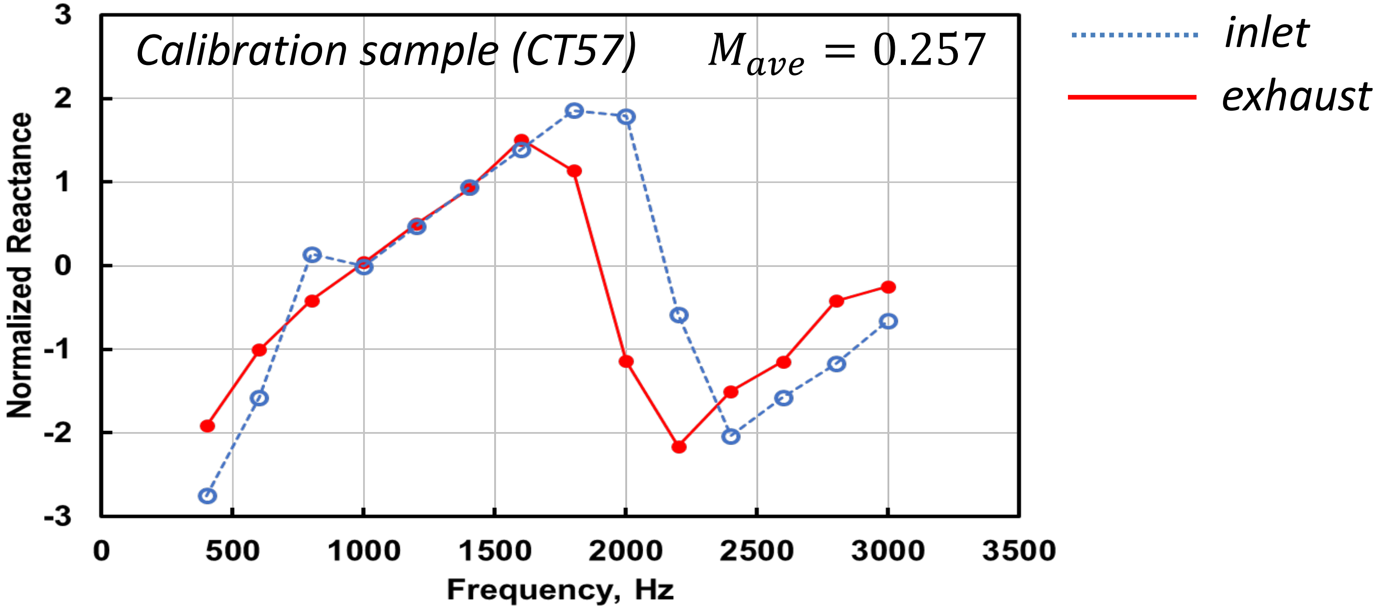
Downstream acoustic drivers

Flow survey

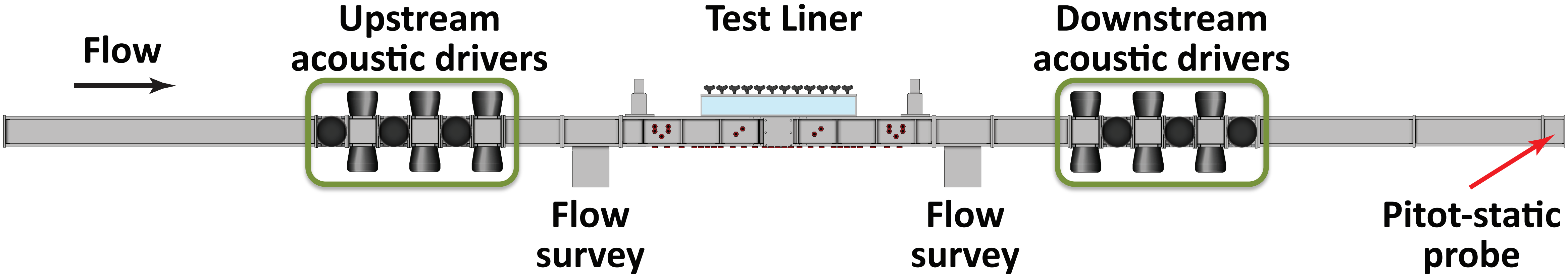
Flow survey

Pitot-static probe

- Renou & Auregan found that educed impedance was source location dependent
- We found similar results using our calibration liner



$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Inlet/Aft Mode Impedance Eduction]



Renou, Auregan, "Failure of the Ingard-Myers boundary condition for a lined duct: An experimental investigation," Journal of the Acoustical Society of America, Vol. 130(1), 2011

- Experimentally observed difference between inlet and aft impedance results

Eversman, Gallman, "Impedance Eduction with an Extended Search Procedure," AIAA Journal, Vol. 49(9), Sept 2011

- *Included M and ζ in eduction process – choice of M (for a single tunnel setting) may vary between liners*

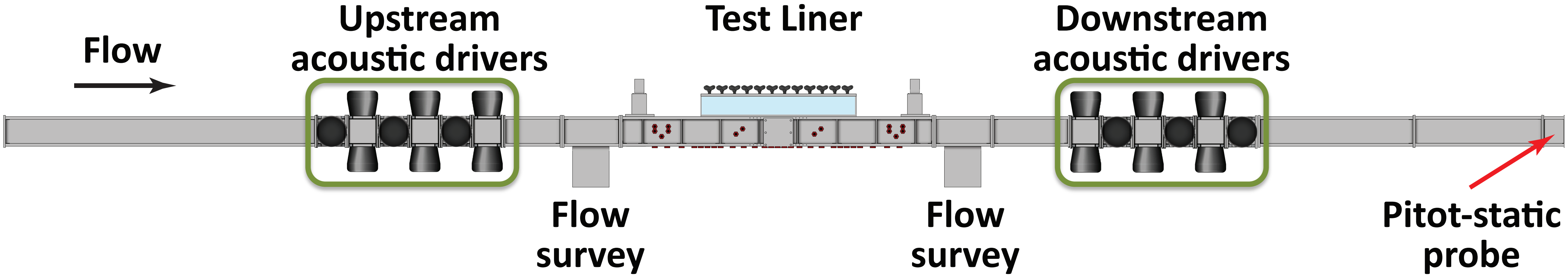
Watson, Jones, "Evaluation of Wall Boundary Conditions for Impedance Eduction Using a Dual-Source Method," AIAA Paper 2012-2199, June 2012

- Similar inlet/aft differences for multiple liners (linear and nonlinear) – proposed to use average of inlet/aft results

Schulz, Weng, Bake, Enghardt, Ronneberger, "Modeling of liner impedance with grazing shear flow using a new momentum transfer boundary condition," AIAA 2017-3377, June 2016.

- Tested multiple liners; proposed adding a new term (momentum transfer BC)

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Inlet/Aft Mode Impedance Eduction]



Nark, Jones, Piot, "Assessment of Axial Wave Number and Mean Flow Uncertainty on Acoustic Liner Impedance Eduction," AIAA 2018-3444, June 2018.

- Minor adjustment to M_{ave} improves comparison between inlet and aft mode impedances

Roncen, Piot, Mery, Simon, Jones, Nark, "Influence of Source Propagation Direction and Shear Flow Profile in Impedance Eduction of Acoustic Liners," AIAA 2019-2469, May 2019.

- Evaluated effects of shear flow profile and K_n uncertainty on inlet and aft results

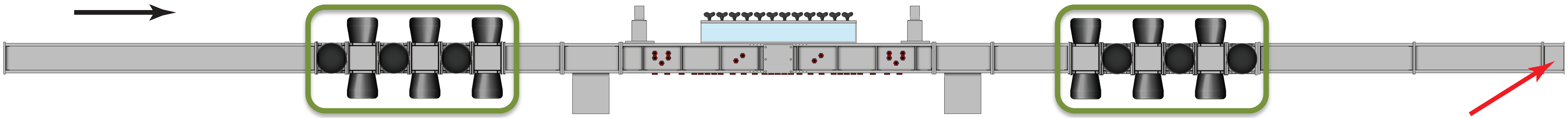
Rienstra, "Solutions and Properties of the Pridmore-Brown Equation," AIAA 2023-2594, May 2019.

- Implemented solution to Pridmore-Brown that enables investigation of the acoustic pressure field in the presence of a prescribed mean flow profile

Bonomo, Quintino, Cordioli, Avallone, Jones, Howerton, Nark, "A Comparison of Impedance Eduction Test Rigs with Different Flow Profiles," AIAA 2023-3346, June 2023.

- Explored effects of boundary layer displacement thickness on 'uniform-flow' educed impedance

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Inlet/Aft Mode Impedance Eduction]



Flow

Upstream acoustic drivers

Test Liner

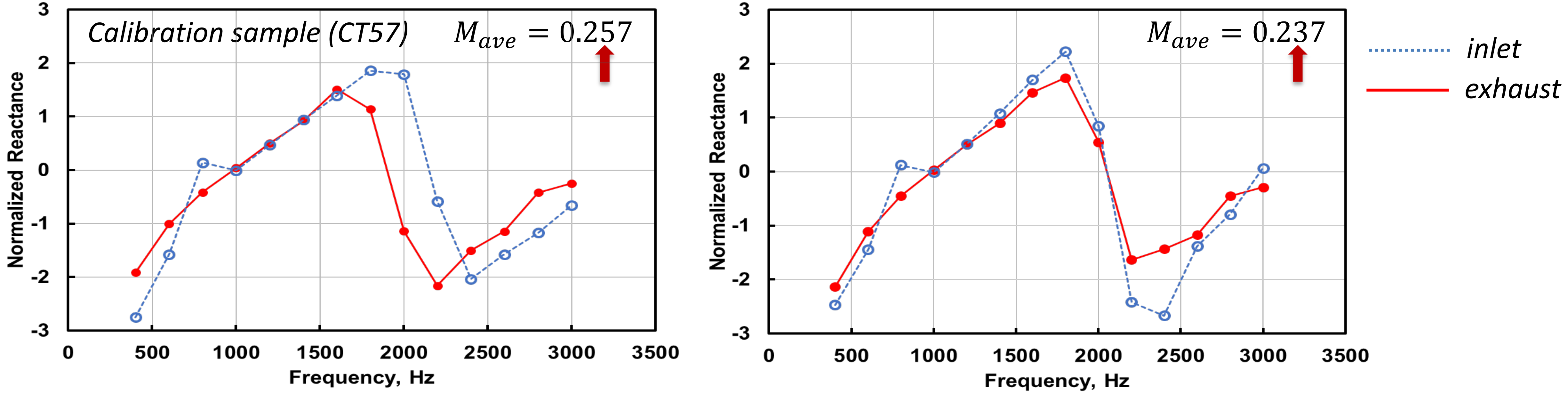
Downstream acoustic drivers

Flow survey

Flow survey

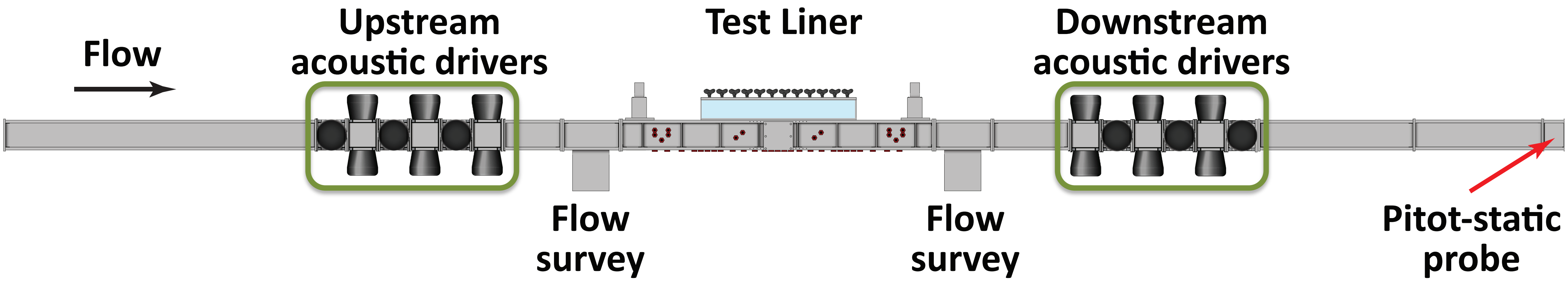
Pitot-static probe

Use combination of inlet & exhaust results with calibration liner to fine tune estimate of M_{ave}.



Goal is to set centerline Mach and total temperature to within ± 0.002 and ± 0.28°C (± 0.5°F) of target values.

$\zeta(f, \mathrm{SPL}, M)$ [GFIT: Inlet/Aft Mode Impedance Eduction]



- Most researchers tend to fall into one of two schools of thought:
  1. The first group assumes the acoustic impedance of the liner to be independent of the flow direction, although it is affected by other changes in the aeroacoustic environment that often accompany a change in flow direction.
  2. The second view is that the liner has a distinct acoustic impedance depending on the flow direction.

NASA perspective

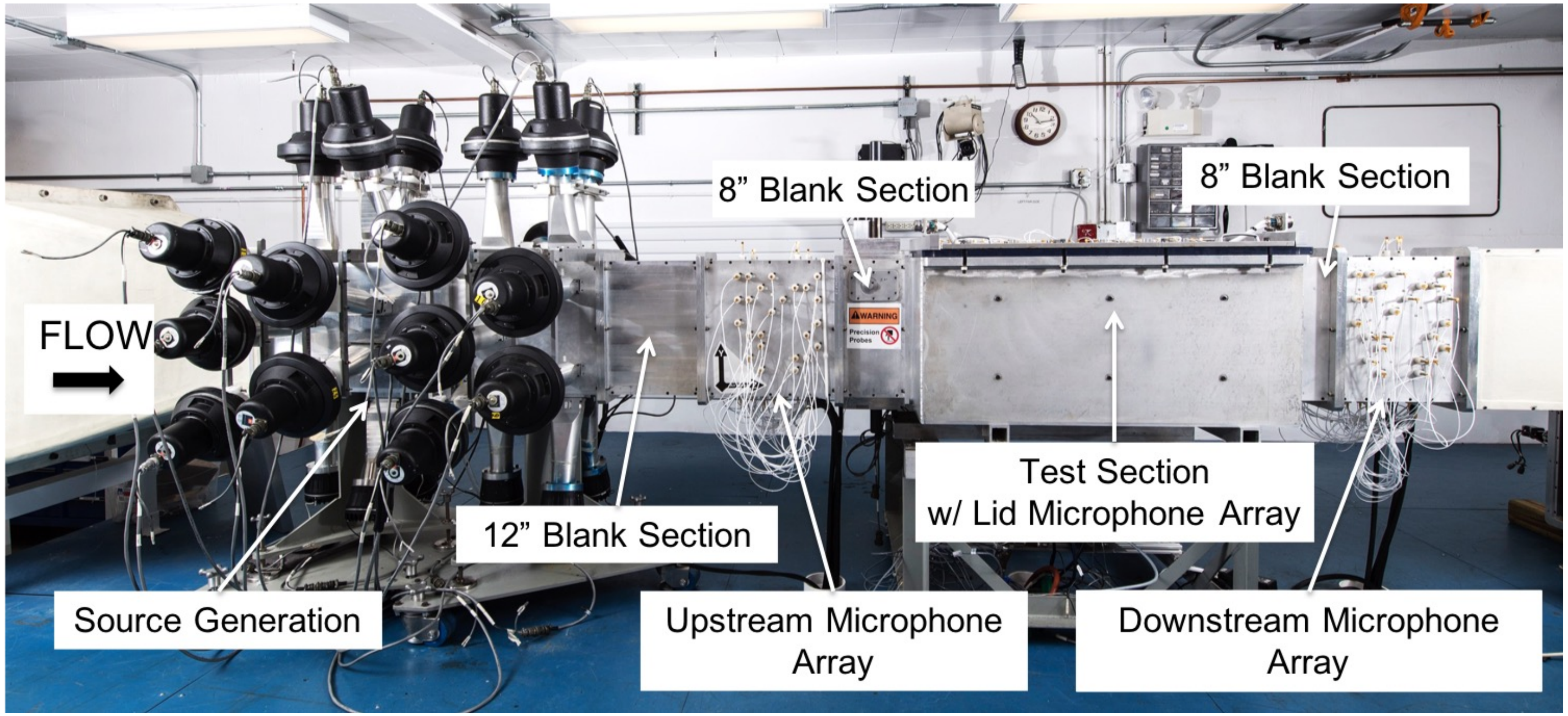
The correct answer (i.e., how one defines “effective” impedance) may lie somewhere in the middle.

- IFAR Challenge #5 seeks clarity on this issue.
  - Test 4 liners (linear and nonlinear) in GFIT
  - National labs (NASA, ONERA, DLR, JAXA, KTH, UFSC) process data using independent approaches.
- Don’t use uniform flow impedance eduction to feed a propagation code with shear flow (may be ok for linear liners)
- Goal: predict sound field in the desired duct

ζ Verification [CDTR]

Features:

- 6”x15” (152mm x 381mm) cross-section, 158 mics
- Evaluate effects of higher-order modes & curvature (M=0.5 flow, 0.4 < f < 3.0 kHz, SPL ≤ 140 dB)
- Controlled mode generation (m=2, n=5), 32 drivers
- Traverse for flow surveys



[Source: NASA]

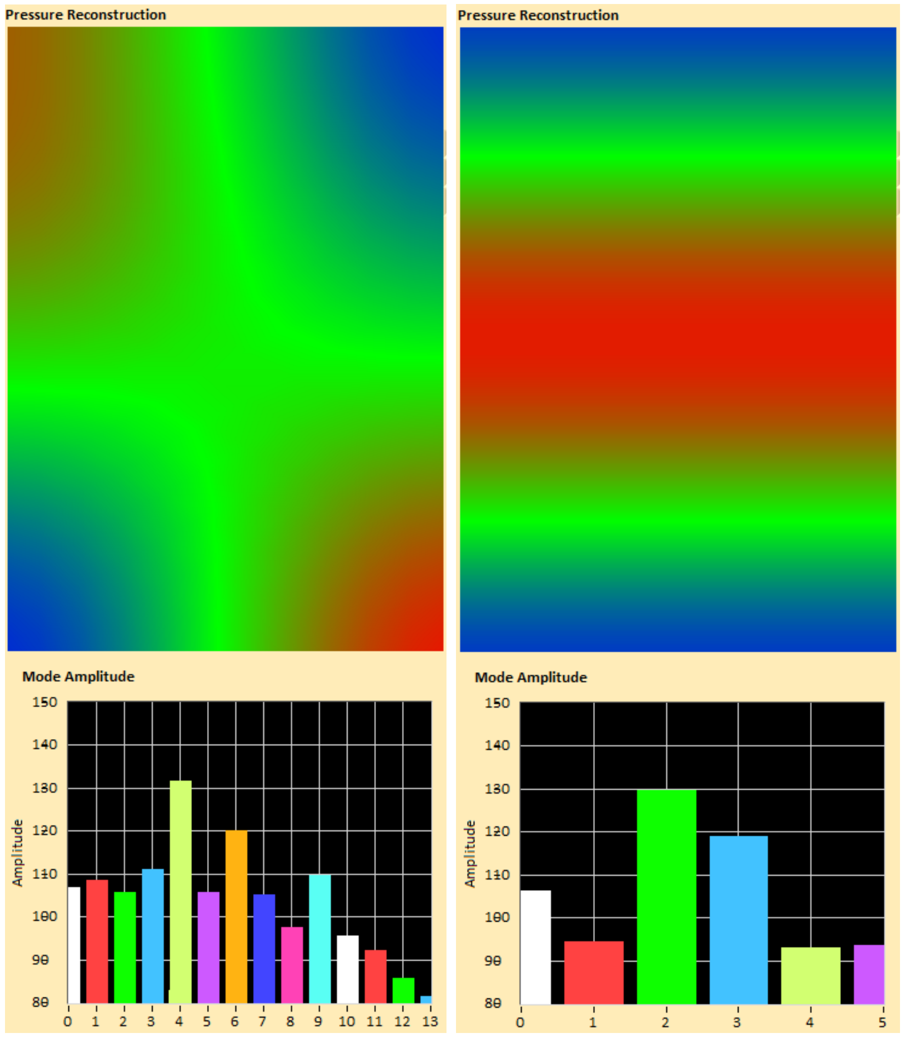
ζ Verification [CDTR]

Mode Control:

- Amplitude/phase control for each driver
- Pseudo-real-time control system to drive to desired mode
- Maximize desired mode / Suppress other modes (10 dB separation)
- Minimum of 1 driver and 1 mic per mode

Red = positive pressure
Blue = negative pressure
Green = no pressure

(1,1) mode *(0,2) mode*



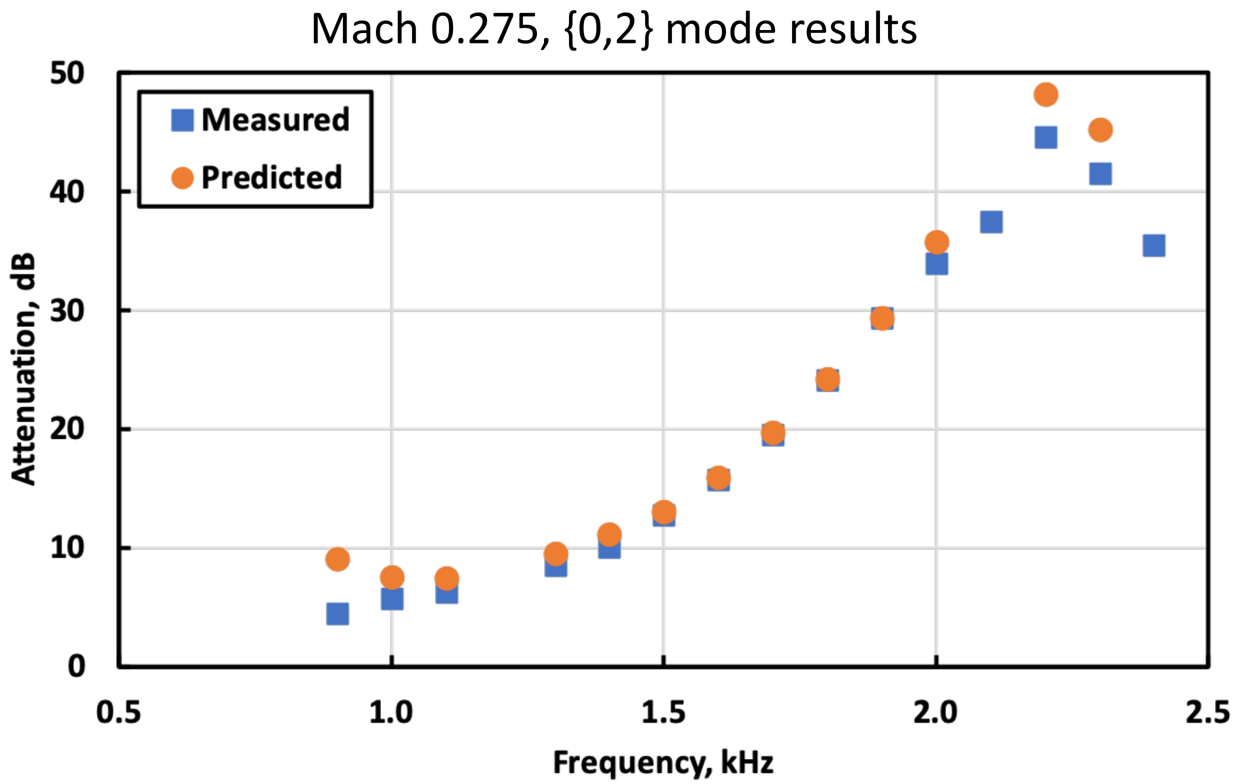
Mode Amplitude

Modal Counter

ζ Verification [CDTR]

Method:

- Use impedance educed from GFIT with source information to perform propagation predictions
- Install liner with similar geometric parameters to that tested in GFIT in the CDTR sidewall(s)
- Acquire acoustic pressure profiles at simulation conditions
- Favorable comparison used to validate impedance eduction and propagation computational approaches



Reality Check

August 2018 flight test of NASA-designed inlet on B737-MAX

[Source: Boeing]

- Available info (**limited!**):
  - Estimates of M_{ave} at fan face and inlet exhaust
  - Representative flow lines
  - Location and available depth for liner
  - Target frequencies

Benefit (EPNL) re: Production Inlet

CUM (Inlet)	CUM (Airplane)
3.2 EPNdB	0.7 EPNdB

1. *Wong, Nesbitt, Jones, Nark: "Flight Test Methodology for NASA Advanced Inlet Liner on 737MAX-7 Test Bed (Quiet Technology Demonstrator 3)," AIAA 2019-2763, May 2019*
2. *Nark, Jones: "Design of an Advanced Inlet Liner for the Quiet Technology Demonstrator 3," AIAA 2019-2764*
3. *Nark, Jones: "An Acoustic Liner Design Methodology Based on a Statistical Source Model," International Journal of Aeroacoustics, June 2021*

Measurement Issues

Importance of Calibration Samples

- Useful for impedance eduction method validation

Signal Extraction / Signal Processing

- Cross-spectrum analysis useful for measuring tones buried in flow noise

Measurement of Higher-Order Modes

- Uniform-flow mode description degrades as shear flow profile becomes more pronounced

Mean Flow Profile Effects

- Rice-Heidelberg estimate for the effects of mean flow for conventional perforates is a function of the boundary layer displacement thickness (see Bonomo)

Liner Drag

- Static pressure differences over the length of the liner (in a GFIT-like duct) can be used to estimate the drag due to an acoustic liner

Note: Remember that acoustic liners have multiple good AND bad "features"
(e.g., sound absorption, thermal barrier; added weight, drag, self-noise)

1. *Bonomo, Quintino, Cordioli, Avallone, Jones, Howerton, Nark, "A Comparison of Impedance Eduction Test Rigs with Different Flow Profiles," AIAA 2023-3346, June 2023*
2. *Goldstein, Rice, "Effect of Shear on Duct Wall Impedance," J. of Sound and Vibration, Vol. 30(1), 1973.*

A few additional references

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Acknowledgements

NASA Langley Liner Physics Team

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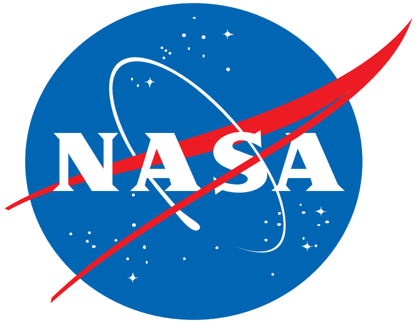
- Jordan Kreitzman
- Douglas Nark (Co-Lead)
- Eric Nesbitt
- Max Reid

Advanced Air Transport Technology Project
of the NASA Advanced Air Vehicle Program

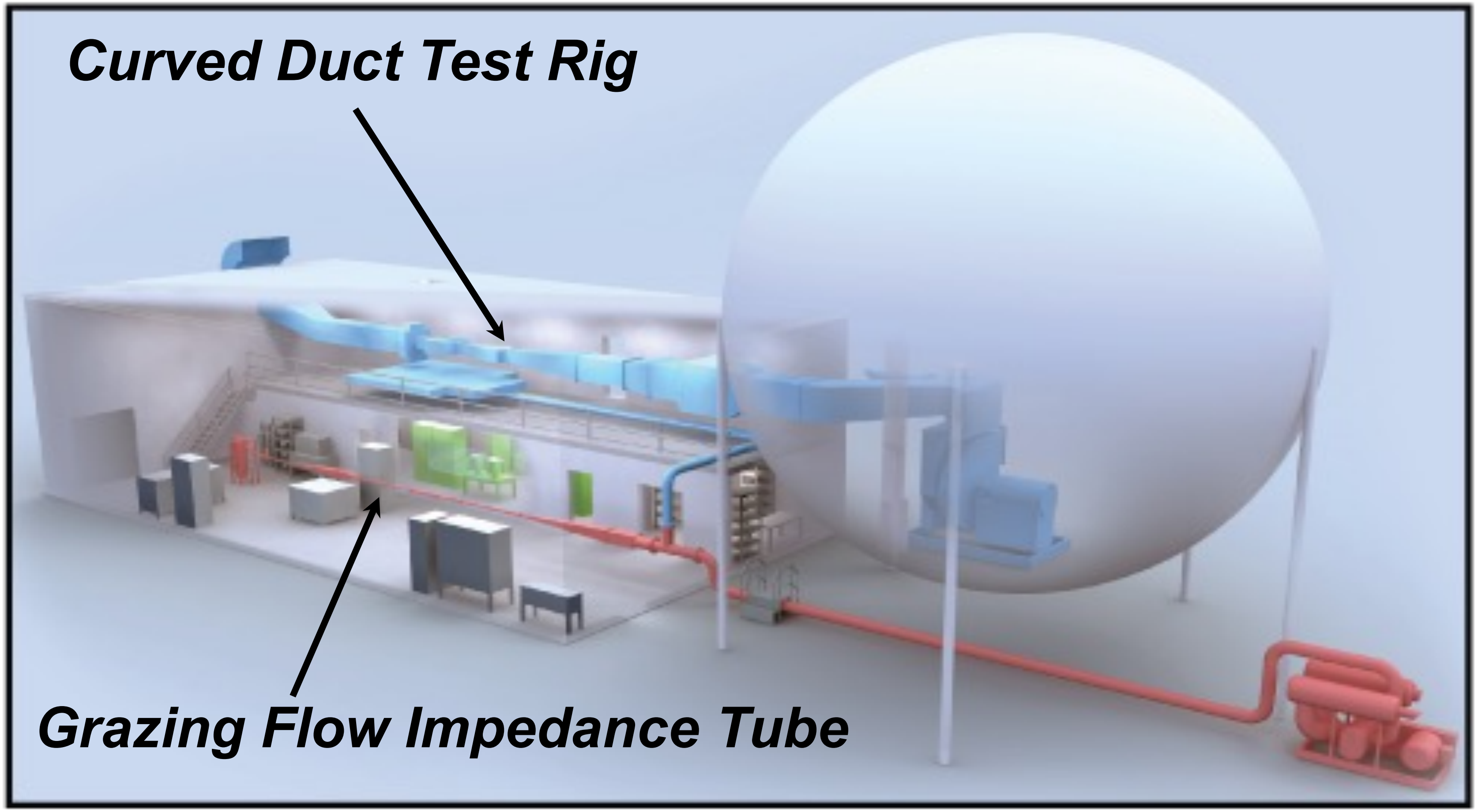

NASA

Backup Slides

NASA LaRC Liner Technology Facility

Purpose:

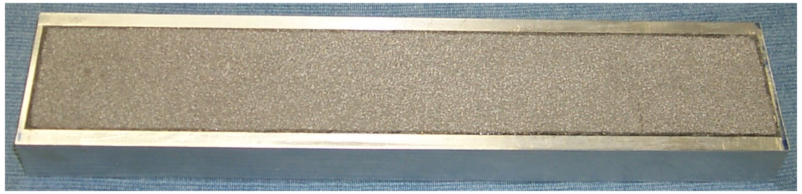
Perform acoustic measurements under a variety of physical conditions to characterize the response of liners and determine their effective impedance



Extended-Reacting "Bulk" Liner

Zero-resistance facesheet + unblocked lateral wave

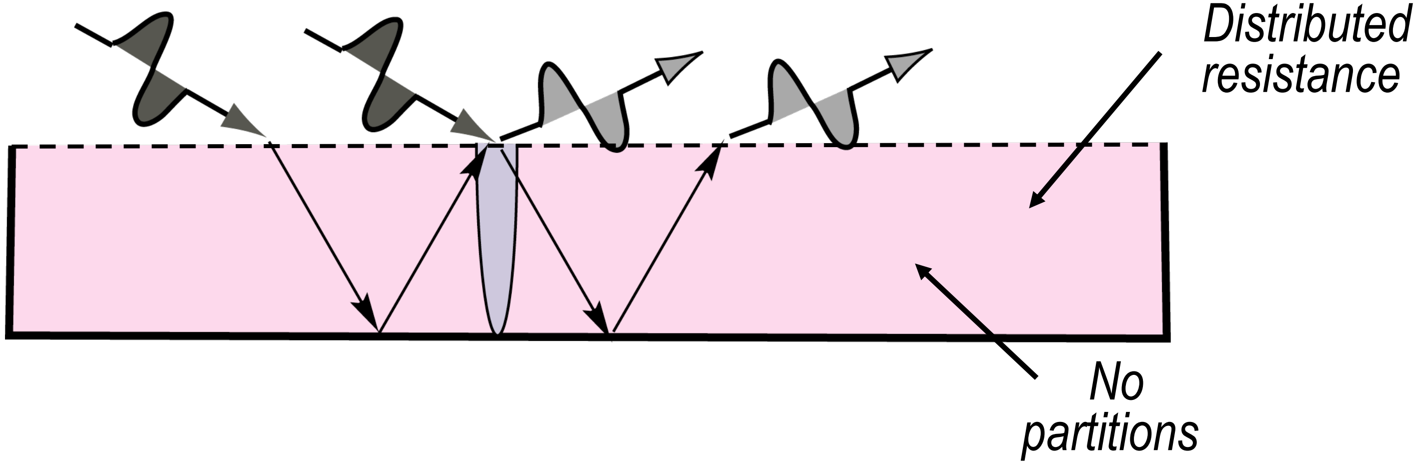
- Continuous distribution of resistance
- Attenuated internal wave propagation
- Reduced internal sound speed



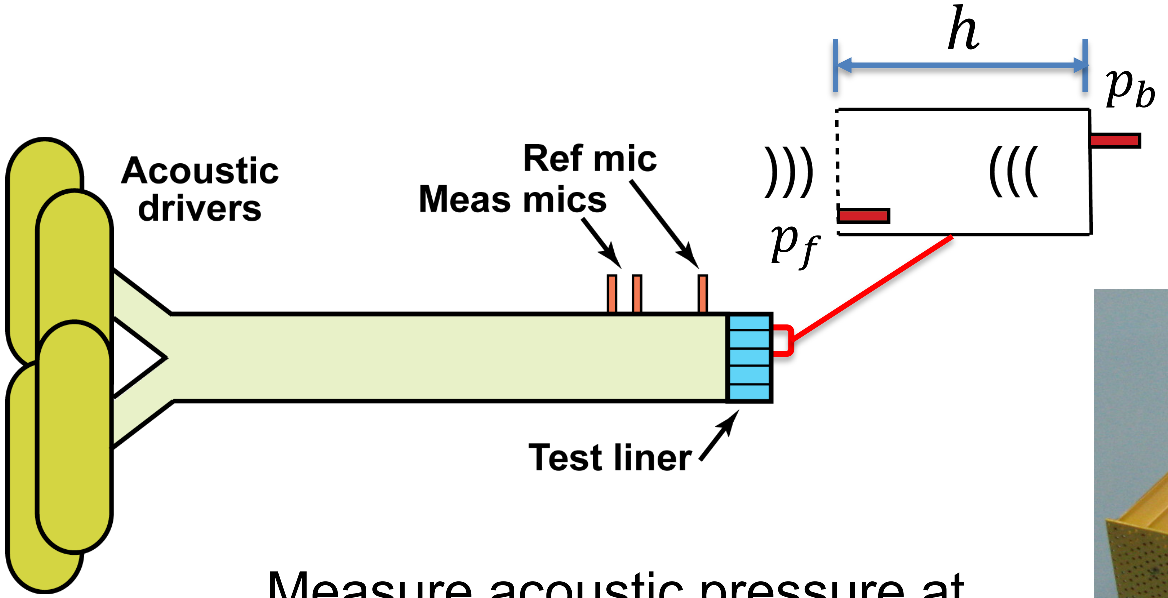
[Source: NASA]

Salient features

- Subdued depth-related resonance
- Improved absorption bandwidth

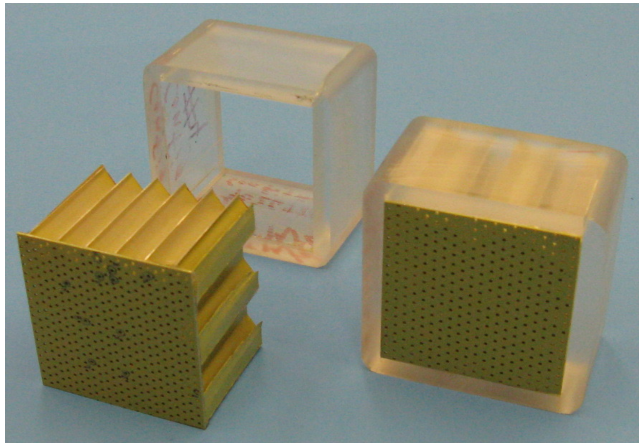


$\zeta(f, \mathrm{SPL})$ at M=0 [*In Situ* Method]



Measure acoustic pressure at

- facesheet, p_f
- backplate, p_b



[Source: NASA]

$$\zeta = \frac{p_f}{u_f} = \frac{-i}{\sin(kh)} \frac{p_b^* p_f}{p_b^* p_b}$$

** denotes complex conjugate*
k = freespace wavenumber

$\zeta(f, \mathrm{SPL})$ at M=0.0 [*In Situ* Method]

Pros:

- Very simple and quick
- Can be used in lab and in aircraft engine

Cons:

- Provides local, not global, impedance
- Facesheet microphone positioning is critical
  - Mic must be outside hydrodynamic near field of the perforate
  - Need to account for blockage of cell
  - Care needed regarding sealing around edges of microphone
- Backplate microphone
  - Difference in results when microphone is mounted at center versus near the edge of the cell

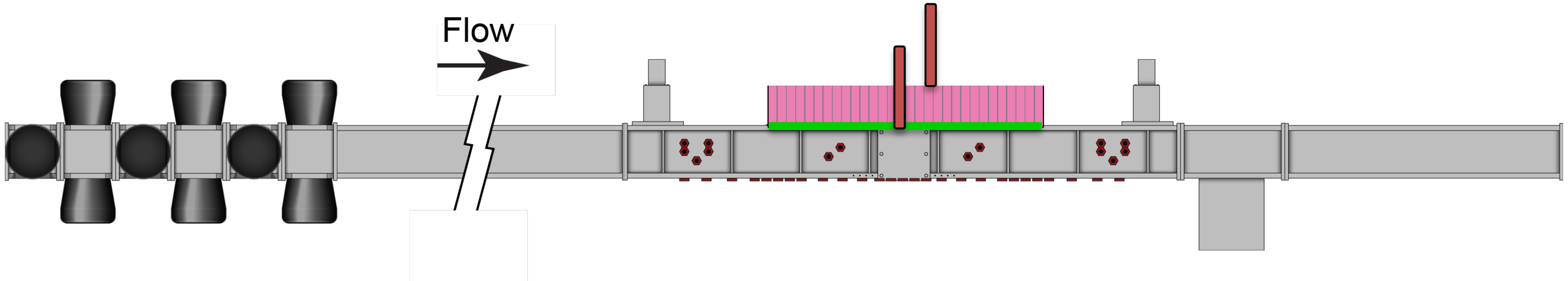
Dean: "An In Situ Method of Wall Acoustic Impedance Measurement in Flow Ducts," Journal of Sound and Vibration, 1974

Murray, Ferrante, and Scofano: "Manufacturing Process and Boundary Layer Influences on Perforate Liner Impedance," AIAA 2005-2849

$\zeta(f, \mathrm{SPL}, \mathrm{M})$ [*In Situ* Method]

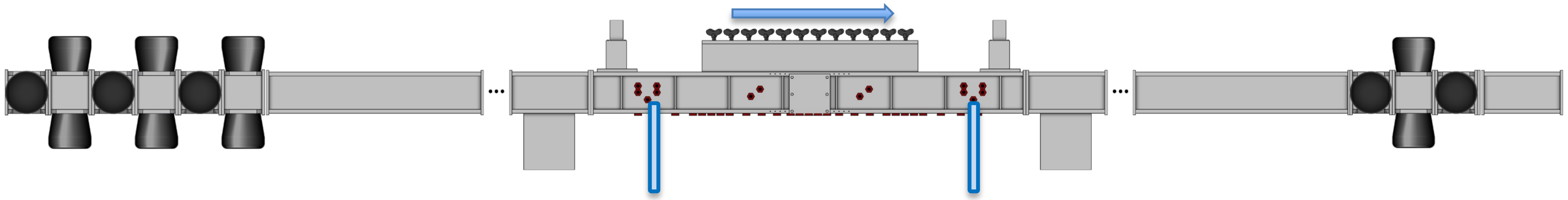
- Same setup as described for normal incidence
- Very efficient but sensitive to microphone placement issues
- Provides local instead of global impedance

$$\zeta = \frac{p_f}{u_f} = \frac{-i}{\sin(kh)} \frac{p_b^* p_f}{p_b^* p_b}$$



$\zeta(f, \mathrm{SPL}, \mathrm{M})$ [GFIT: Special Topics]

Liner Drag:



Investigating statistical modeling to enable improved fidelity of results

Goal = 80% reduction; difficult to assess beyond ~50%

Liner Drag (relative to conventional liner)

Computation Method:

- $(\mathrm{D_C} - \mathrm{D_{Goal}})/(\mathrm{D_C} - \mathrm{D_S}) = 0.8$
- Conventional liner, $\mathrm{D_C}$
- NASA best, $\mathrm{D_{NB}}$
- NASA Goal = 80% reduction, $\mathrm{D_{Goal}}$
- Smooth wall (hardwall), $\mathrm{D_S}$