



Evaluation of Variable-Depth Liners with Slotted Cores

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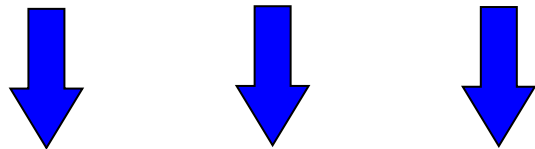
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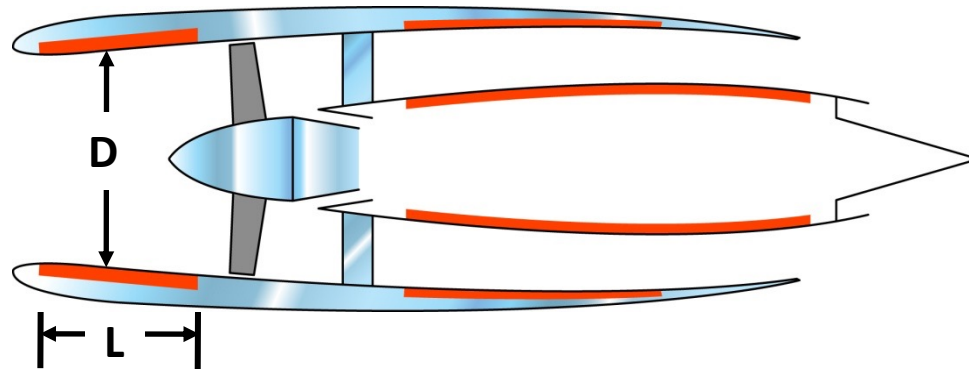
- Background and Purpose
- Impedance Prediction Models
- Experimental Set Up
- Modeling/Design Questions
- Results
 - Slotted-Core Liners with Conventional Phenolic Core
 - Bent-Chamber Liners with Additive Manufactured Core
- Concluding Remarks

Aircraft Engine Trends

- Bypass Ratio ↑
- Fan rotation speed ↓
- L/D ↓
- Advanced Fan Design



**Need for broadband
and low-frequency
sound absorption**



Liner Options

Broadband (~1-3 kHz)

1. 2DOF/MDOF liners
2. Variable-impedance liners (e.g., **variable-depth**)

Low frequency (~0.6 kHz)

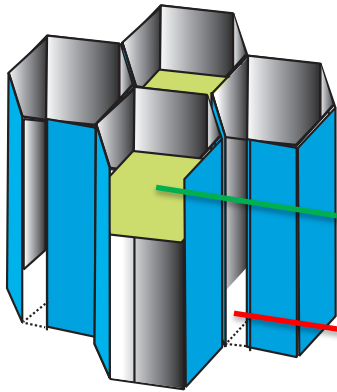
1. SDOF with increased core depth
2. **Single-layer liner with bent chambers**

Purpose



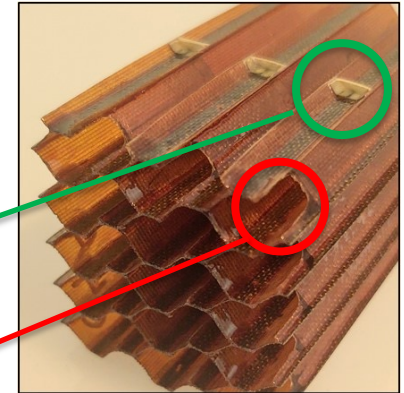
Goal: To develop a liner concept that:

- Provides broadband (to include lower frequencies) sound absorption
- Requires less weight and total thickness than current conventional liners
- Employs flightworthy components (e.g., load-bearing, nonflammable, no fluid retention)
- Behaves in a predictable manner



Slotted-core liner concept

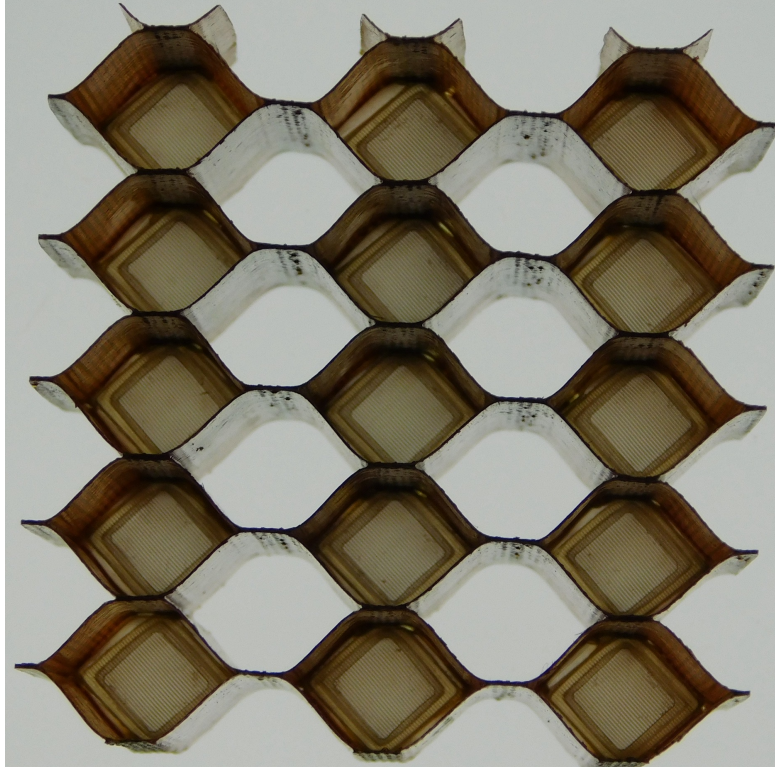
- Conventional phenolic honeycomb core
- Two distinct chambers
- Embedded PEEK film caps to approximate a rigid boundary condition
- Slots at bottom of core (similar to current drainage slots)



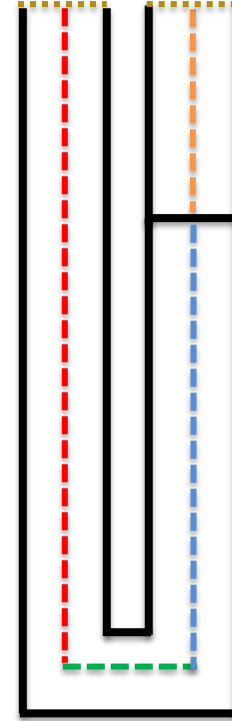
Two-Chamber Configuration



Core with embedded PEEK film - Top View



Sketch of two chambers



Impedance Prediction Models (ZKTL, TPM)



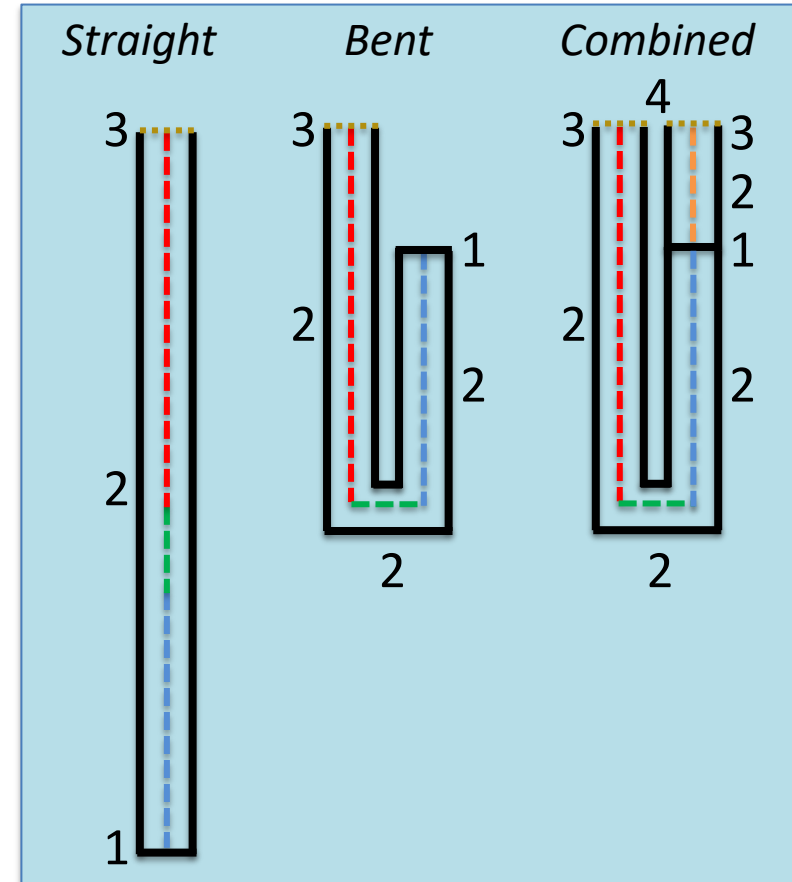
$$\{\text{Perforate}\} \quad \zeta = \theta + i\chi = f(d, t, \sigma, L, \zeta_{\text{bp}})$$

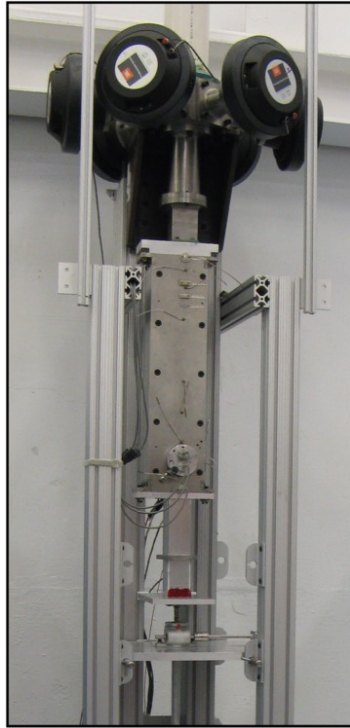
$$\{\text{Mesh}\} \quad \zeta = \theta + i\chi = f(R_f, L, \zeta_{\text{bp}})$$

ZKTL is linear, TPM is nonlinear

Calculation Process

1. Start at backplate
2. Use ZKTL to account for sound transmission through individual chambers
Choices: $L = L_{\text{ave}}$ or $L = L_C$
3. Use ZKTL or TPM to include effects of wire mesh or perforate facesheet, respectively, for each chamber
4. Combine at surface $\rightarrow$ effective impedance





Normal Incidence Tube (NIT)

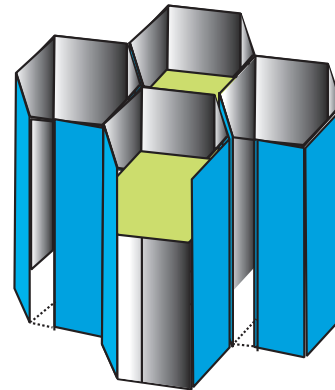
- 2" x 2" waveguide
- Freq: 0.4 to 3.0 kHz
- Source Type: Swept Sine
- Source SPL: 120, 140 dB
- Two-Microphone Method

Modeling/Design Questions

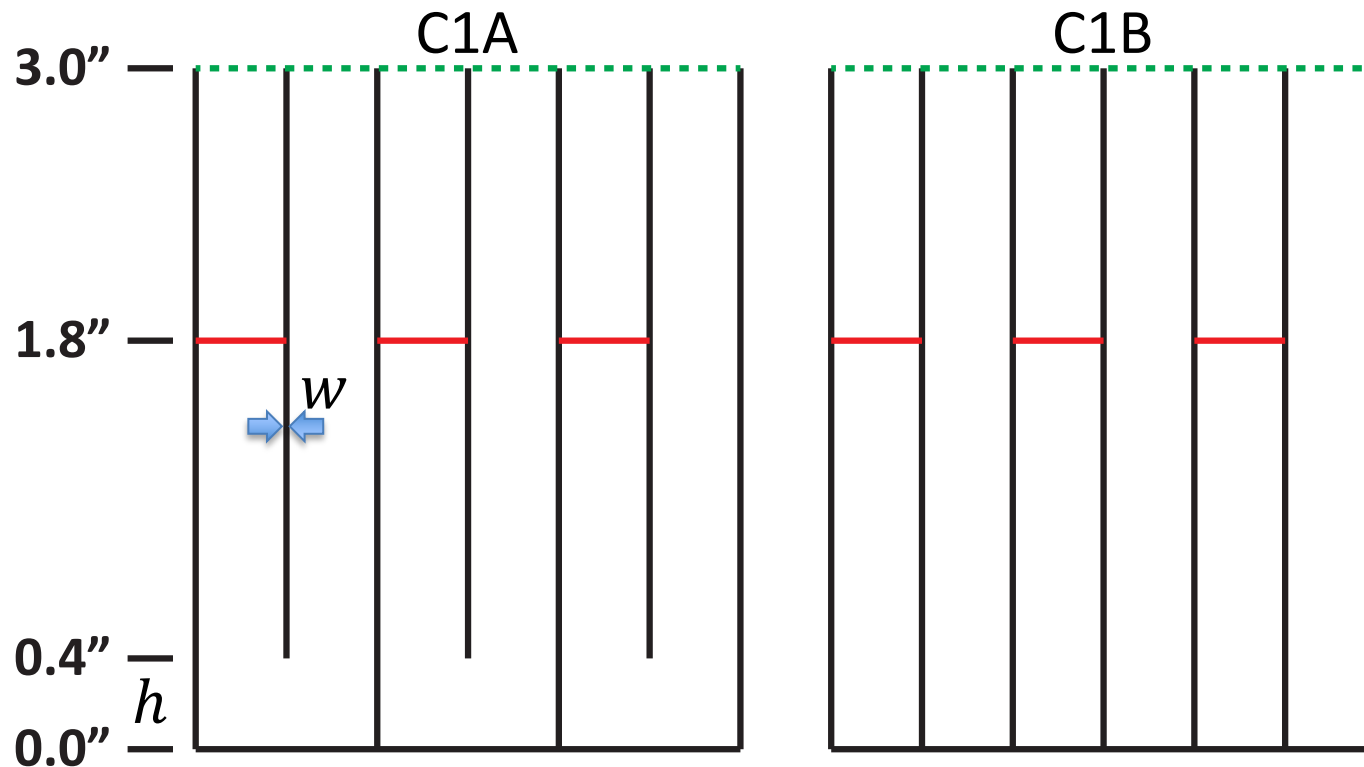


1. Can a two-chamber configuration provide broadband noise absorption?
2. Does PEEK film provide a rigid wall boundary condition?
3. What are the effects of bending the chamber?
4. What are the effects of eliminating the slots?
5. Does sound transmit through the partitions?
6. What is the impact of phase differences at the surface of adjacent chambers?
7. What are the effects of tangential mean flow over the liner surface?

- Items 1 – 4 are addressed in this study
- Item 5 is partially addressed
- Items 6 – 7 are proposed for future work



Variable-Depth Liners with and without Slots

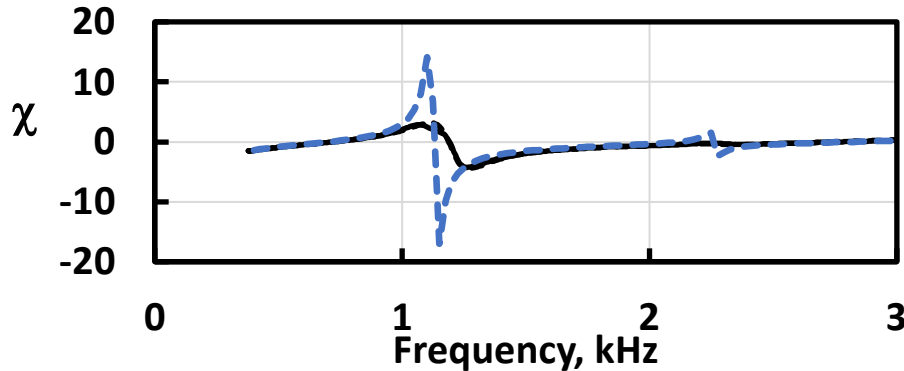
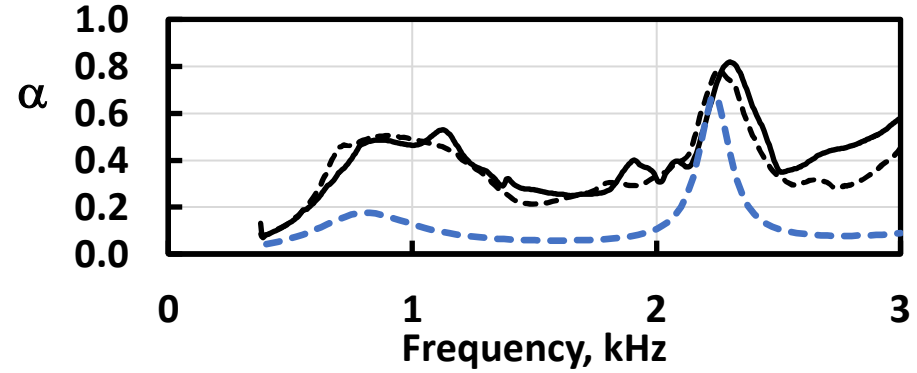
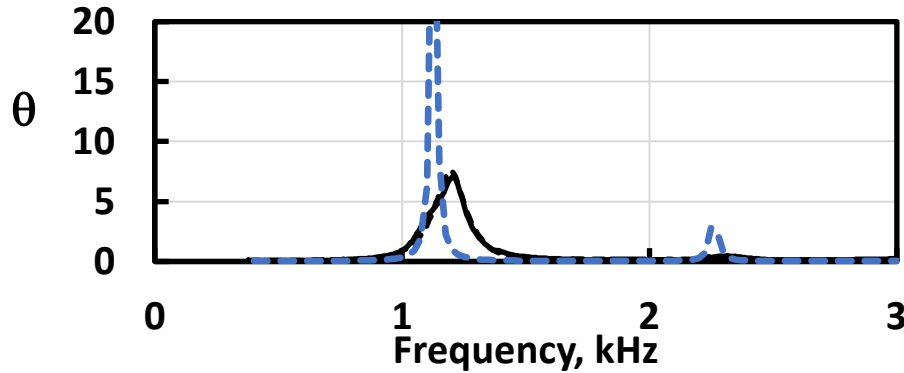


Label	Size
w	0.000"
h	0.400"
L_{ave}	4.775"
L_C	4.430"

----- Facesheet
—— PEEK

Oversized to support model evaluation

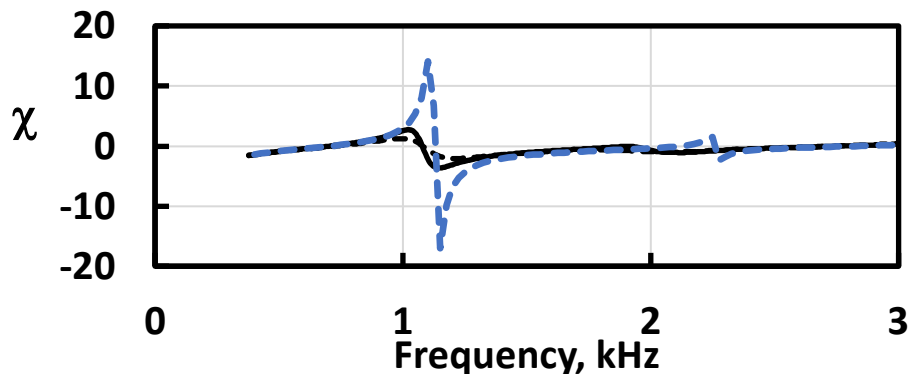
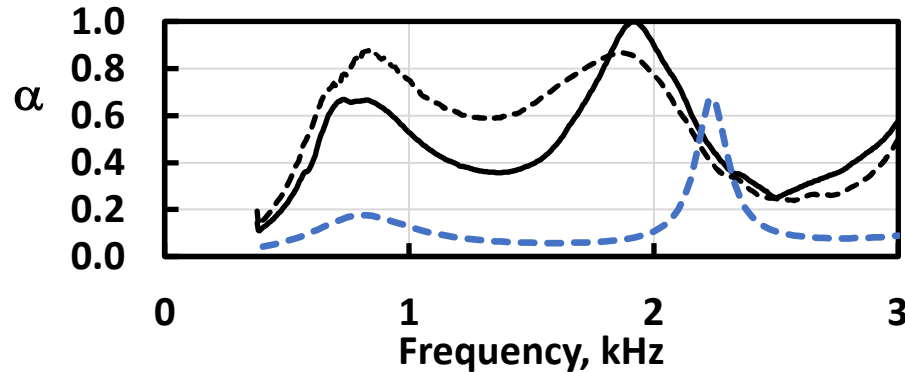
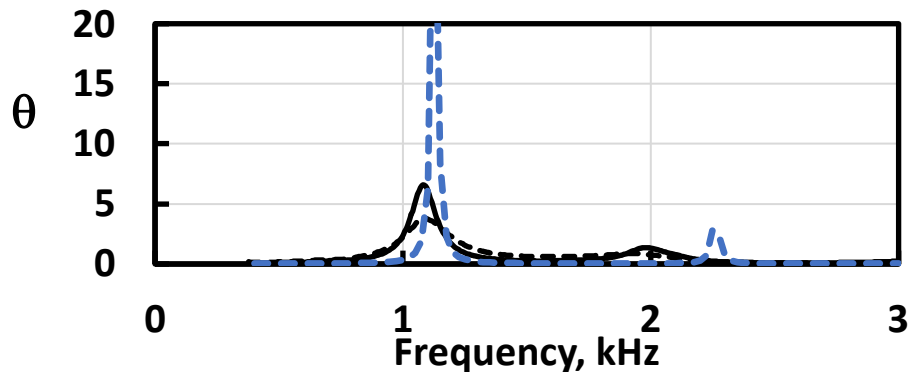
Variable-Depth with Slots – C1A (no facesheet)



— Meas, 120 dB - - - - Pred, L_C
- - - - Meas, 140 dB

- 2 chambers $\rightarrow$ broadband absorption
- $\zeta_{\text{Meas}} \approx \zeta_{\text{Pred}}(L_C)$, except for magnitude near antiresonance $\rightarrow$ PEEK film acoustically rigid
- Small ζ differences $\rightarrow$ large α changes

Variable-Depth without Slots – C1B (no facesheet)



— Meas, 120 dB - - - - Pred, L_C
- - - - Meas, 140 dB

- No change in ZKTL prediction
- Slight increase in $\theta \rightarrow$ much better α
- Broadband absorption achieved with or without slots
- Prediction captures trends, but improvements are needed

Are the modeling errors caused by bent chamber?

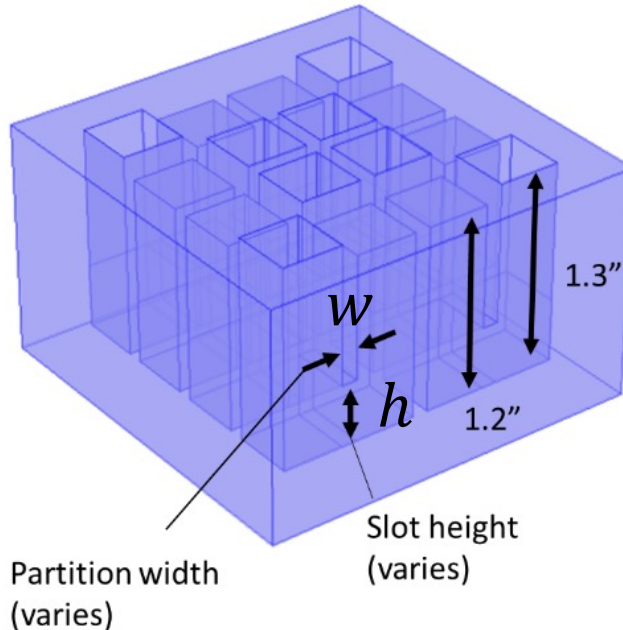
Bent Chamber Evaluation



Modeling Options

1. ZKTL with average length (L_{ave})
2. ZKTL with Cummings correction (L_C)
3. Model slot as perforate with TPM

*Additively
manufactured
samples*



- Evaluated 11 slot configurations
- 0.400"x0.400" chambers
- No facesheet

$$0.032'' \leq h \leq 0.800''$$

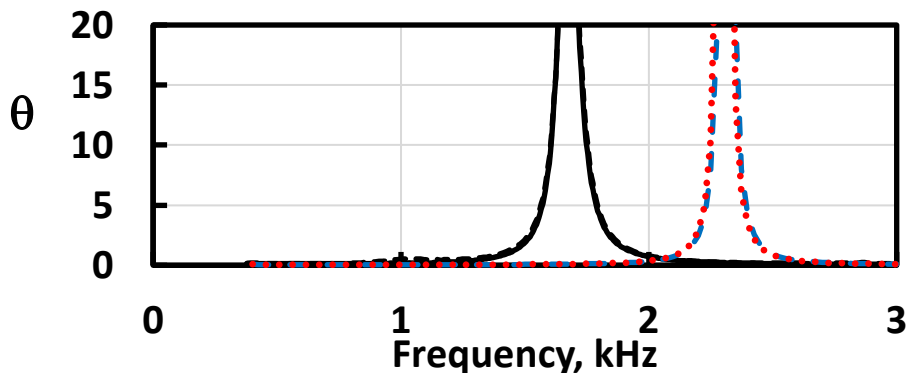
$$0.032'' \leq w \leq 0.150''$$

Effects of Slot Height ($h \leq 0.1''$)

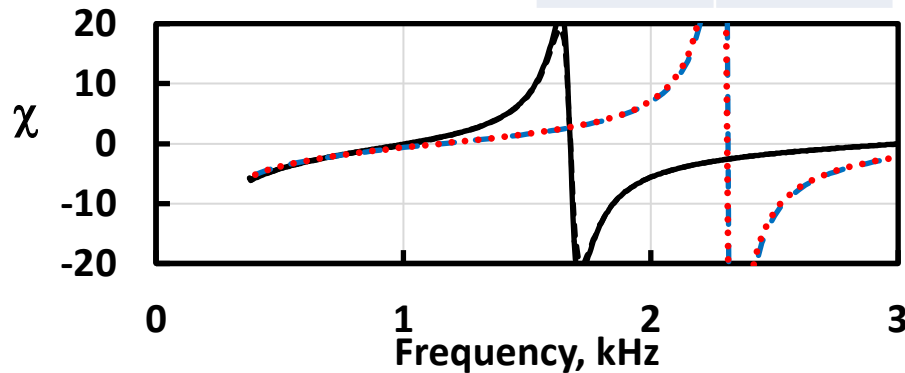


- Slot height $\leq$ chamber diameter
- $\zeta(L_{ave}) \approx \zeta(L_C)$
- f_{res} is properly predicted
- $f_{antires}$ is overpredicted

Label	Size
w	0.100"
h	0.064"
L_{ave}	2.936"
L_C	2.924"



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

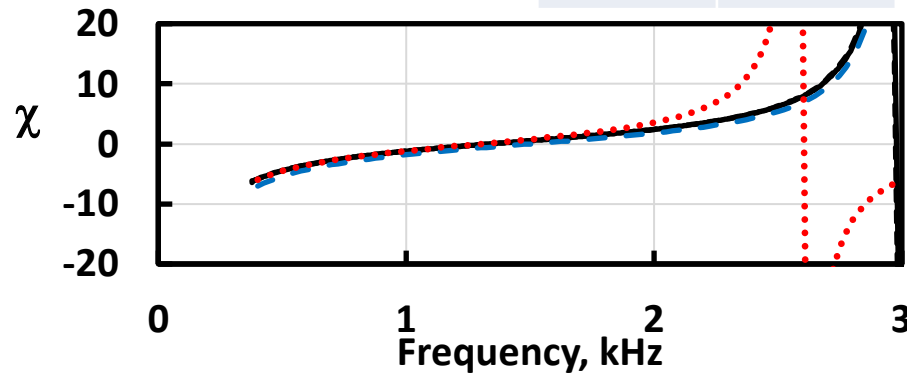
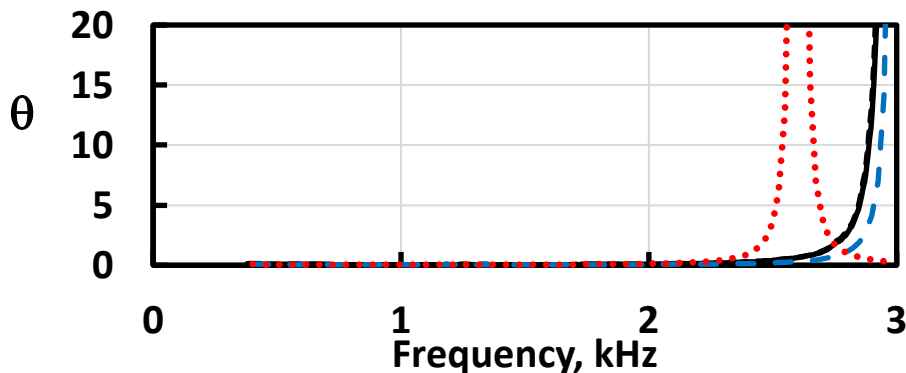


Effects of Slot Height ($h \geq 0.4''$)



- Slot height $\geq$ chamber diameter
- $\zeta(L_{ave}) \approx \zeta(L_C)$
- f_{res} is properly predicted (with L_C or L_{ave})
- $f_{antires}$ is
 - underpredicted with L_{ave}
 - properly predicted with L_C

Label	Size
w	0.100"
h	0.400"
L_{ave}	2.600"
L_C	2.252"



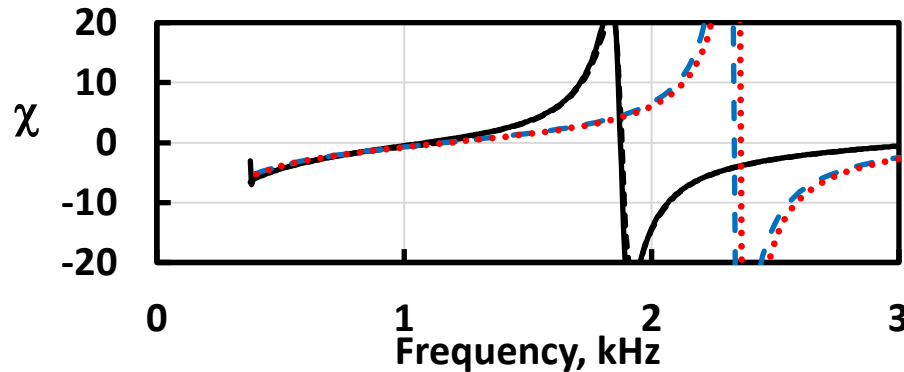
— Meas, 120 dB - - - - Pred, L_C
 - - - - Meas, 140 dB ····· Pred, L_{Ave}

Effects of Partition Thickness ($h = 0.064''$)

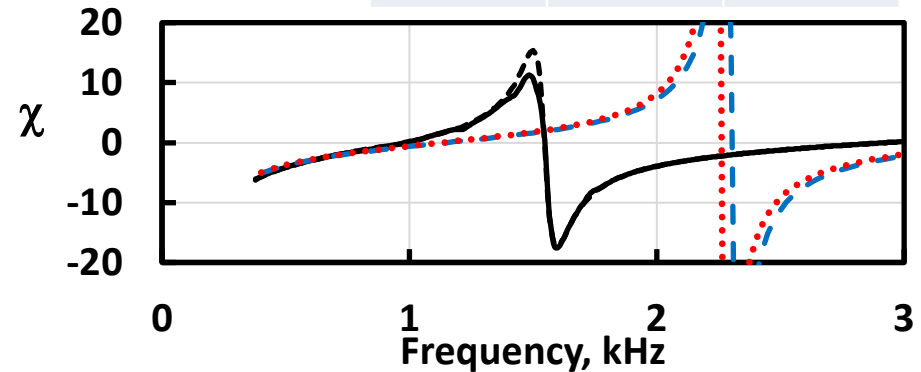


- Slot height $<$ chamber diameter
- $\zeta(L_{ave}) \approx \zeta(L_C)$ for this range of w
- f_{res} is properly predicted
- $f_{antires}$ is overpredicted

Label	Size	Size
w	0.032"	0.150"
h	0.064"	0.064"
L_{ave}	2.868"	2.986"
L_C	2.903"	2.939"



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

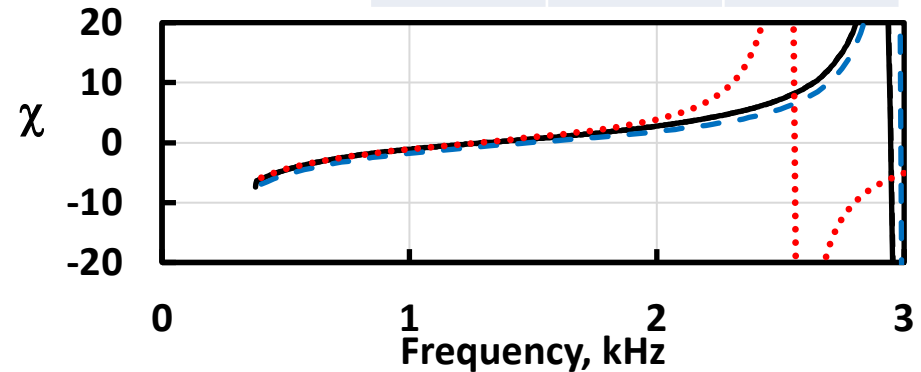
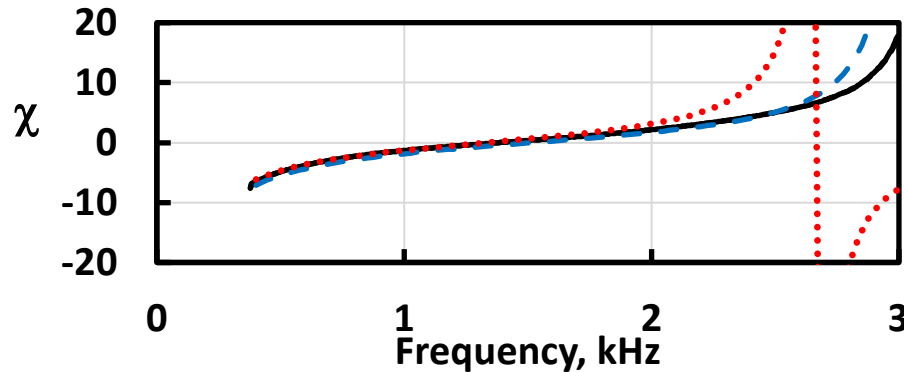


Effects of Partition Thickness ($h = 0.400''$)



- Slot height = chamber diameter
- $\zeta(L_{ave}) \approx \zeta(L_C)$
- f_{res} is properly predicted (with L_C or L_{ave})
- $f_{antires}$ is
 - underpredicted with L_{ave}
 - properly predicted with L_C

Label	Size	Size
w	0.032"	0.150"
h	0.400"	0.400"
L_{ave}	2.532"	2.650"
L_C	2.231"	2.267"



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

Concluding Remarks



Slotted-Core Liners

1. **Two distinct chambers → broadband absorption**
2. PEEK film provides an acceptable rigid wall boundary condition
3. Effect of slots on frequency range of absorption is minimal

Bent-Chamber Liners

1. **Slot height has significant impact on impedance; could be used as a tuning tool (e.g., to achieve low-frequency sound absorption)**
2. Slot width has minimal impact on impedance

Proposed Future Work

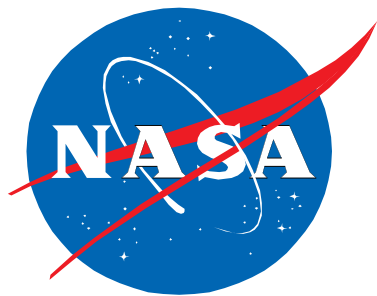
1. Continue model development
2. Examine effects of sound transmission through the partitions
3. Examine impact of phase differences at the surface of adjacent chambers
4. Extend phenolic version of slotted-core to include four distinct chambers

Acknowledgements

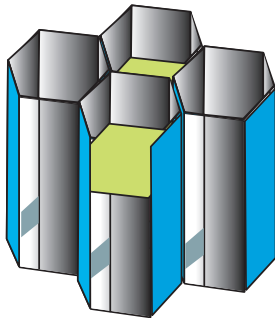


- Clark Smith, Manuel Mejia, and Lisa Bowen of the Hexcel Corporation for support in fabrication of phenolic-core liners.
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- Advanced Air Transport Technology Project of the NASA Advanced Air Vehicles Program for funding this work

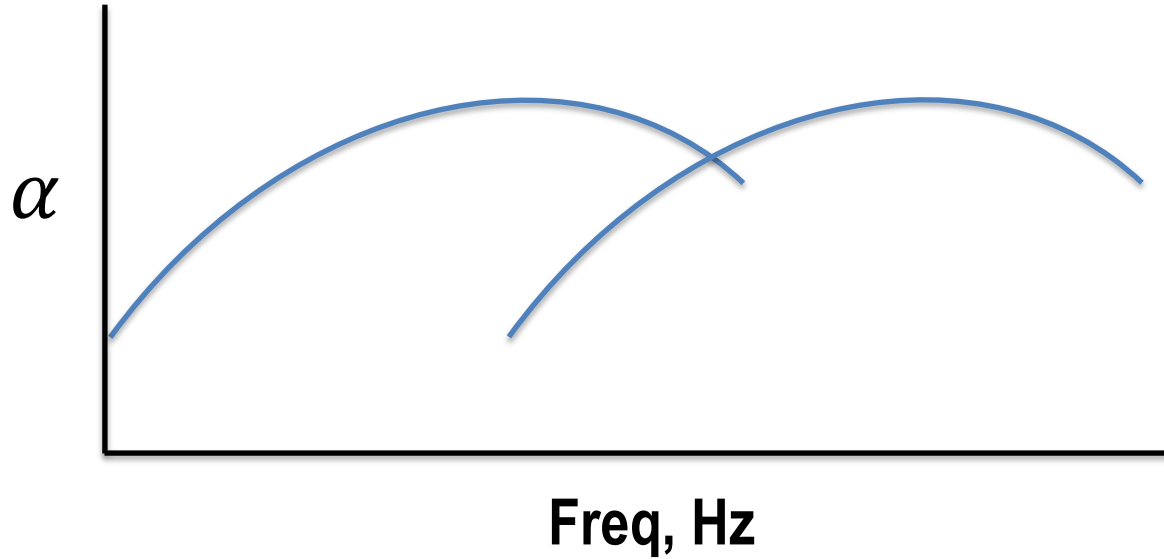




1. Use variable-depth, i.e., combine chambers of different depths
 - Considered by numerous researchers
2. Use bent chambers to reduce thickness
 - Typically modeled as unwrapped straight chambers
 - Works well for key features (e.g., resonance)
 - Ability to accurately predict bent-chamber impedance (especially resonance and antiresonance) is more important for this type of liner
 - Packaging becomes more important/challenging
(see Marinova et al., NASA TM-2020-220560)



Residual Benefits of Multiple Chamber Lengths



Impedance Prediction Models (ZKTL, TPM)



ZKTL

$$\begin{pmatrix} p_0 \\ u_0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} p_{n+1} \\ u_{n+1} \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} p_n \\ u_n \end{pmatrix}$$

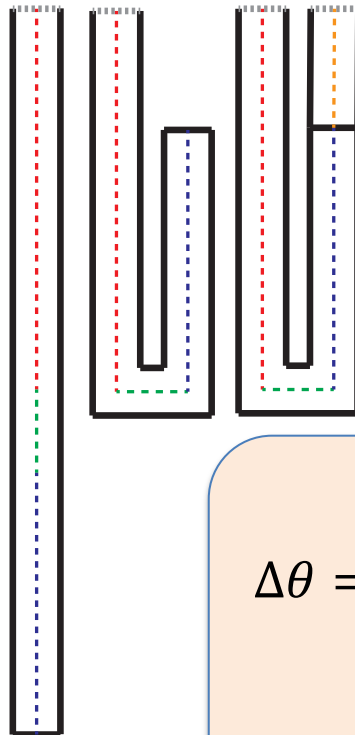
$$T_{11} = T_{22} = \cosh(k\Gamma h)$$

$$T_{12} = \zeta_c \sinh(k\Gamma h)$$

$$T_{21} = \zeta_c^{-1} \sinh(k\Gamma h)$$

$$\beta_i = u_n/p_n \quad \beta_s = \Omega \sum_{i=1}^N \beta_i$$

$$\zeta_s = 1/\beta_s$$



$$\zeta = \theta + i\chi$$

1. Start at backplate
2. Use ZKTL or COMSOL to compute to facesheet
3. Use TPM to include effects of facesheet
4. Combine → effective impedance

TPM

$$\Delta\theta = \frac{a\mu t}{2\rho c(\sigma C_D)d^2} + \frac{k_i + k_e}{2c(\sigma C_D)^2} V_{rms}$$

$$\Delta\chi = \frac{k(t + \epsilon d)}{\sigma C_D}$$

* Also considered COMSOL MultiPhysics

Liner Options

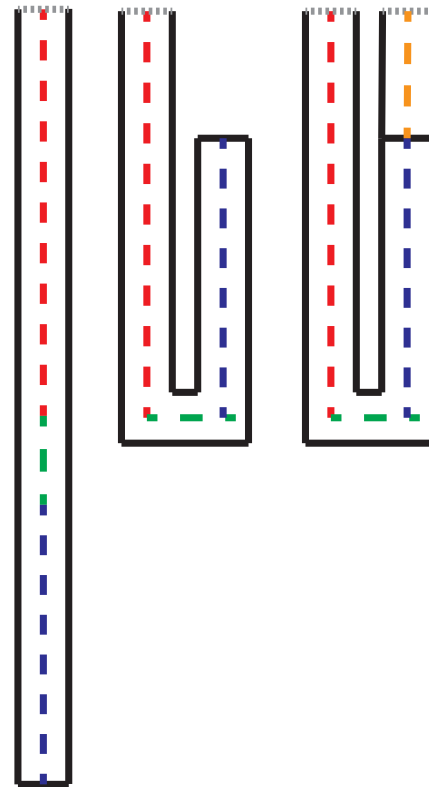


Low frequency

1. SDOF with increased core depth
2. **Single-layer liner with bent chambers to reduce thickness**
 - Considered by numerous researchers
 - Modeling challenges

Broadband

1. 2DOF/MDOF liners
2. Variable-impedance liners (e.g., **variable-depth**)



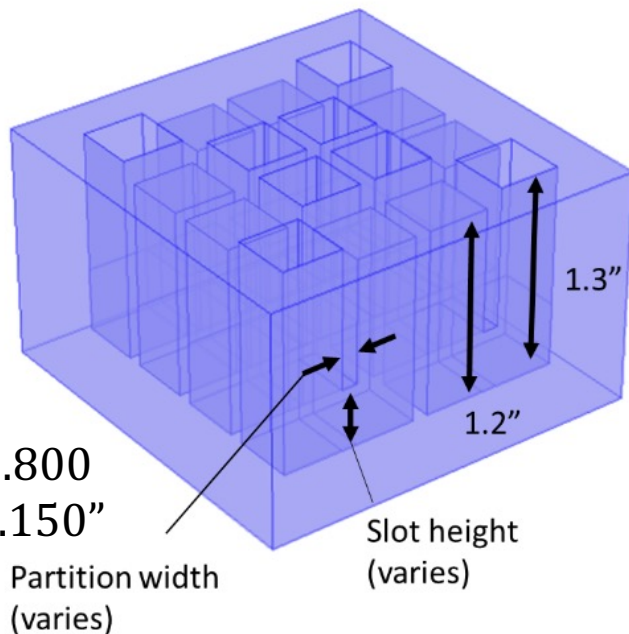
Bent Chamber Evaluation



Modeling Options

1. ZKTL with average length (L_{ave})
2. ZKTL with Cummings correction (L_C)
3. Model slot as perforate (*perf*) with TPM

*Additively
manufactured
samples*



$$0.032'' \leq h \leq 0.800$$
$$0.032'' \leq w \leq 0.150''$$

Configuration	h, in	w, in
1	0.032	0.100
2	0.064	0.032
3	0.064	0.064
4	0.064	0.100
5	0.064	0.150
6	0.100	0.100
7	0.400	0.032
8	0.400	0.064
9	0.400	0.100
10	0.400	0.150
11	0.800	0.100

Effects of Slot Height ($w = 0.100''$) - COMSOL



- COMSOL predicts major impact of slot height on frequency where antiresonance occurs
- This is of limited concern for uniform-depth liners, but significant for variable-depth liners

