A Study on 3D-printed and Segmented Liners

KTH Aeronautical and Vehicle Engineering

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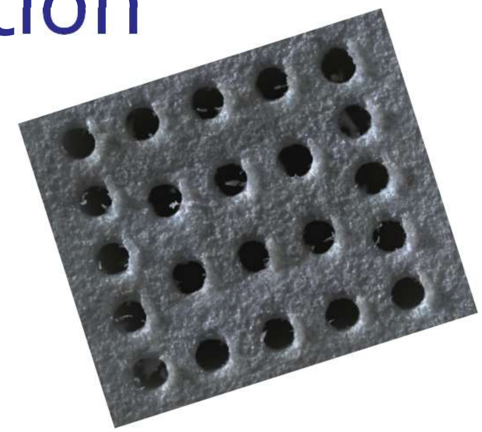
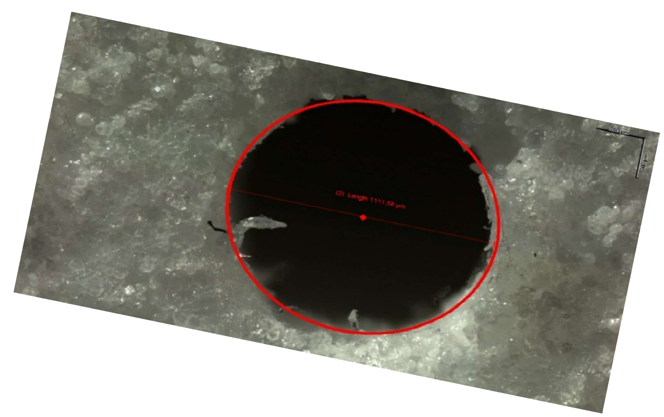
Outline of the presentation



1. Introduction
2. Experimental setup
3. 3-D Printed Liner fabrication
4. Experimental analysis techniques
   Scattering matrix
   Impedance determination
5. Results and discussion
6. Concluding remarks



Introduction

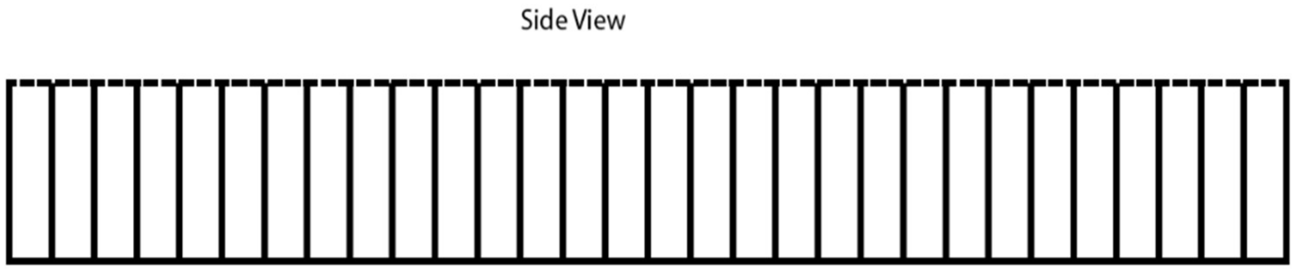
The IFAR Acoustic Liner Challenge is a NASA initiative where data from multiple test rigs with liner configurations fabricated using 3D printing is collected and compared.

The first is a uniform liner (next slide), for which the impedance should be nearly constant over the length of the liner.

The second is a two-segment liner (slide 5), where the only difference between the two axial segments is the depth of the core.

To fit in the KTH liner test facility the number of cells has been modified in the following way: one segment liner 30x5 chambers, two segment liner 10x5 chambers in segment 1 and 20x5 chambers in segment 2. Dimensions are given in the figure captions for Figures 1 and 2.

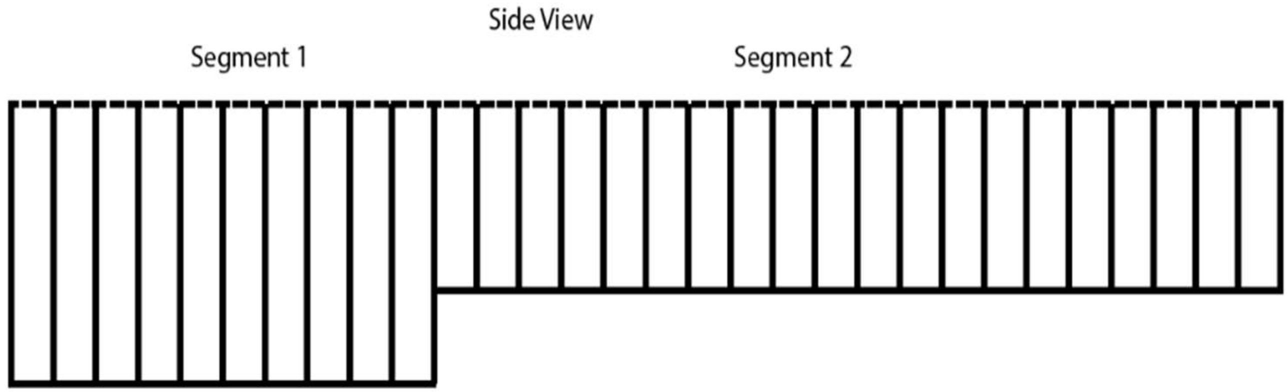
Introduction



30 X 4 Chambers
Core depth: 2.0″
Chamber dimensions: 0.4″X0.4″
Axial partition thickness: 0.133″
Spanwise partition thickness: 0.129″
Drawing has no backplate; we used 0.13″-thick aluminum plate
Facesheet Properties
- Hole diameter: 0.044″ (drawing), 0.043″ (as built)
- Sheet thickness: 0.032″ (drawing), 0.032″ (as built)
- # holes per chamber: 22
- Porosity: 12.5% (drawing), 12.0% (as built)

The KTH liner design was modified to have 30x5 chambers having a length of 405 mm and a width of 67.5 mm.

Introduction



Segment 1
Core depth: 3.0″
10 X 4 Chambers

Segment 2
Core depth: 2.0″
20 X 4 Chambers

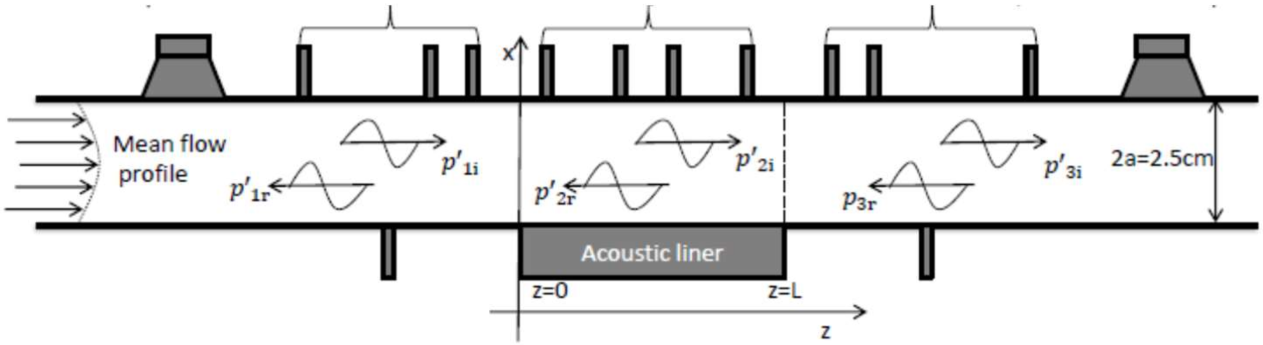
Chamber dimensions: 0.4″X0.4″
Axial partition thickness: 0.133″
Spanwise partition thickness: 0.129″
Drawing has no backplate; we used 0.13″-thick aluminum plate
Facesheet Properties
- Hole diameter: 0.044″ (drawing), 0.043″ (as built)
- Sheet thickness: 0.032″ (drawing), 0.032″ (as built)
- # holes per chamber: 22
- Porosity: 12.5% (drawing), 12.0% (as built)

The KTH liner design was modified to have 10x5 chambers in segment 1 having a length of 135 mm and 20x5 chambers in segment 2 having a length of 170 mm both with a width of 67.5 mm.

Liner impedance eduction technology

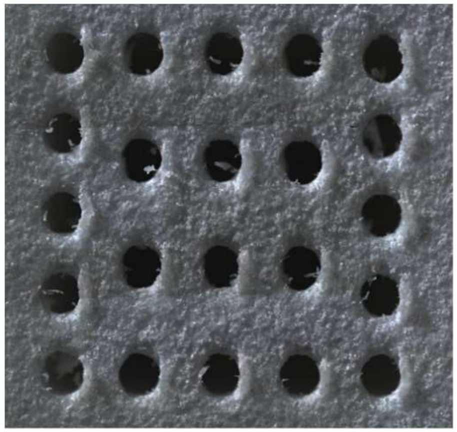
- **Test Flow duct at KTH**

3 upstream mics 10 mics in lined section, 3 downstream mics



Average Mach number	**0~0.3M**	Centrifugal fan with silencing ducts
Incident SPL	**≤130dB**	
Frequency range	**250~3000Hz (tones)**	For these measurements
Wall sound pressure measurement	**10 Mics: above liner** **3 Mics: upstream of liner** **3 Mics: downstream of liner**	Microphones: B&K 4338 ¼ inch
Flow speed Measurement	**16 points over the duct central cross section**	Traversing Pitot tube

3-D printed liner manufacturing



The liners were fabricated using selective layer sintering (SLS) of a PA 2200 polyamide powder on a Formiga P 110 commercial SLS printer with a specified accuracy of 0.2mm +- 0.002mm/mm. The quality of the printed parts was assessed on an Olympus BX53M microscope.

The diameter of 25 randomly picked holes along the silencers was measured and the average value was calculated to be 1.1 mm.

The back side of the cavities was closed with 20mm thick plywood plates and sealed with silicon.

Experimental analysis techniques

Plane wave scattering matrix

$$\begin{pmatrix} p_{ur} \\ p_{dr} \end{pmatrix} = \begin{bmatrix} \rho_d & \tau_u \\ \tau_d & \rho_u \end{bmatrix} \begin{pmatrix} p_{ui} \\ p_{di} \end{pmatrix}$$

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Based on the scattering matrix transmission loss (T_L) and reflection (R), transmission (T) and absorption (A) factors can also be determined:

$$T_{Ld} = -10Log(\tau_d) \qquad T_{Lu} = -10Log(\tau_u)$$

$$R_d = \frac{(1-M)^2}{(1+M)^2} |\rho_d|^2 \qquad R_u = \frac{(1-M)^2}{(1+M)^2} |\rho_u|^2$$

Experimental analysis techniques

$$T_d = |\tau_d|^2 \qquad T_u = |\tau_u|^2$$

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$$A_d = 1 - R_d - T_d \qquad A_u = 1 - R_u - T_u$$

Impedance determination methods

Approximate method to determine axial wave numbers from the transmission coefficients. Relies on the assumption that only the first mode is of importance in the lined section and that reflections between the soft and hard duct sections can be neglected.

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$$\tau_d = \exp(-\mathrm{j}k_{z1d}L) \quad \tau_u = \exp(-\mathrm{j}k_{z1u}L)$$

$$\mathrm{Re}(k_{z1d}) = \frac{-\mathrm{actan}\left(\frac{\mathrm{Im}(\tau_d)}{\mathrm{Re}(\tau_d)}\right)}{L}, \quad \mathrm{Re}(k_{z1u}) = \frac{-\mathrm{actan}\left(\frac{\mathrm{Im}(\tau_u)}{\mathrm{Re}(\tau_u)}\right)}{L},$$

$$\mathrm{Im}(k_{z1d}) = \frac{\ln(|\tau_d|)}{L} \qquad \mathrm{Im}(k_{z1u}) = \frac{\ln(|\tau_u|)}{L}$$

Experimental analysis techniques

We have used our convected Helmholtz Equation – mode matching impedance eduction method[1] where the axial wave number is found by minimizing a cost function consisting of the differences between measured and simulated pressures at four microphone positions.

We have for most of the result used a version of the so-called straight forward technique using the ESPRIT technique[24]

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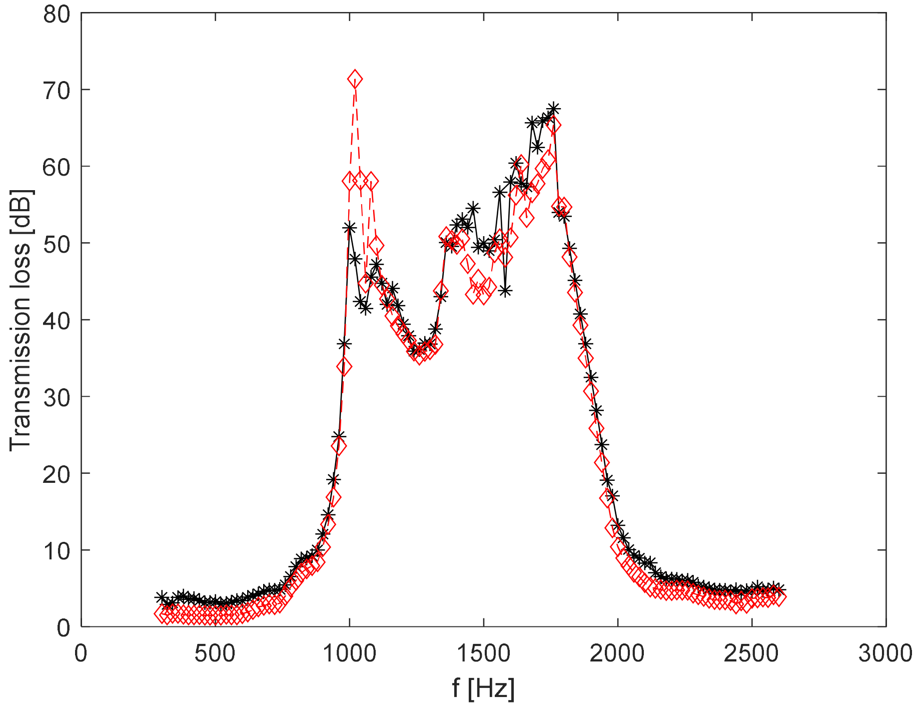
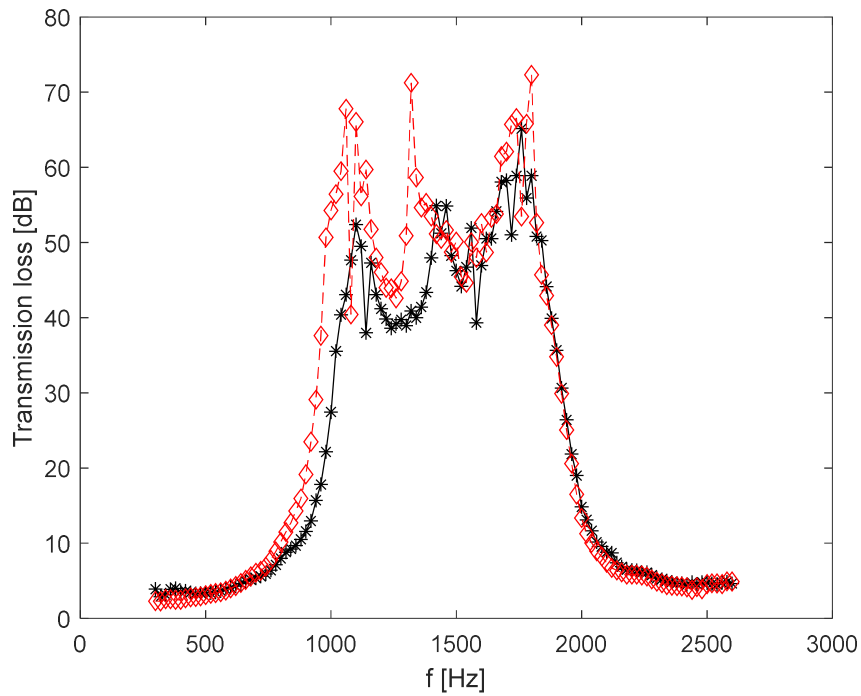
[1]Elnady, T., Bodén, H., and Elhadidi, B., "Validation of an Inverse Semi-Analytical Technique to Educe Liner Impedance," *AIAA Journal*, Vol. 47, No. 12, 2009, pp. 2836-2844.
[2]Potts, D. and Tasche, M. "Parameter estimation for nonincreasing exponential sums by prony-like methods. Linear Algebra and its Applications", 439:1024–1039, 2013.

Results and discussion – Transmission loss
Uniform liner

M =0



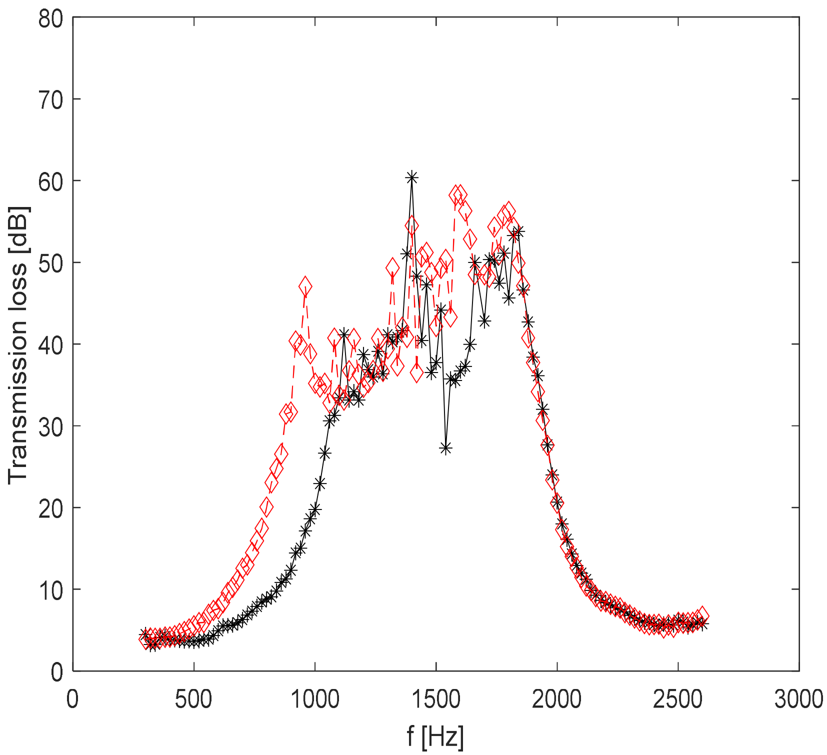
M =0.1



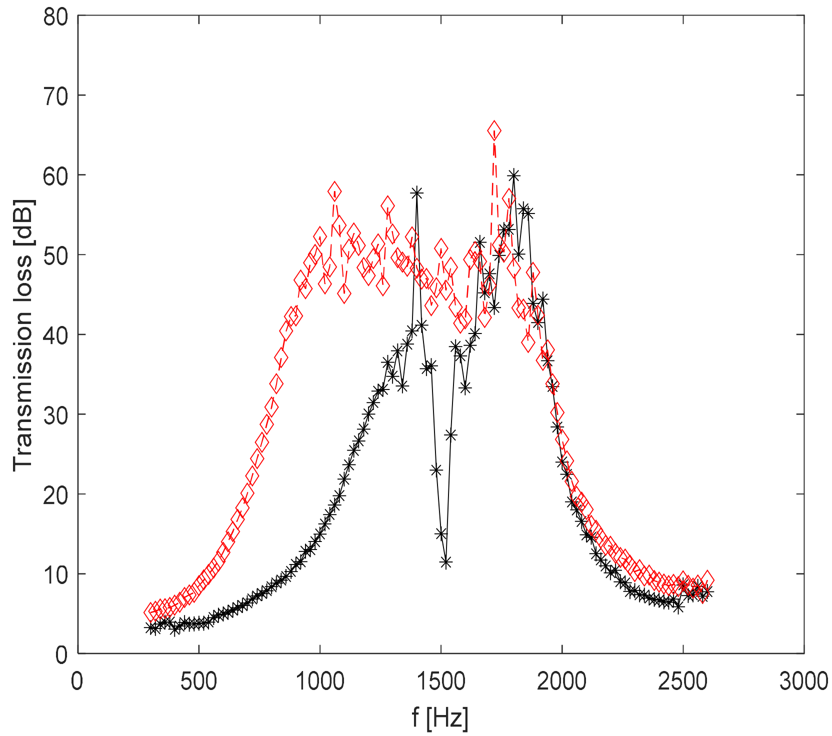
Black – downstream, red - upstream

Results and discussion – Transmission loss
Uniform liner

M =0.2

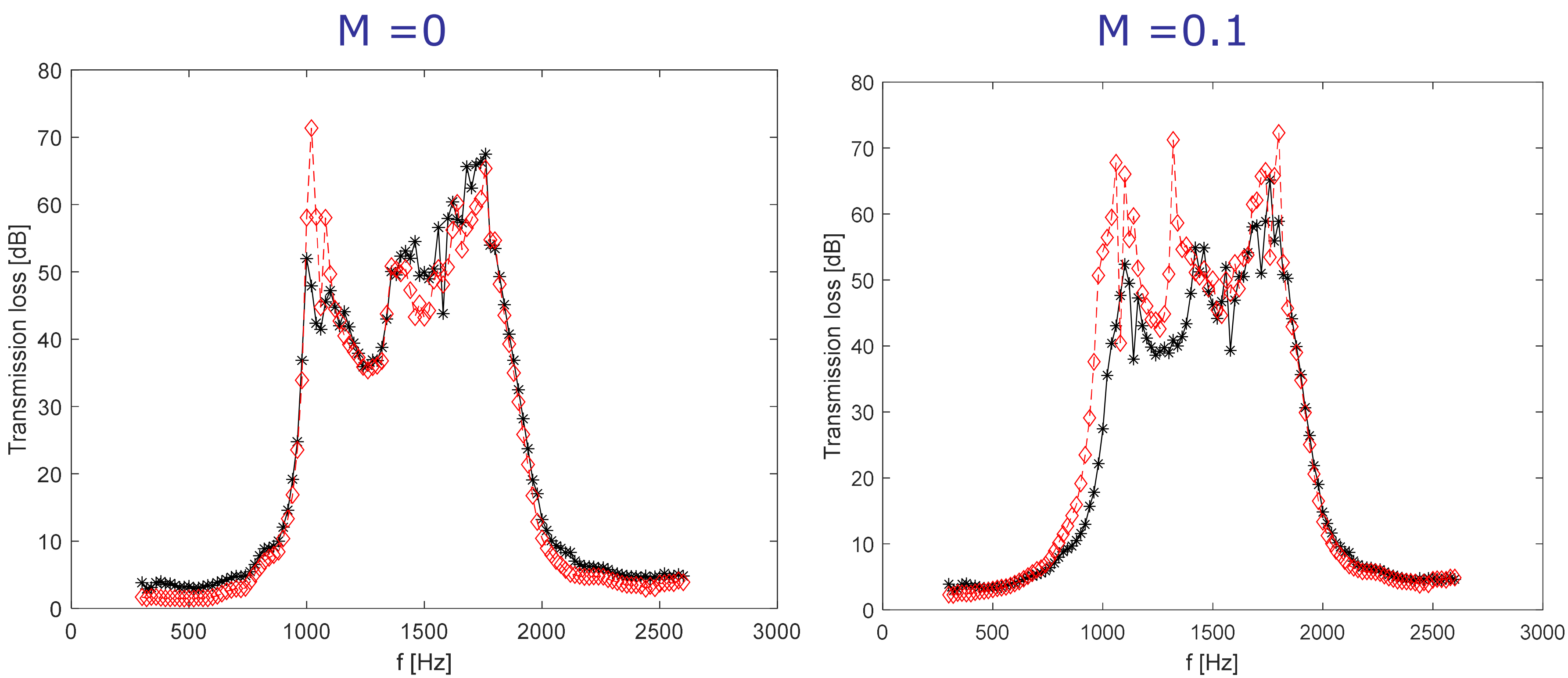


M =0.3



Black – downstream, red - upstream

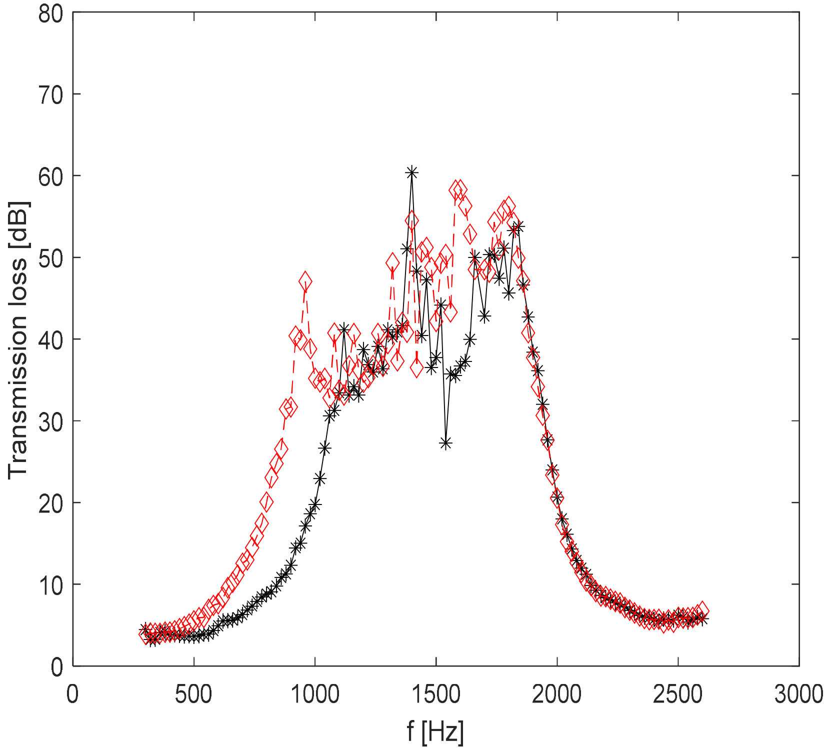
Transmission loss – Two segment liner



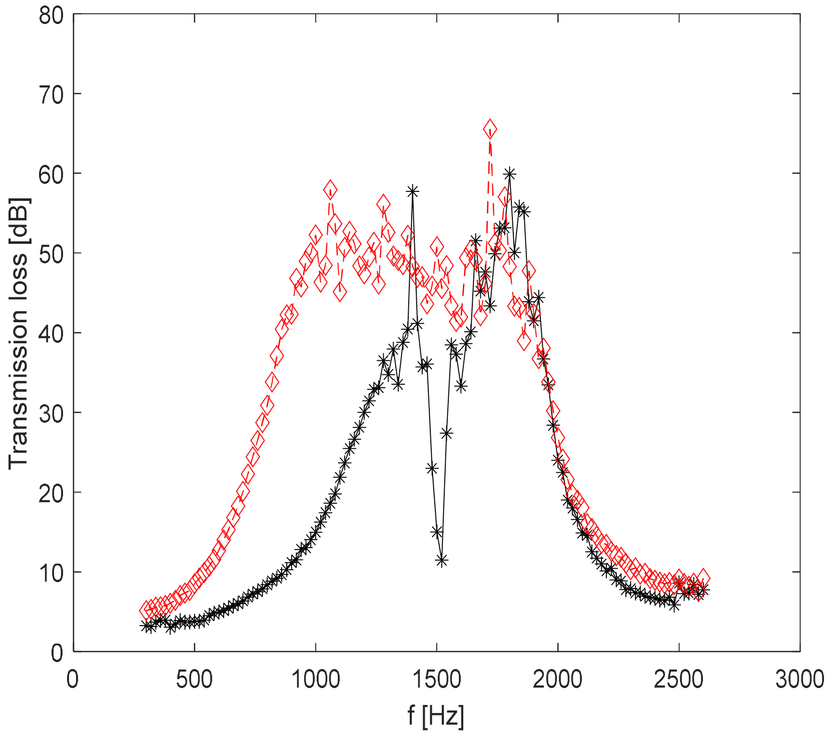
Black – downstream, red - upstream

Transmission loss – Two segment liner

M =0.2



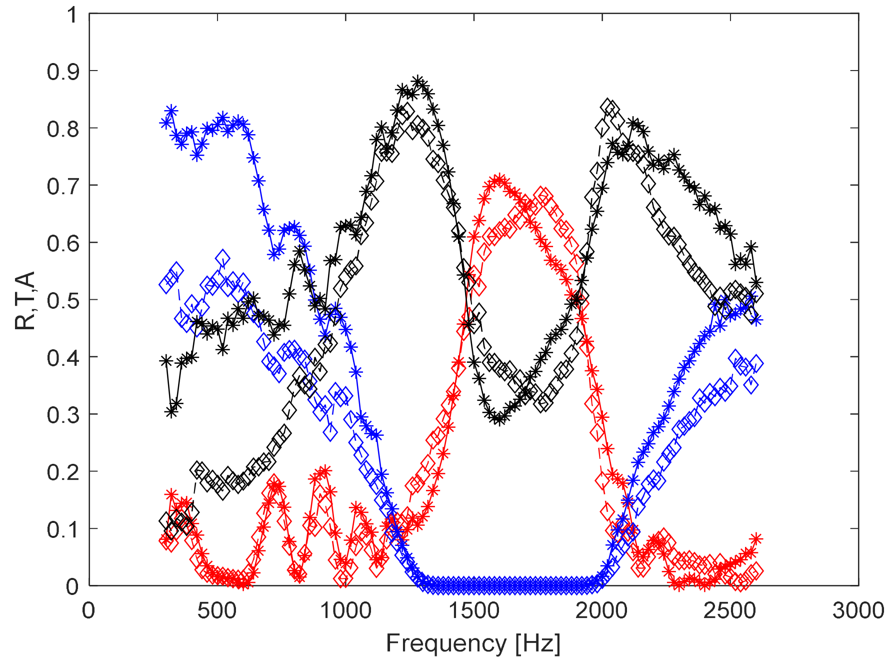
M =0.3



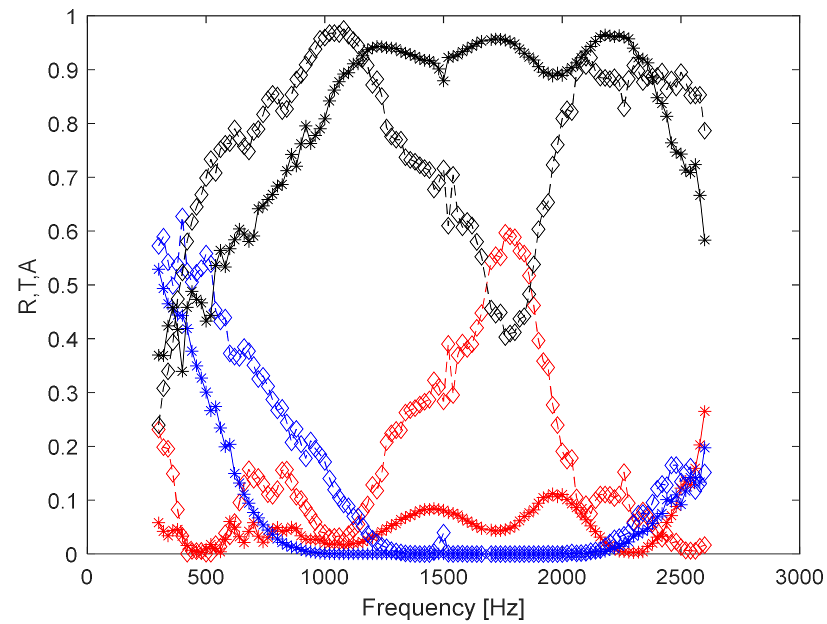
Black – downstream, red - upstream

Results and discussion – Reflectiom, Transmission, Absorption Uniform liner

M =0



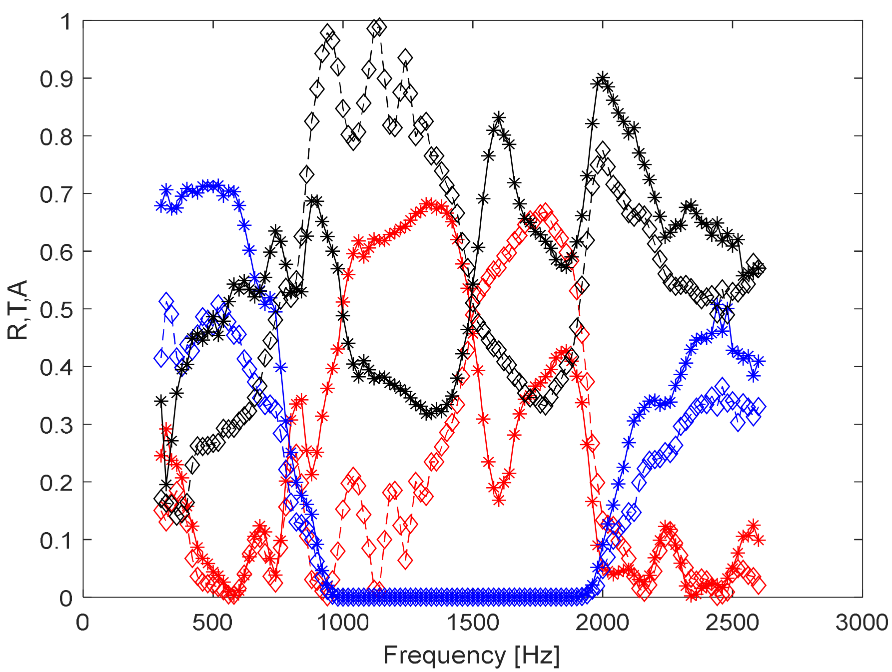
M =0.3



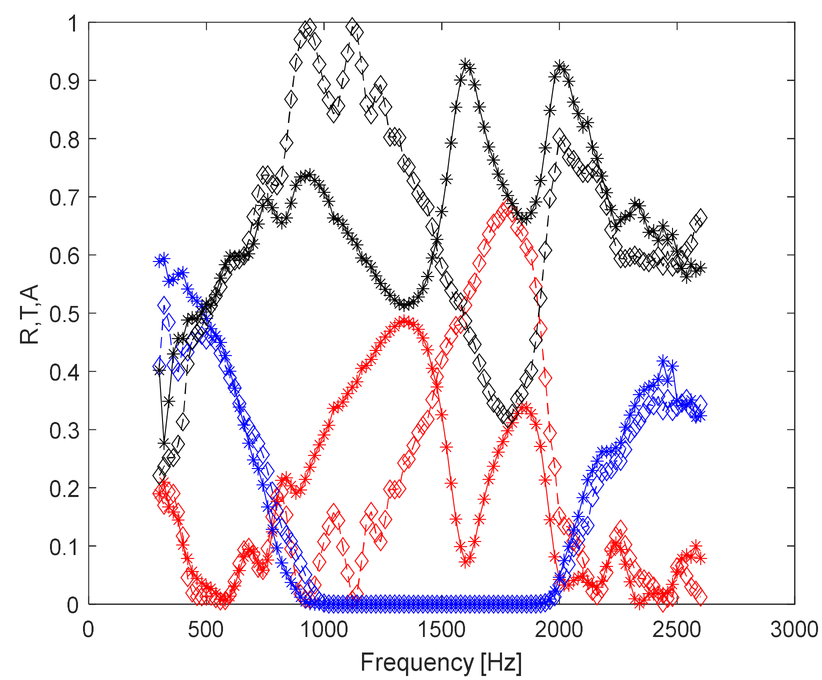
Black – absorption, red - reflection, blue - transmission
Stars – downstream, diamonds - upstream

Results and discussion – Reflectiom, Transmission, Absorption, Two section liner

M =0



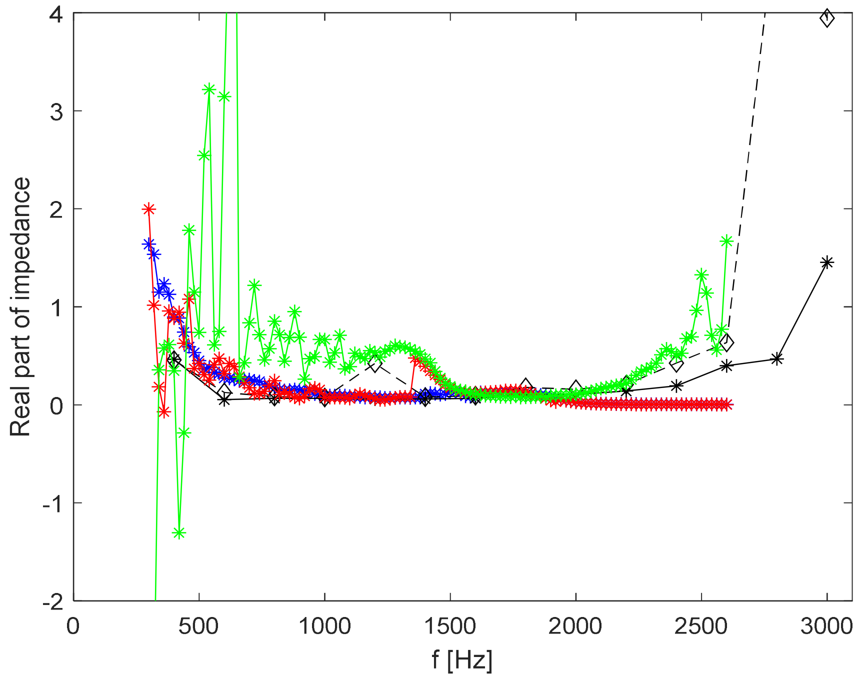
M =0.3



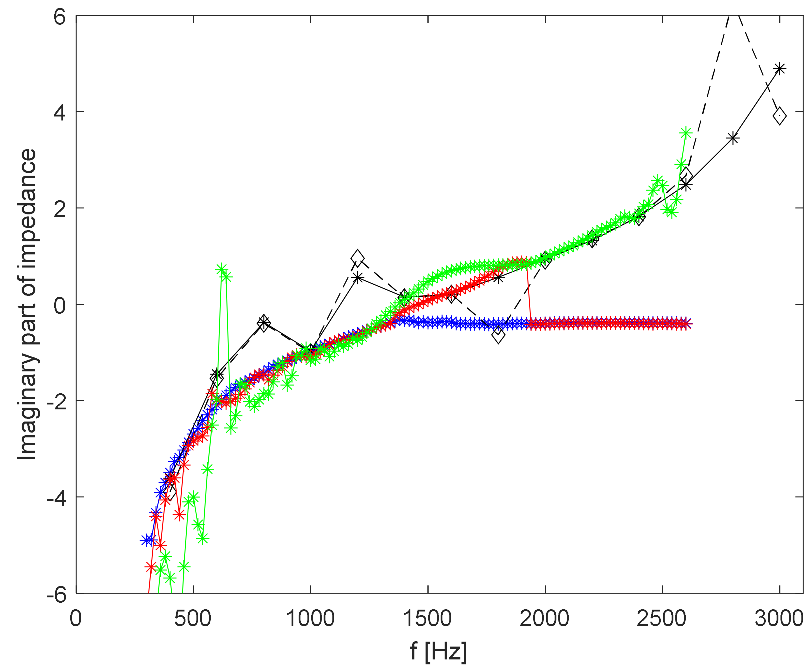
Black – absorption, red - reflection, blue - transmission
Stars – downstream, diamonds - upstream

Liner impedance, Uniform liner, M=0

Real part



Imaginary part

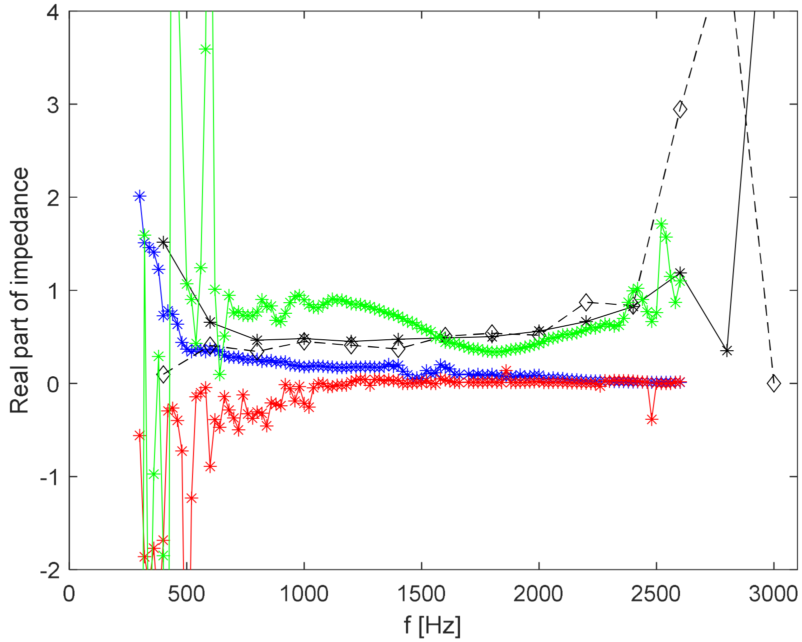


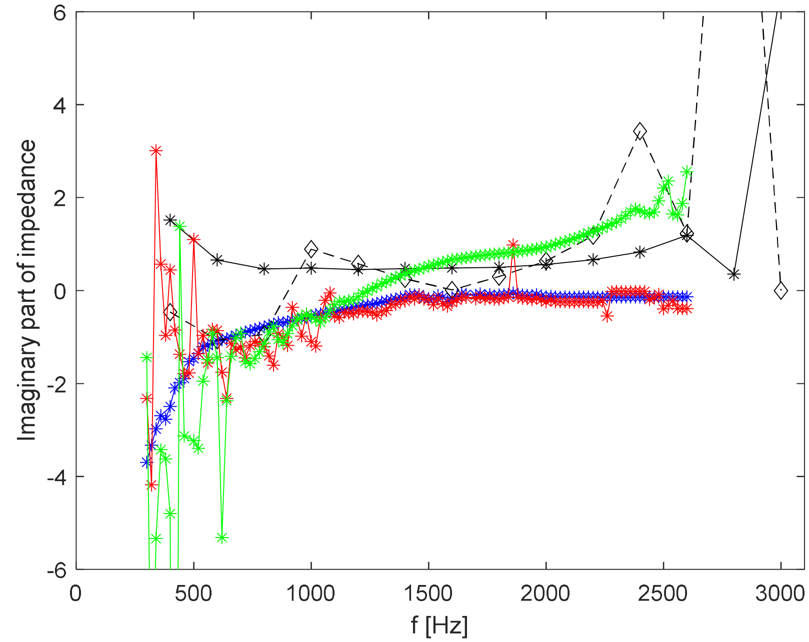
Black stars – NASA-CHE, black diamonds – NASA-KT, blue – SM, red – MM, green - ESPRIT

Liner impedance, Uniform liner, M=0.3

Real part

Imaginary part



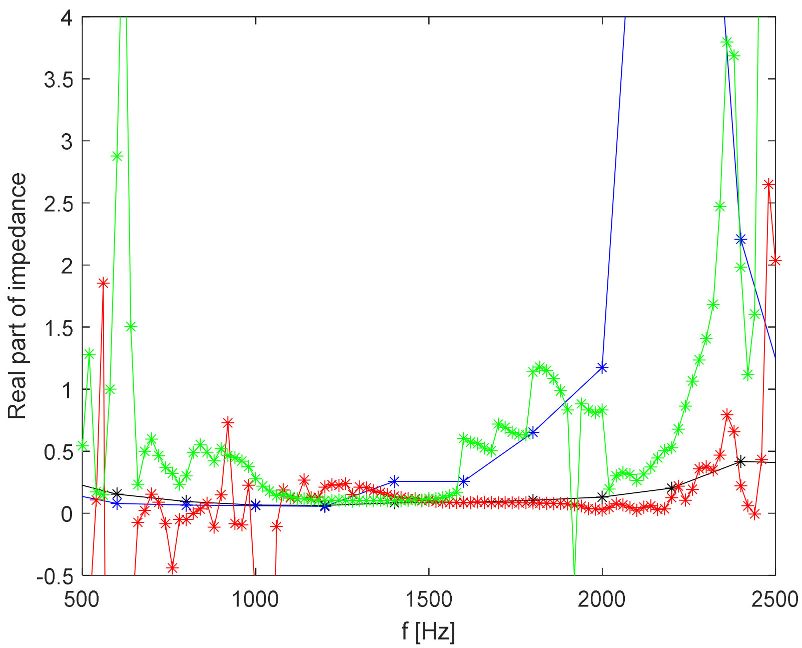


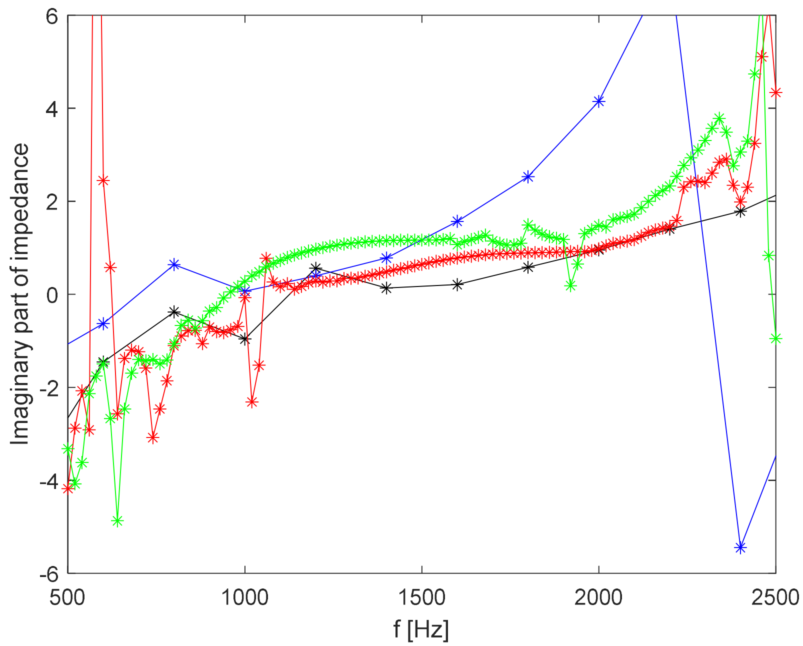
Black stars – NASA-CHE, black diamonds – NASA-KT, blue – SM, red – MM, green - ESPRIT

Liner impedance, Two-segment liner, M=0

Real part

Imaginary part

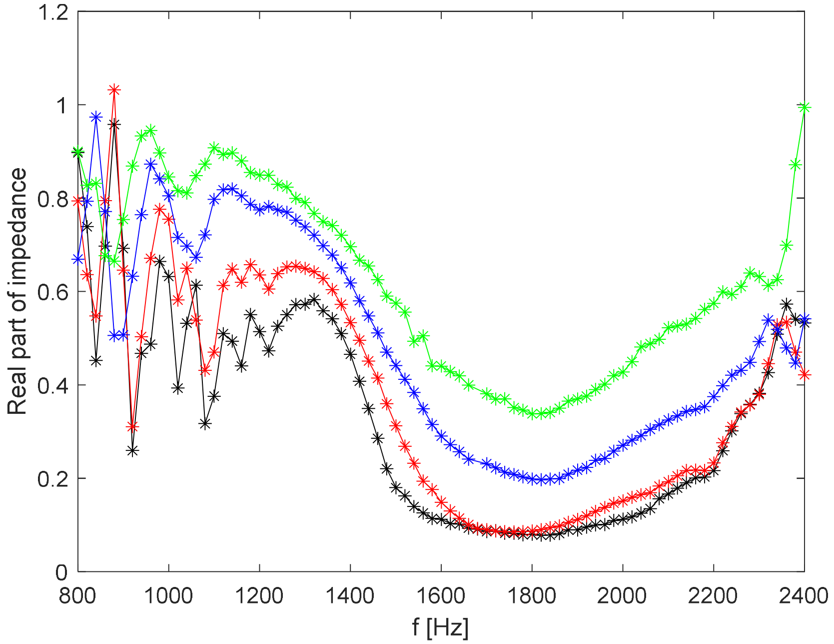




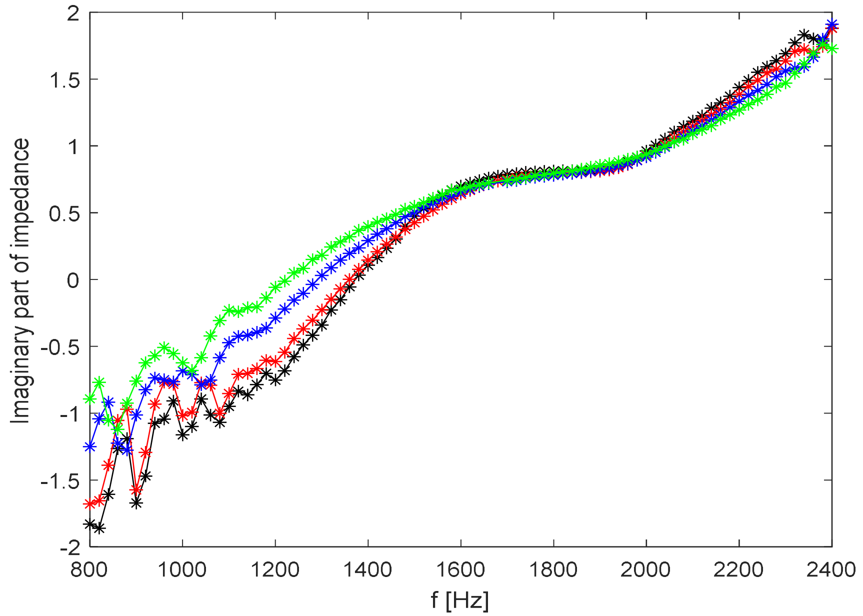
Black – NASA segment 2 (2”), blue – NASA segment 1 (3”), red – ESPRIT segment 2, green – ESPRIT whole liner

Liner impedance, Variation with flow speed

Real part



Imaginary part



Black – M = 0.0, blue – M = 0.1, red – M = 0.2, green - M = 0.3

Concluding remarks

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- Two liners have been designed and manufactured according to the IFAR NASA challenge 1 specifications.
- The quality of the printed parts was assessed on an Olympus BX53M microscope and the quality of the print was found to be consistent with low deviation along the liners despite small slivers inside the perforation that are typical for SLS printing.
- Test were made in the KTH liner test facility without flow and for three different flow speeds with center line Mach numbers 0.1, 0.2 and 0.3.
- The data was evaluated using three different methods: an approximate plane wave scattering matrix method, a convected Helmholtz equation mode matching method and the ESPRIT technique.
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Concluding remarks

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- Comparisons were made with published data from NASA were data was evaluated using a convected Helmholtz equation FE method and the Kumerasan and Tufts technique.
- It was concluded that the ESPRIT method gave reasonable agreement with the NASA results besides the low frequency range.
- This made it probable that the liner manufacturing was of good quality and that the data analysis techniques could give results with reasonable agreement.
- It should be noted that the ESPRIT technique which gave the best result at KTH is in the same family of techniques as the Kumerasan and Tufts technique used by NASA