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Four-Microphone Measurement of Transmission Loss of Automotive Door Seals: Improved Correction Factor

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Four-Microphone Measurement of Transmission Loss of Automotive Door Seals: Improved Correction Factor

* Continuation from Noise-Con 2017 Paper

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Ray W. Herrick Laboratories, Purdue University

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PURDUE MECHANICAL ENGINEERING

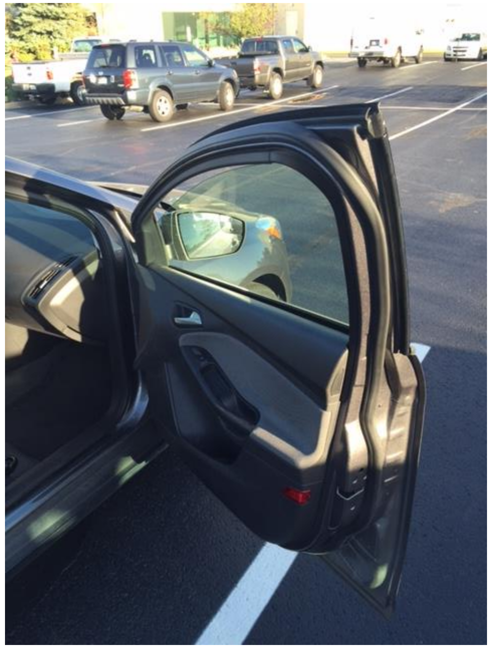
RAY W. HERRICK LABORATORIES

* This project is the work of Weimin Thor and Zhuang Mo, under supervision of Dr. J. Stuart Bolton.

Introduction

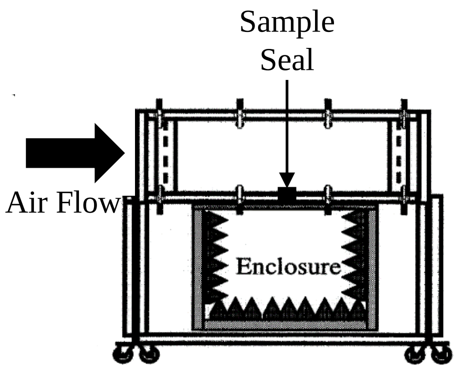
Increasing concern with acoustical environment within a vehicle

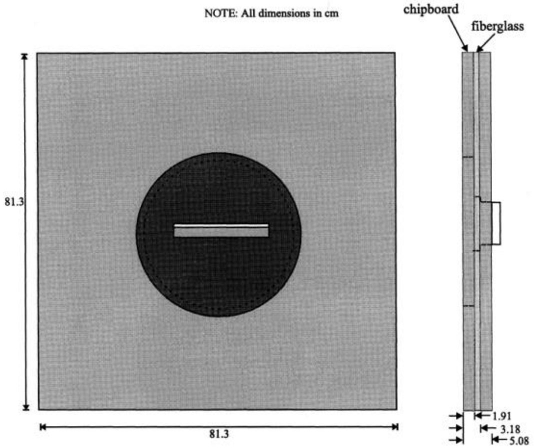
- Previous methods to measure acoustic properties of door seals require large-scale facilities which are expensive and time consuming
- Objective here is to develop a simpler and more economical desktop procedure to allow easy and fast acoustic measurement of automotive door seals
- Procedure described here is adapted from four-mic measurement method (E2611 ASTM International, 2009) and further improved with finite element modeling

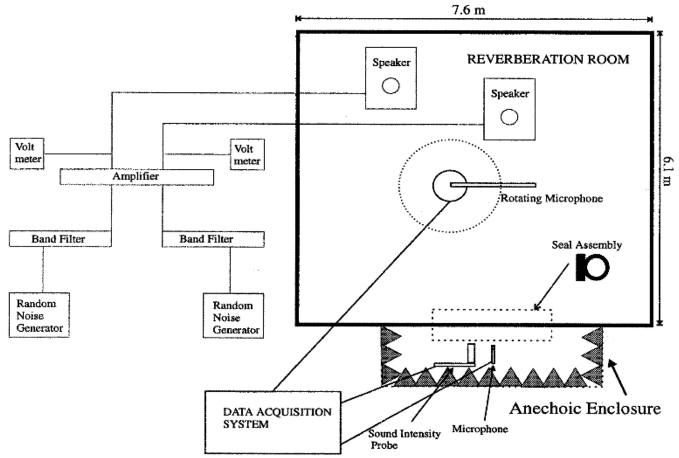


Previous Work

- **Robert J. Danforth III and Luc Mongeau, “Sound Transmission through Road Vehicle Primary Bulb Seal Assemblies,” HL 96-14 Report #3086-2, December 1996**
  - Experiments using a small quiet wind tunnel, bulb seals excited by aerodynamic pressure
  - Sound pressure transmitted into enclosure measured for varying flow velocities, cavity dimensions, and other parameters
  - In addition, noise reduction measurements performed using reverberation room – effect of compression

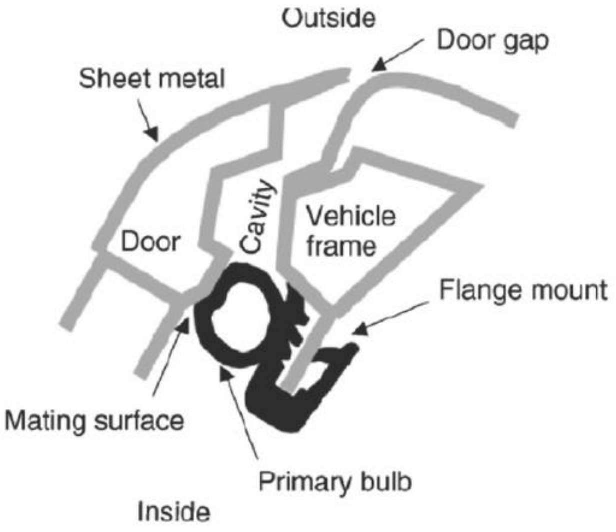


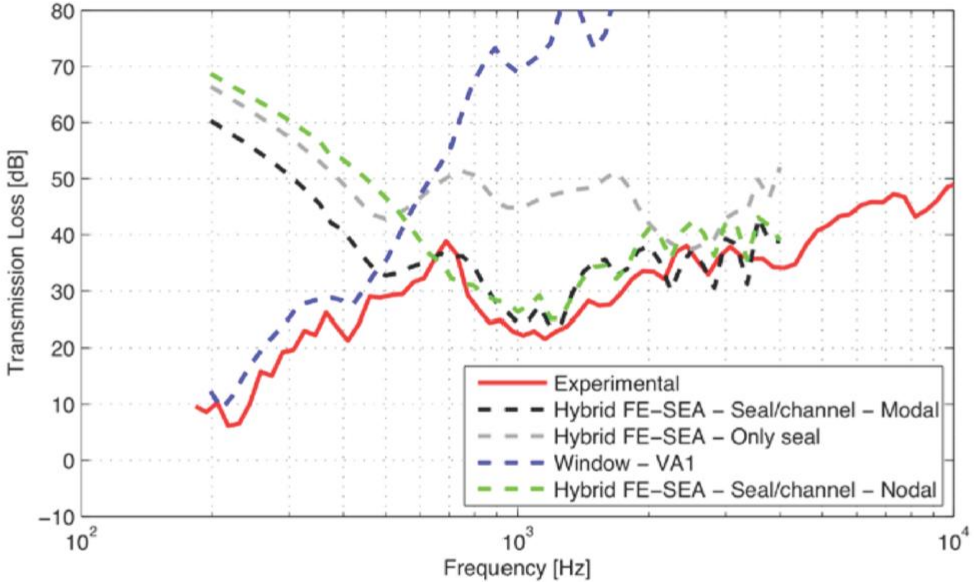




Previous Work

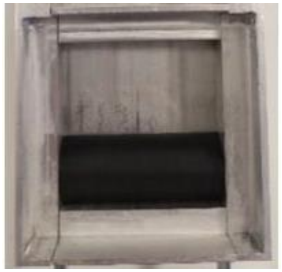
- **Julio A. Cordioli et al., "Application of the Hybrid FE-SEA Method to Predict Sound Transmission Through Complex Sealing Systems," SAE International 2011-01-1708, May 2011**
  - Presented a numerical validation of the Hybrid FE-SEA model
  - Door components mounted in reverberation room aperture
  - Transmitted sound level measured with and without a seal in place
  - Typical STL was about 30 dB

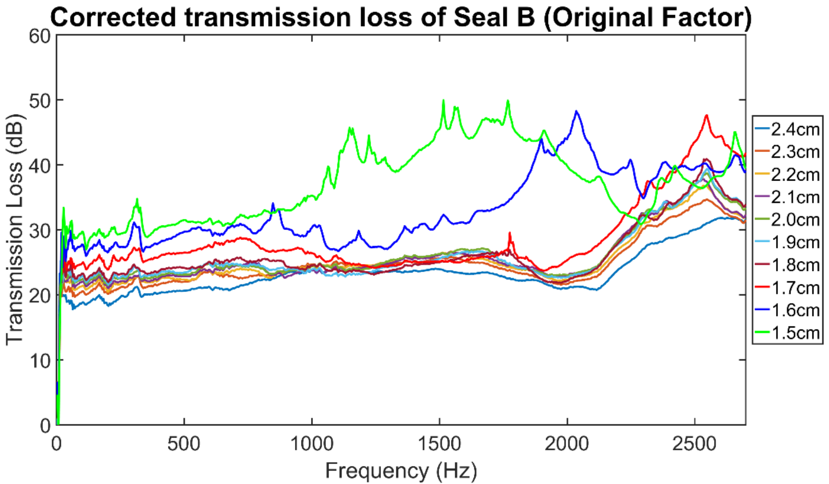




Previous Work

- **Weimin Thor and J. Stuart Bolton, "A Desktop Procedure for Measuring the Transmission Loss of Automotive Door Seals," SAE Technical Paper 2017-01-1760, June 2017**
  - Measured STL of the combination of seal and clamp, thus required a correction factor
  - Described the original development of the procedure, which relied on experimentally determined correction factor
  - Original experimental STL of the seals were in the range of 20 – 30 dB





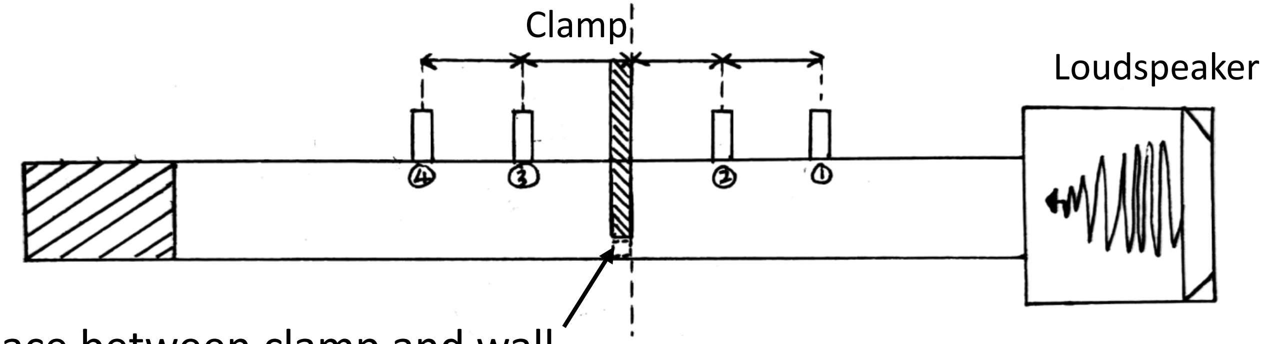
Contents

Goal: To improve the initial desktop procedure by creating correction factors based on materials having transmission loss similar to the door seals

- Measurement Procedure and Apparatus
- Improved Correction Factor Calculation – FE-Model
- Seals Tested
- STL Comparison between Original and Improved Correction Factor

4-Mic Procedure

(E2611 ASTM International, 2009)



- Estimate transfer matrix elements:
  - Transmission Coefficient

$$T_a = \frac{2e^{jkd}}{T_{11} + \frac{T_{12}}{\rho_0 c} + \rho_0 c T_{21} + T}$$

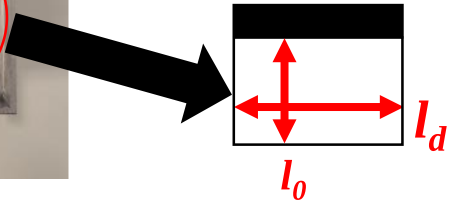
  - Transmission Loss (STL)

$$TL = 20\log_{10}\frac{1}{|T_a|}$$

- Measure combined transmission loss of seal and clamp by using two-load method

Experimental Apparatus

- Apparatus used in the experiment
  - Automotive door seals cut to the width of the standing wave tube (6.35 cm)
  - 6.35 cm × 6.35 cm square standing wave tube

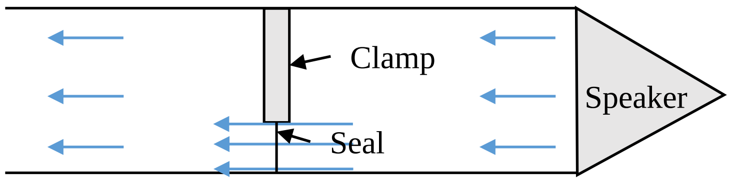


- Seal of width l_d inserted in opening and compressed to varying degrees by changing l_0

- Upper frequency limit of 2700 Hz due to tube dimensions – smaller tube could be used to increase upper frequency limit.

Need for Correction Factor

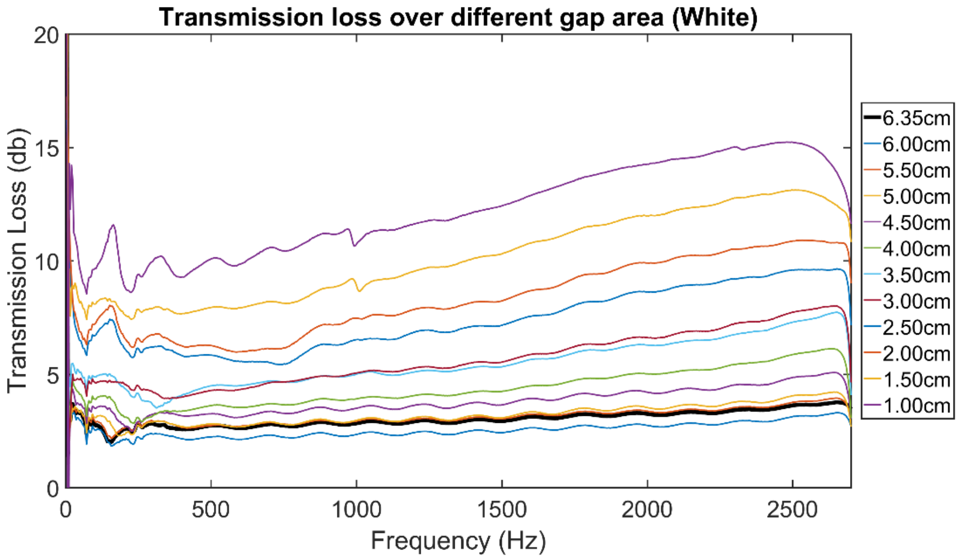
As the seal only takes up part of the standing wave tube, the measured STL includes the contribution of the metal clamp (assumed to have infinite STL)



- Transmission loss (STL) measured is a combination of the seal and clamp, but the desired result is the STL of the seal alone.
- A correction factor is thus needed to account for the area change and inertial-nearfield effects

Need for Correction Factor

- Original correction factor was based on reference materials (fibrous sample) with STL much smaller than those of the door seals



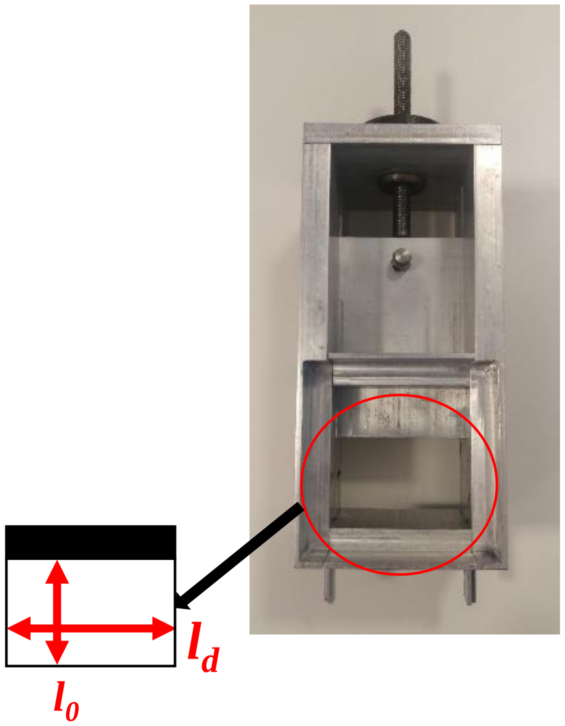
- It was not possible to find reference materials having known and uniform STL at a level similar to the door seals
- Improved: Determined the inertial-nearfield factor by constructing an FE-Model with porous material properties giving a STL of around 30 dB

Area Correction Factor Calculation

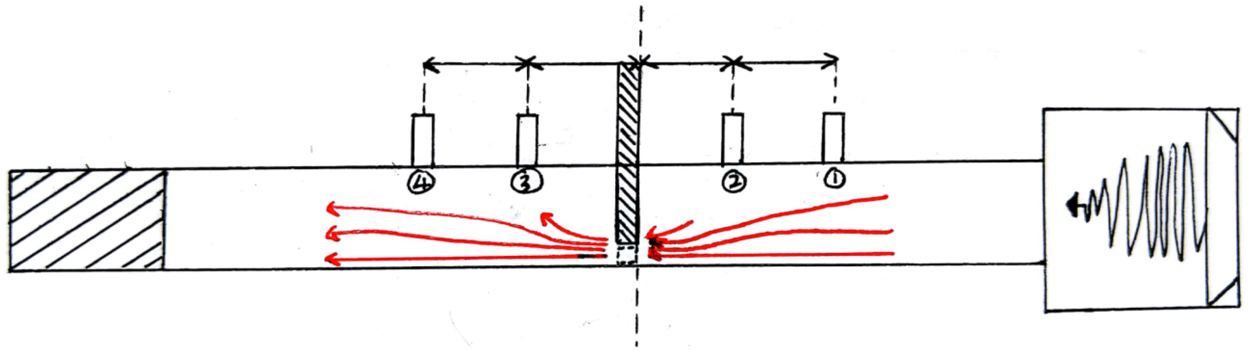
- The transmission coefficient is first adjusted to compensate for an area change:

$$T_{new} = T_{original} \times \frac{s_d}{s_0}$$

  - $s_d = l_d \times l_d$
  - $s_0 = l_d \times l_0$
- $T_{original}$ is the transmission coefficient of the combined system
- T_{new} is the adjusted transmission coefficient accounting for the area change



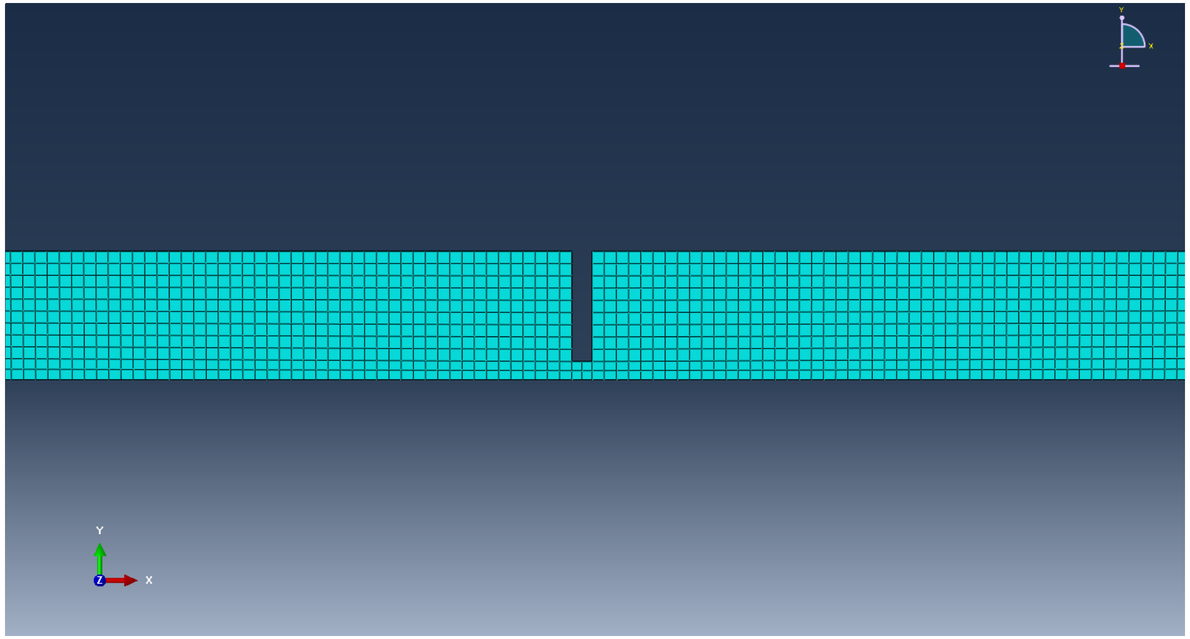
Inertial Correction Factor Calculation



- Acceleration of fluid into and out of sample creates inertial-nearfield which affects the STL of the clamp-sample system
- Determine effect of inertial-nearfield by measuring STL of sample having a known STLs at various clamp openings
- Original correction factor was based on materials having STLs much lower than door seals
- FE-Model made it possible to create “samples” that have near uniform STLs close to those of the door seals

Finite Element Model Construction

- Length of standing wave tube in FE-Model was extended to 101 cm to reduce the impact of the near-field close to the sample
- Tube walls and clamp were assumed to be rigid
- Approximate global size of mesh was 0.006 m – seed interval along *z*-direction is 0.01 m



Finite Element Model Construction

- Porous material properties required to complete the FE-Model was calculated using the Johnson-Champoux-Allard-Pride-Lafarge (JCAPL) model[1] to obtain a material with STL in the range of 25 dB to 35 dB

Symbol	Parameter	Value	Symbol	Parameter	Value
σ	Air Flow Resistivity [Rayls/m]	1×10^6	k_0'	Static Thermal Permeability [m²]	1×10^{-10}
ϕ	Open Porosity	0.99	Λ'	Thermal Characteristic Length [m]	1.5×10^{-6}
α_∞	High-Frequency Limit of Tortuosity	1.0	α_0'	Static Thermal Tortuosity	2.0
α_0	Static Viscous Tortuosity	2.0	P_0	Ambient Pressure [Pa]	1×10^5
Λ	Viscous Characteristic Length [m]	1×10^{-6}	γ	Air Heat Capacity Ratio	1.4
ρ_0	Air Density [kg/m³]	1.225	C_p	Air Specific Heat Capacity [J/kg·K]	1005
η	Air Dynamic Viscosity [Pa·s]	1.84×10^{-5}	κ	Air Thermal Conductivity [W/m·K]	0.024

[1] http://apmr.matelys.com/PropagationModels/MotionlessSkeleton/JohnsonChampouxAllardPrideLafargeModel.html

Inertial Correction Factor Calculation

* Calculated with results from FE-Model

- Transmission coefficient ($T_{original}$) is calculated by FE-Model for various clamp openings
- After obtaining the adjusted transmission coefficient (T_{new}) for the FE-Model with the respective area adjustment, the correction factor ($\alpha = f\left(\frac{l_0}{l_d}, \omega\right)$) accounting for nearfield effect can be obtained

$$\alpha = \frac{T_{new,duct}}{T_{new}}$$

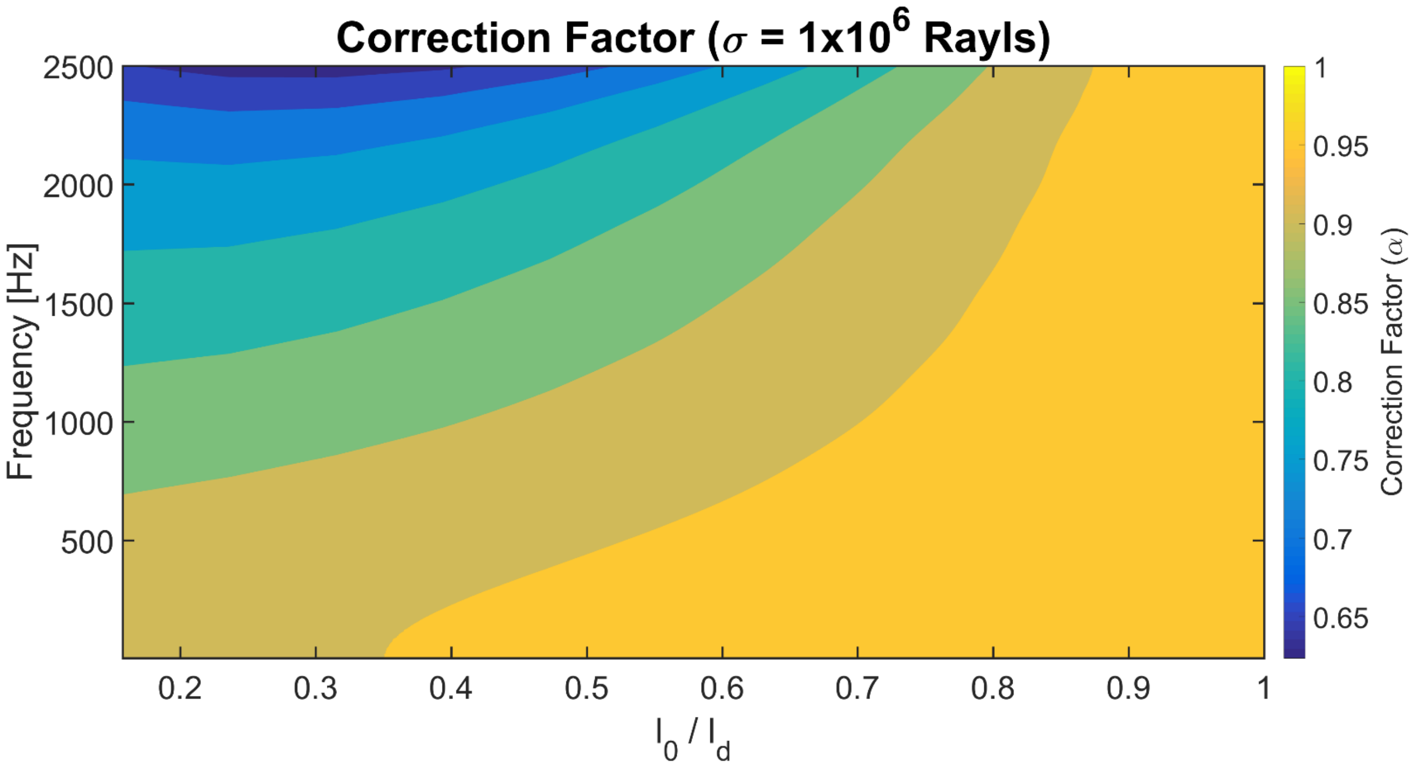
  - $T_{new,duct}$ is the known transmission coefficient of the reference FE-Model porous material at full duct width (l_0 = 6.35 cm)
  - Porous material from FE-Model has STL close to that of the different seals of interest

Inertial Correction Factor Calculation

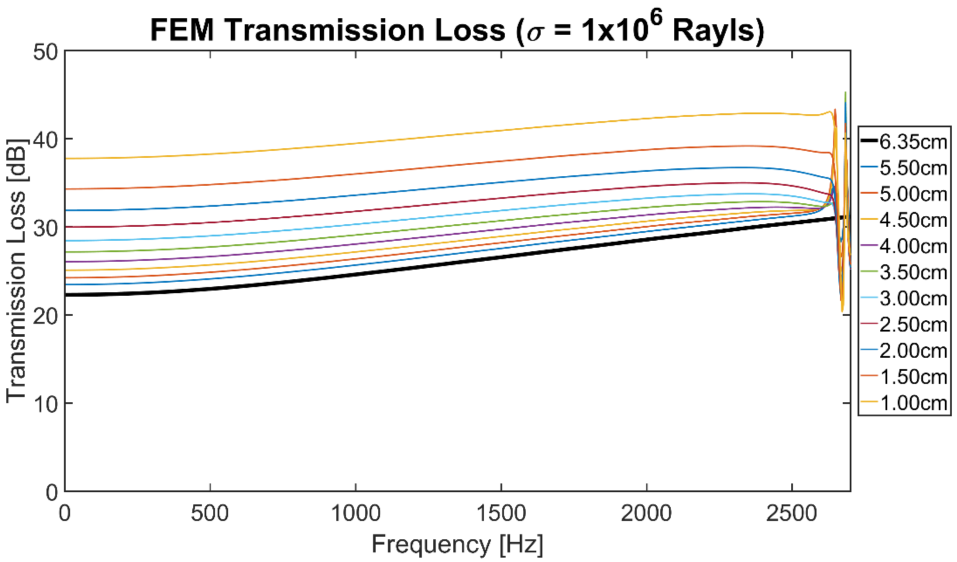
* Calculated with results from FE-Model

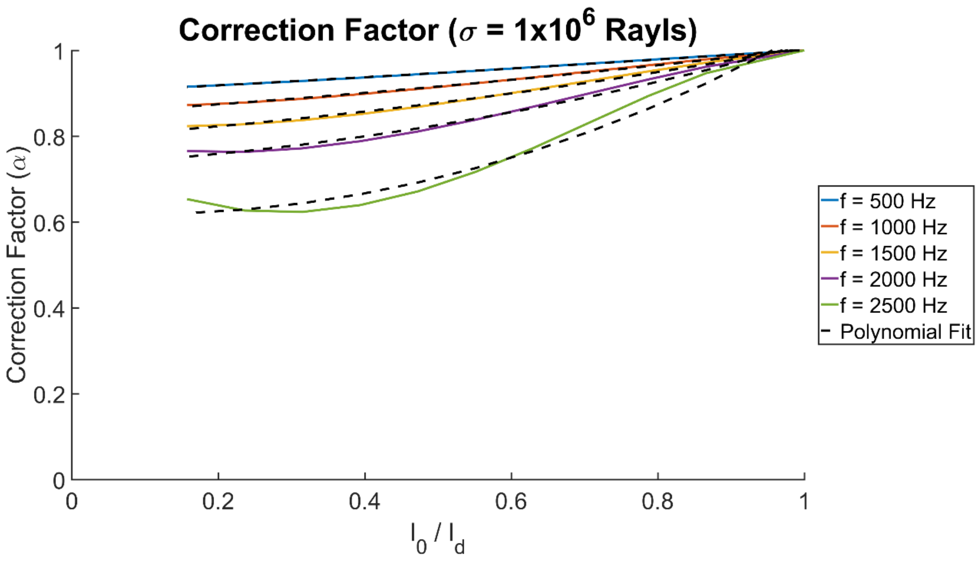
- At every frequency of interest, a polynomial was fitted to obtain a second-order polynomial equation representing the inertial-correction factor (α_c):

$$\alpha_c\left(\frac{l_0}{l_d},\omega\right) = a_1\left(\frac{l_0}{l_d}\right)^2 + a_2\left(\frac{l_0}{l_d}\right) + a_3$$



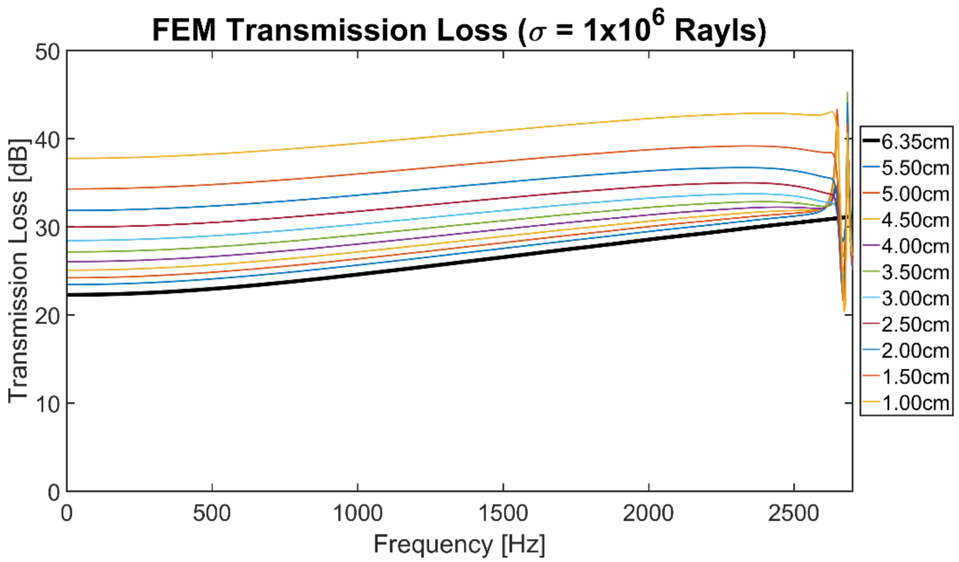
Improved Correction Factor

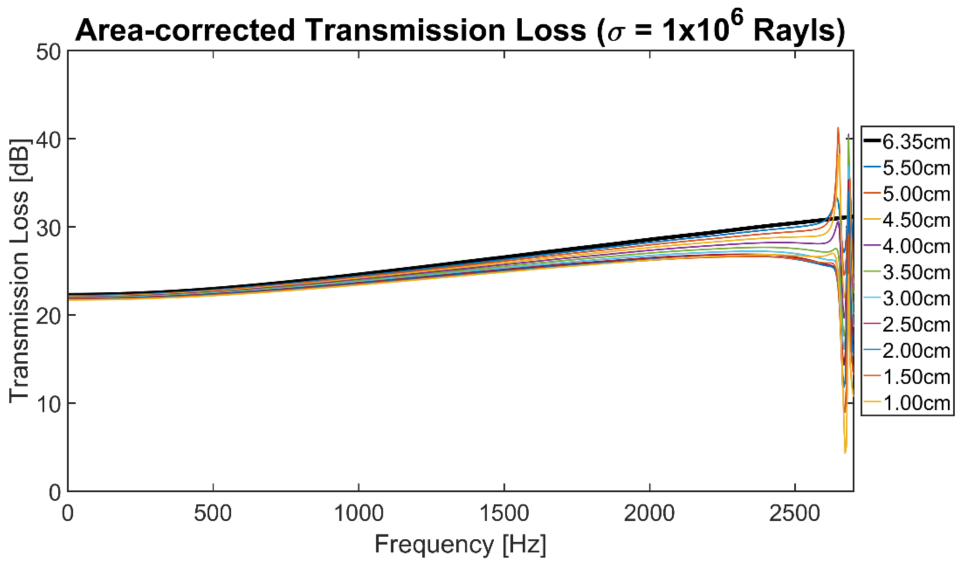




- Around 2600 Hz, results were neglected as higher order modes invalidate the assumption of plane waves within the standing wave tubes
- Correction is most significant for small values of $^{l_0}/_{l_d}$ (i.e., small sample size) and high frequencies
- Inertial-nearfield effect is the most important under those conditions

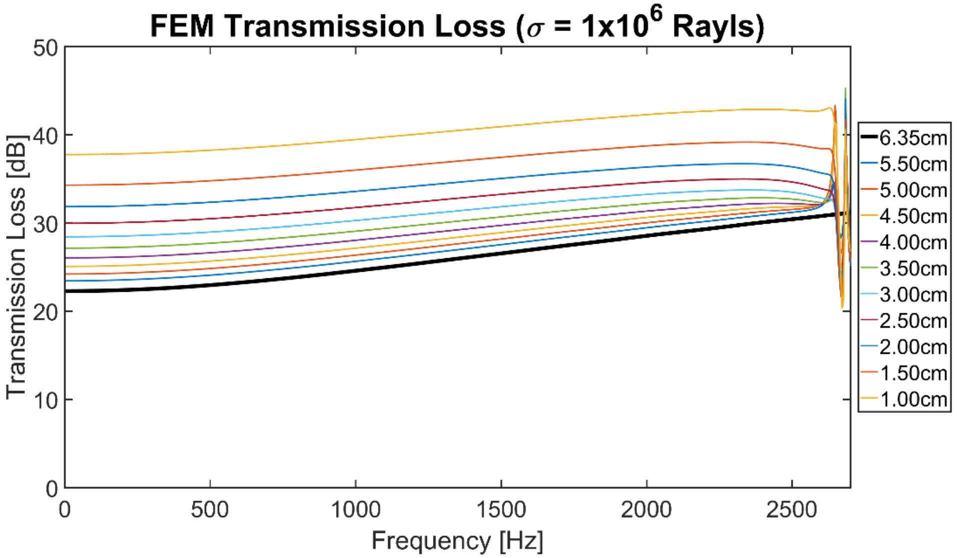
Area-Corrected Transmission Loss

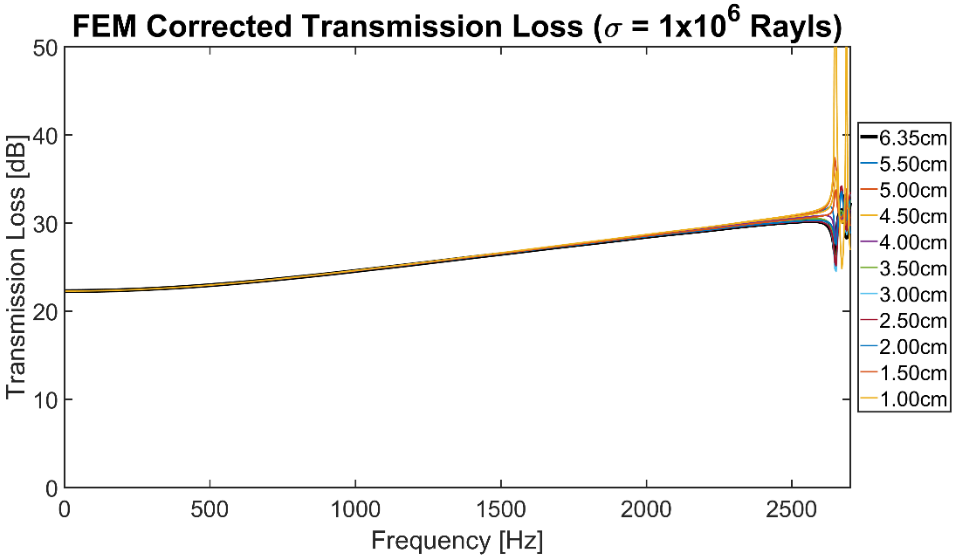




- The corrected transmission loss after only the area-correction does not match with the known transmission loss of the porous material at full width
- This is evidence that a near-field correction is required

Need for Inertial-Nearfield Correction





- Correction procedure applied to FE generated data
- When correction factor was applied, all transmission loss values collapse to full-width value
- The transmission loss of the material generated by the FE-Model was successfully corrected, thus validating the correction factor

Door Seal Data Processing

Experimental Procedure

- White noise ranging from 0 Hz to 2700 Hz was generated, and sound pressure was measured at four locations with Bruel and Kjær microphones
- Samples were tested ten times at an increment of 0.1 cm compression level
- Data collected were processed with MATLAB where the corrected transmission coefficients were obtained to generate the transmission loss

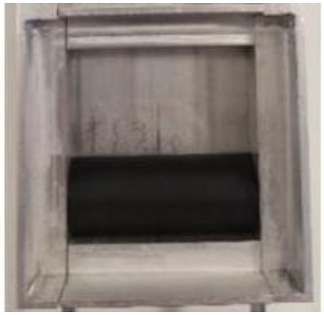
$$T_{seal,new} = T_{original} \times \frac{l_d}{l_0}$$ (Area correction)

$$T_{seal} = \alpha_c\left(\frac{l_0}{l_d}, \omega\right) \times T_{seal,new}$$ (Inertial-Nearfield correction)

$$TL_{seal} = 20\log_{10}\frac{1}{|T_{seal}|}$$

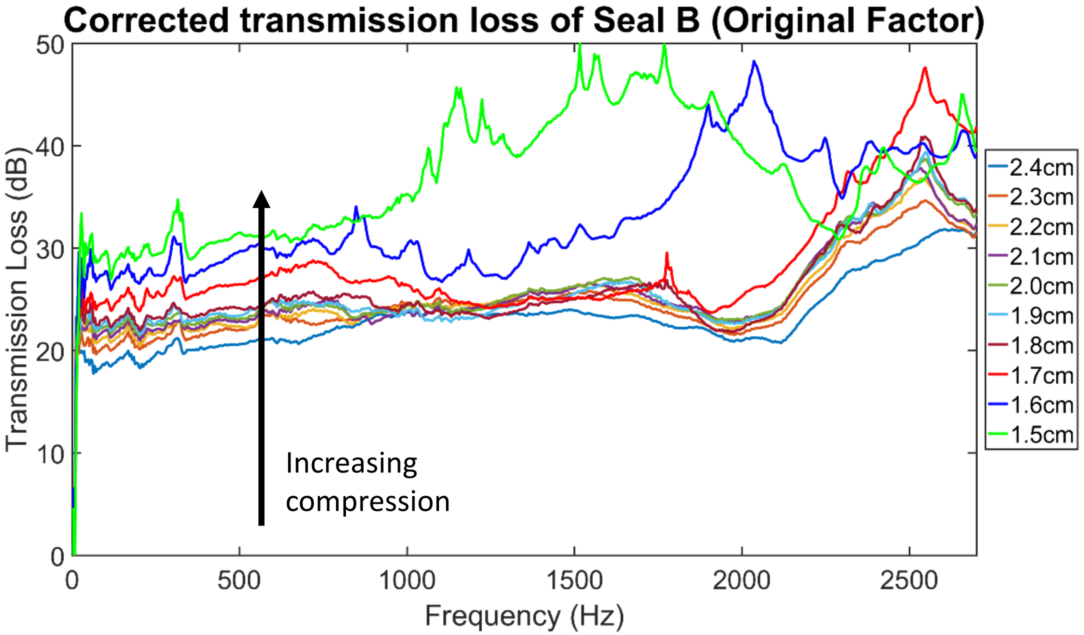
Seals Tested

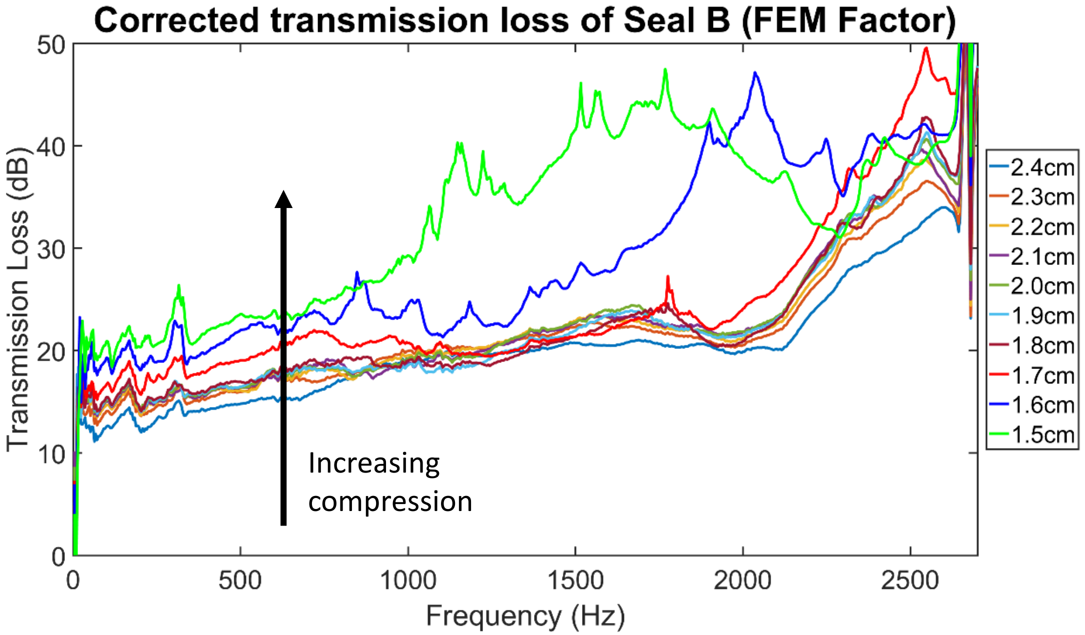
- Two seals were selected to show the comparison between the original and improved correction factors

Primary Bulb Seals			Multiple Chamber Seals		
Seal (B)	Characteristics	Clamped	Seal (E)	Characteristics	Clamped
	• Designed to have only one air cavity • No vent holes • Compressed 2.4 – 1.5 cm			• Designed to have two or more air cavities • No vent holes • Compressed 3.9 – 3.0 cm	

Corrected Average Transmission Loss

(Seal B)

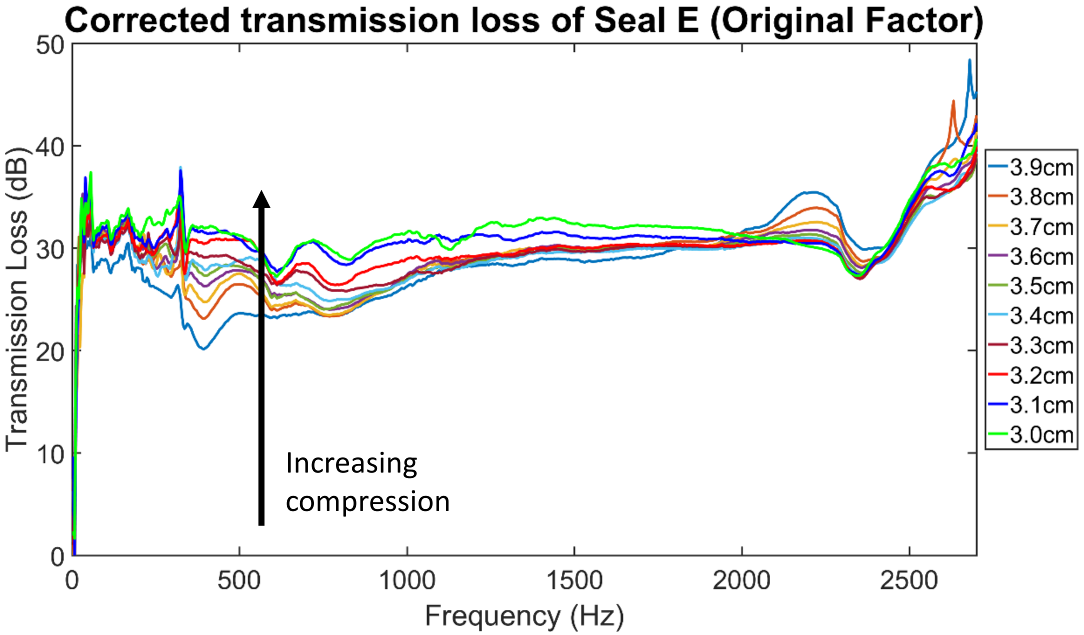


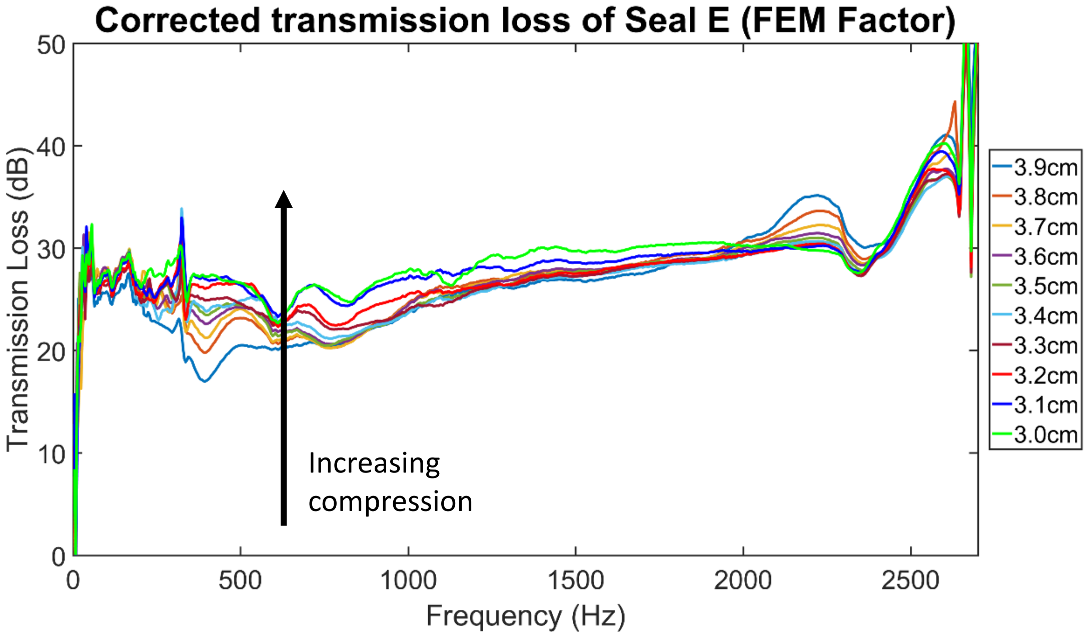


- Transmission loss reduced compared to original estimate
- The improved correction factor caused a significant change of about 5 – 7 dB to the level of transmission loss
- Improved correction factor did not alter the general trend of the corrected transmission loss

Corrected Average Transmission Loss

(Seal E)





- The improved correction factor had a smaller impact on the transmission loss of Seal E compared to Seal B at around 3 dB
- The improved correction factor still showed that the transmission loss of Seal E is almost independent of compression

Conclusion

An improved version of the desktop procedure for measuring acoustic properties for door sealing systems was described

- This new procedure, based on FEM-derived correction factor, can replace previously conventional methods which made used of reverberation chambers and wind tunnels
- The new FE-Model can also help users adapt the correction factor to better suit the actual STL of the seal which increases the versatility of this procedure
- A new modified clamp system that simulate real world application should be the next step of the research to increase accuracy of our measurement

Acknowledgement

- John Nalevanko (Ford Motor Company) – Financial support / Seal provider
- 3M Company – Provider of the square standing wave tube
- Caleb Wagner – Fabricator of the sample holder

Thank you for your attention!

References (i)

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