A study of metric for mid-frequency performance assessment of vehicle panel stacks

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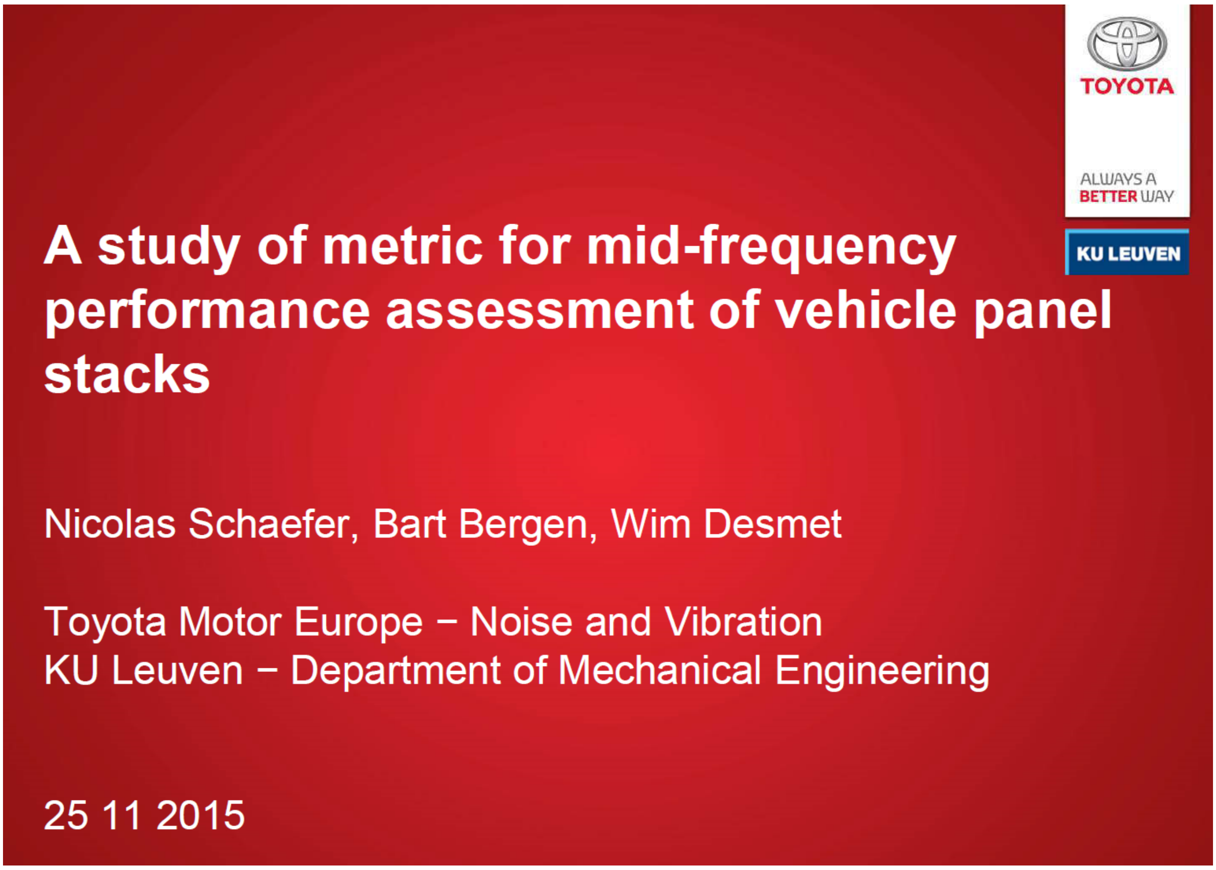
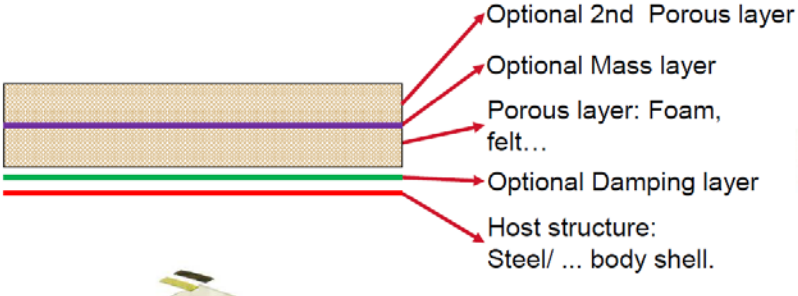
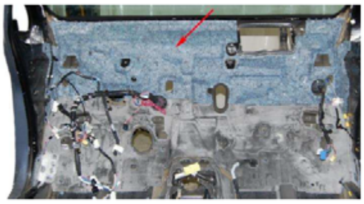
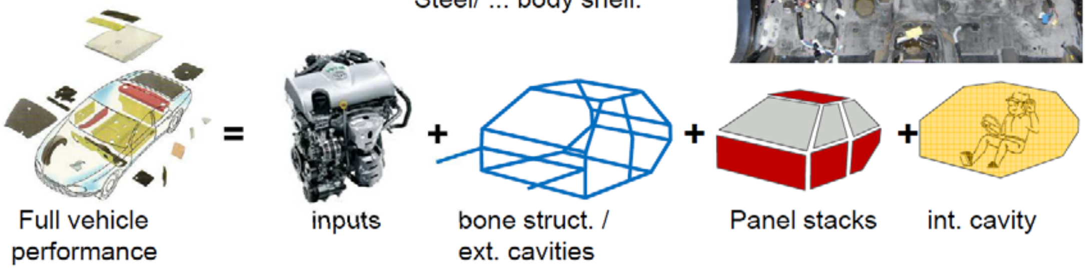


Introduction and objectives
Mid-frequency panel stack design







Mid-frequency (100-1000 Hz) simulation of **full vehicle** is very challenging ➔ Breakdown
➔ Performance simulation needs to be broken down to **individual panel stack level**

➔ A **metric** is needed to define the performance for one **panel stack**.

2 25-nov.-2015

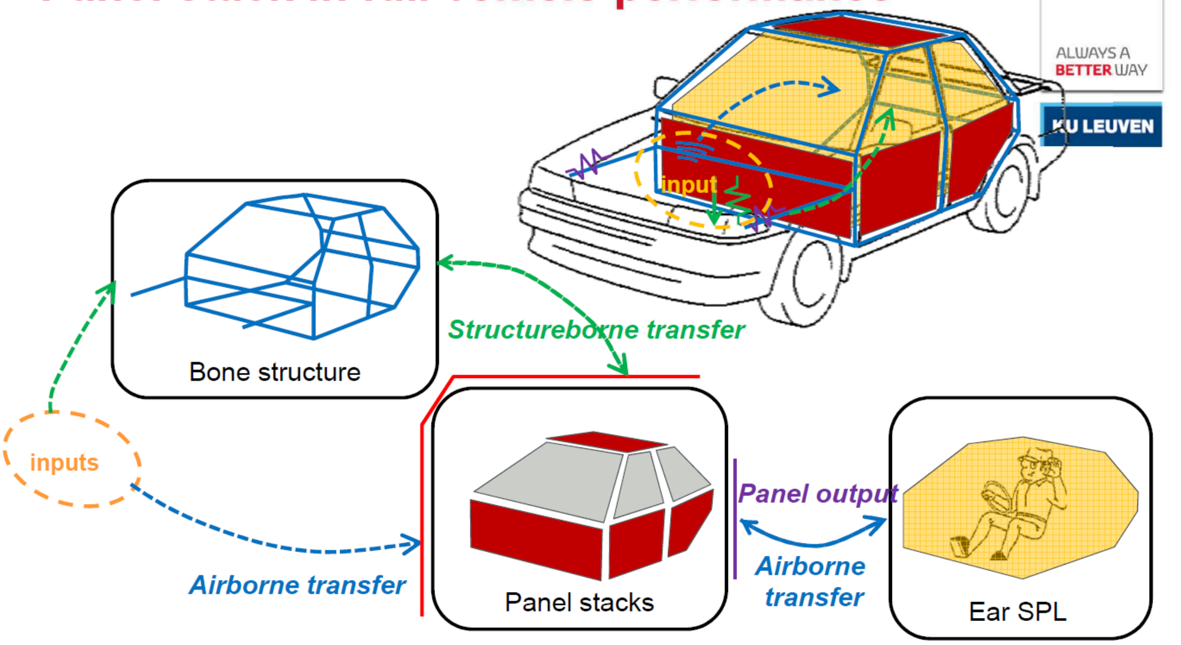
A study of metric for mid-frequency performance assessment of vehicle panel stacks
Contents

1. **Introduction and objectives**
   - Common transmission metric for panel
   - Limitations with current metric
   - Novel transmission metric objectives
2. **Metric definition**
   - Metric input quantity
   - Metric output quantity
   - Breakdown of the metric
3. **Conclusions and next steps**

3 25-nov.-2015

Introduction and objectives

Introduction and objectives
Panel stack in full vehicle performance



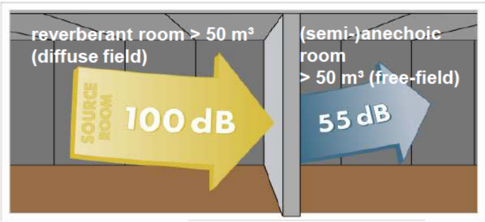
$$M = \frac{Panel\ output}{Panel\ input}$$

Fully Coupled system
➔ Some assumptions need to be made

Introduction and objectives
Common metrics for stack performance

Transmission Loss (TL)

Definition: $TL = 10\log_{10}\frac{\text{Incident power}}{\text{Transmitted power}}$



Standard measurements [1], [2]
- Coupled rooms
  - Reverberant room , diffuse field
  - Semi-anechoic room, free-field

- Smaller Cabins

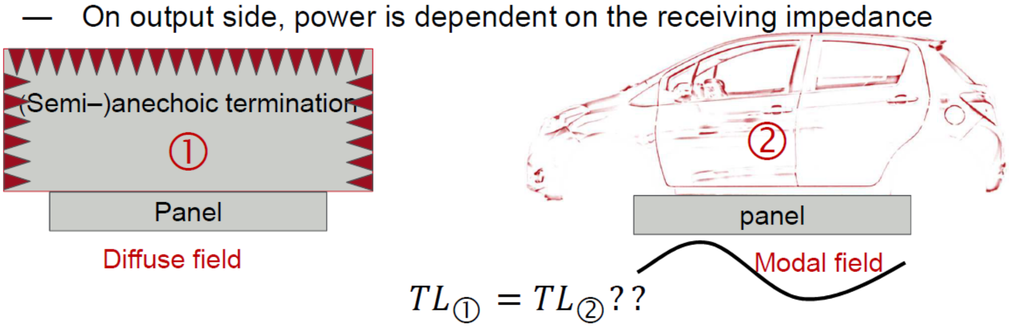
References
[1] ASTM E90-02
[2] ISO 140-1:1997

6 25-nov.-2015

Introduction and objectives
Limitations with transmission loss

Transmission loss (TL)
- Mainly airborne noise contributions
- High-frequency assumptions

Moving to mid-frequencies (100-1000 Hz)
- Structureborne needs to be taken into account
- Modal behaviours appear:
  - On input side, more complex fields than diffuse
  - On output side, power is dependent on the receiving impedance



$$TL_{①} = TL_{②}??$$

➔ Change from **ideal** to **vehicle** condition doesn't lead to **expected performance**

7 25-nov.-2015

Introduction and objectives
Limitations with Transmission Loss

Mid-frequency breakdown of the metric

Development situation: e.g. "*TL is too low*"

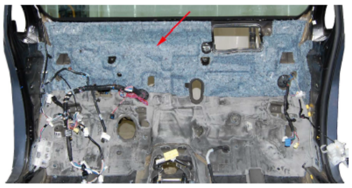
In high frequency range, breakdown of performance is possible

- 1D models: Transfer Matrix Method, mass-spring…

➔ Can tell the contribution for which layer / coupling between layers

In mid-frequency range, root cause can be more difficult to identify:

- Additionally, due to modal behavior, "good match" of modes is possible, e.g.
  - Panel with interior cavity acoustic mode
  - Engine compartment with panel (airborne input)
  - Bone structure with panel (structureborne)

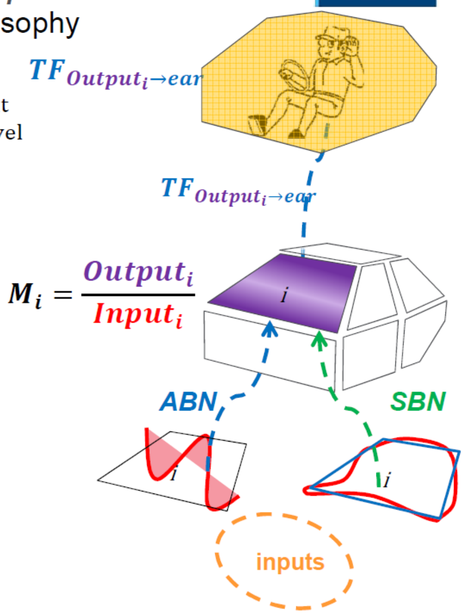


➔ **TL does not support a contribution breakdown** of performance in Mid-frequencies

Introduction and objectives
Goals for a novel mid-frequency metric for stack performance

Requirements for a new MF metric M_i

- Compatible with panel contribution analysis philosophy
  - $\underbrace{p_{ear}}_{\text{target}} = \underbrace{\sum_{i=panel} p_i}_{\text{breakdown}}$ with $p_i = \underbrace{\mathbf{Input}_i}_{\text{known}} \; \underbrace{\mathbf{M}_i}_{\text{target at panel level}}$



Step 1: Define which ***Input*** quantity to look at:
- Structureborne and airborne inputs
- Modal input field patterns

Step 2: Define an ***Output*** quantity which handles:
- "Full Vehicle" measurements
- "Panel alone" measurements / simulation

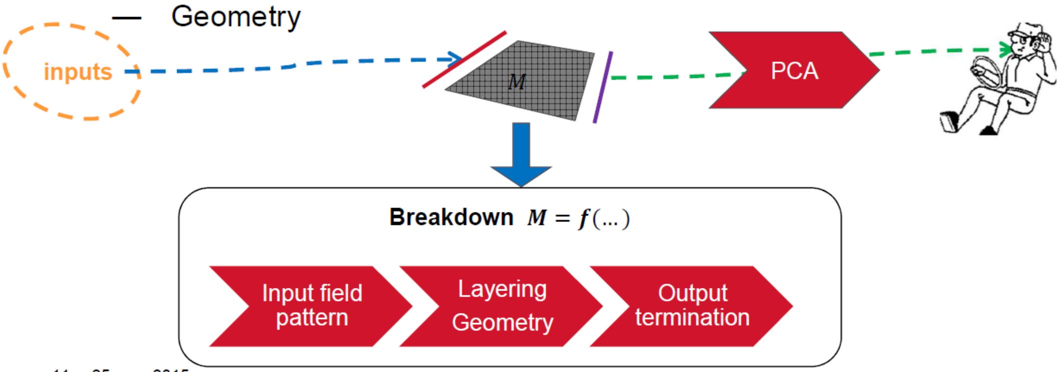
Step 3: Breakdown of the performance $M_i = f_i(\dots)$ in mechanism parameters, function of:
- Layering
- ***Input*** field pattern / ***Output*** termination
- Geometry

Metric definition

Metric definition
Contents

$$M = \frac{Output}{Input} = f(\dots)$$

1. Definition of $Input$ quantity
2. Definition of $Output$ quantity
3. Breakdown of the metric $M = f(\dots)$ of
   - Layering
   - Input field pattern / Output termination
   - Geometry

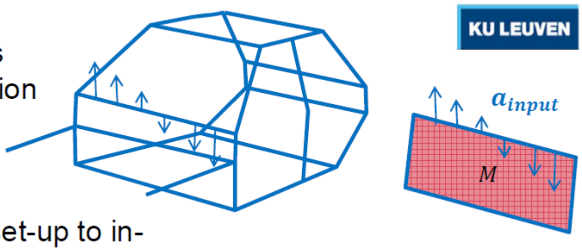


Metric definition
Metric input quantity

Defining *Input* quantity

Available:

- Acoustic pressure / structural stresses
- Acoustic velocity / structural acceleration
- Energy / power



Good input quantity:

- Predictable change from a dedicated set-up to in-vehicle condition (e.g. back-coupling the bone structure in case of SBN input)
- Model-able in Finite Element simulation
- Easily instrument-able

➔ **Choice of input quantities:**

- Structure-borne: bone acceleration a_{input}
- Air-borne: pressure p_{input}

Metric definition
Metric output quantity

Defining *Output* quantity

Available:

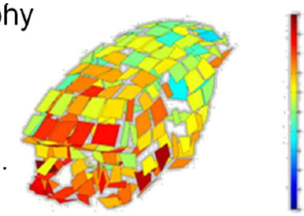
- Acoustic pressure / structural stresses
- Acoustic velocity / structural displacement
- Energy / power

Back-coupling from the interior to the structure is expected to be small in mid-frequencies

Velocity is compatible with Panel Contribution Analysis philosophy

$$p_{ear} = \sum_i \frac{p}{Q_i} Q_i$$

With Q_i the volume velocity and $\frac{p}{Q_i}$ the transfer function.



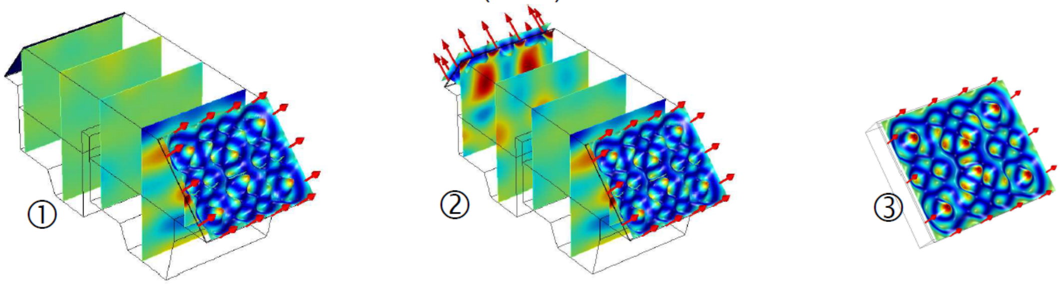
➔ Expectation: **panel behaves as a velocity source**

Metric definition
Metric output quantity

Confirmation with FE models

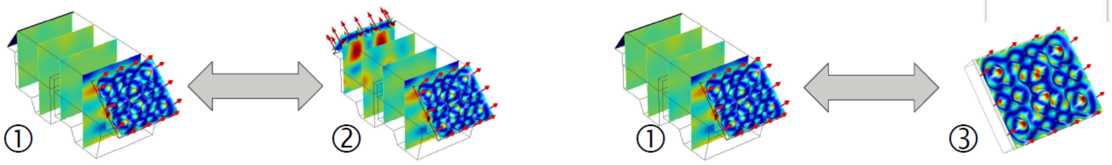
- Direct frequency response, frequency range up to 1000 Hz
- Structure-borne input on panel edges
- Receiving impedance on other trim parts

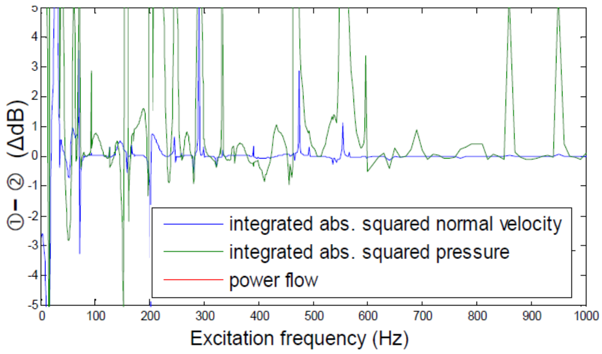
3 Models
① Full-vehicle, input on the windshield
② Full-vehicle, input on the windshield & the rear window
③ Windshield alone in anechoic field (PML)

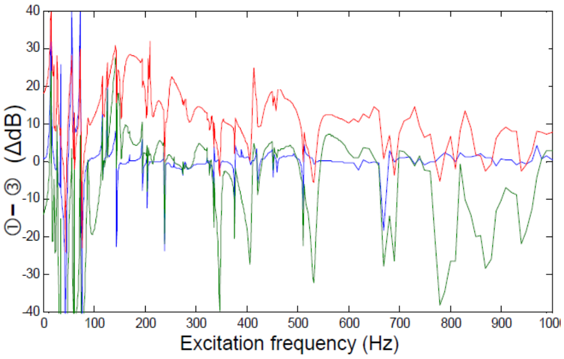


➔ **Confirmation** with integrated quantities over the windshield surface

Metric definition
Metric output quantity







In Mid-frequencies (100-1000 Hz)

- Perturbation from another source: limited impact on integrated squared velocity.
- Change from another environment: more impact, but velocity related integration is still the least sensitive.

➔ As expected, **velocity-related value** is a good choice as an output quantity.

Metric definition
Breakdown of the metric

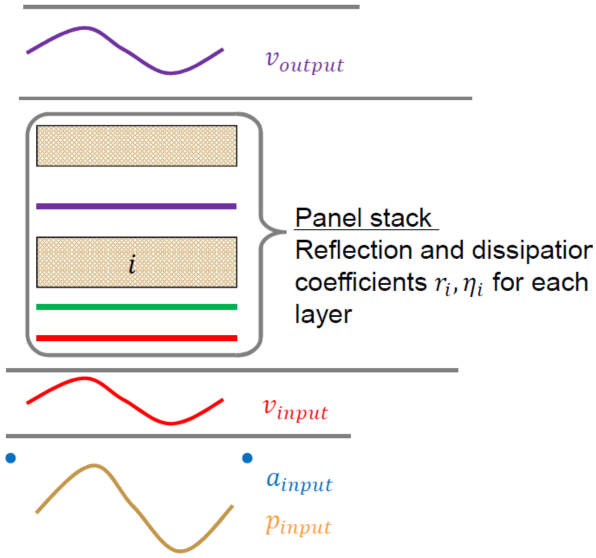
Objectives

In-situ panel response $ISPR = \frac{v_{output}}{p_{input} || a_{input}} = \frac{v_{output}}{v_{input}} \frac{v_{input}}{p_{input} || a_{input}}$

Breakdown of the velocity ratio
$VR = \frac{v_{output}}{v_{input}} = f(\eta_i, r_i)$

in:
- Reflection r_i
- Dissipation η_i

From:
- Layering
- Input field pattern
- Output termination
- Geometry



16 25-nov.-2015

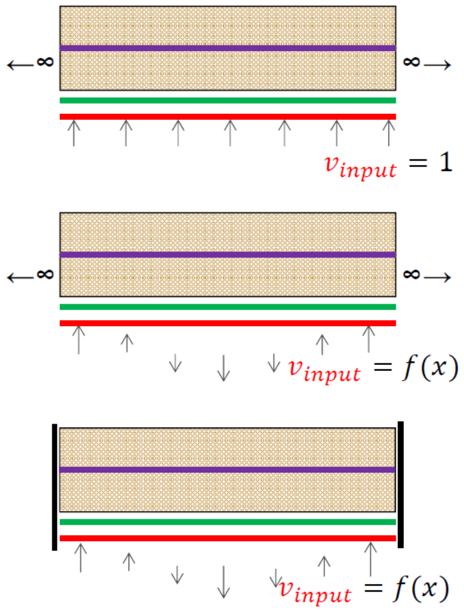
Metric definition
Breakdown of the metric

Method $VR = \frac{v_{output}}{v_{input}} = f(\eta_i, r_i)$

1. Breakdown from **the layering**
Determination in 1D infinite case in:
   — Dissipation coefficient from each layer
   — Reflection coefficient between each pair

2. Breakdown from **input field pattern**
   — Evolution of the dissipation and reflection coefficients

3. Breakdown from **the geometry**
   — Evolution of the dissipation and reflection coefficients



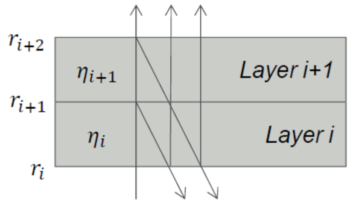
17 25-nov.-2015

Metric definition
Breakdown of the metric

Layering – 1D multi-layered panel case

Assumption: a plane wave velocity through a layer i:

- Is attenuated of a complex factor η_i
- Is reflected to the next interface with a factor r_{i+1}



A general formulation : $VR = \frac{v_{output}}{v_{input}} = \frac{\prod \eta_i (1 - r_{i+1})}{\alpha_n}$

With:

- $\alpha_n = \alpha_{n-1} - r_{n+1}\beta_n$ with $\alpha_0 = 1$
- $\beta_n = \eta_n^2\left(\beta_{n-1} + r_n\left(\sum_{i=1}^{n-2} r_{i+1}\beta_i - 1\right)\right)$ with $\beta_1 = \eta_1^2$

- exact for solutions to 1D Helmholtz equation (fluid / elastic compressional)
- Similar to TMM

➔ This formulation gives a **useful tool to understand which layer / pair of layers contributes to the velocity ratio VR**

18 25-nov.-2015

Metric definition
Breakdown of the metric

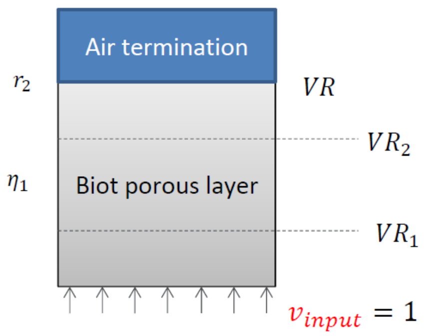
Layering – Discrepancy for Biot case

$$VR = \frac{v_{output}}{v_{input}} = \frac{\prod \eta_i (1 - r_{i+1})}{\alpha_n}$$

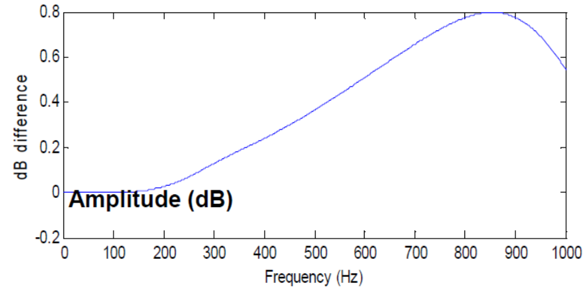
- Exact for 1D-fluid and elastic layers
- Discrepancy in case of Biot formulation

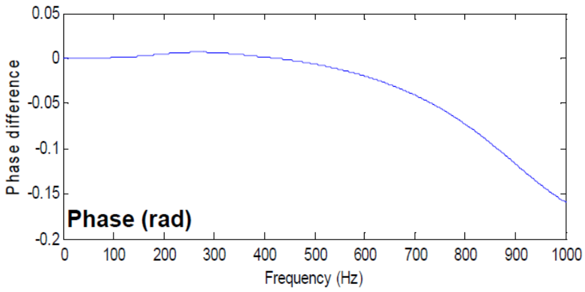
Invert problem solving $\{VR_1, VR_2\} \Rightarrow \{\eta_1, r_2\}$

$VR_{fitted} = f(\eta_1, r_2)$ % VR_{FE}



➔ Controllable discrepancy





19 25-nov.-2015

Metric definition
Breakdown of the metric

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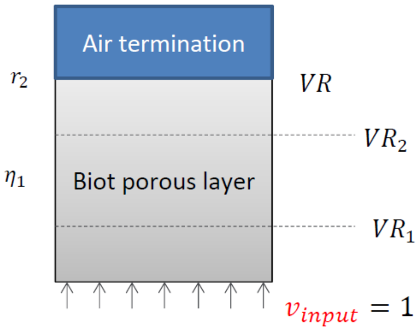
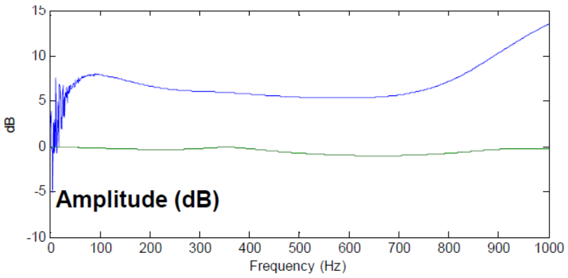
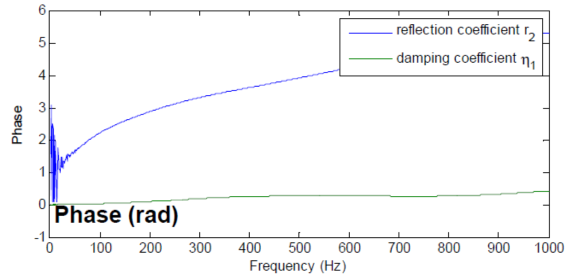






➔ Controllable discrepancy

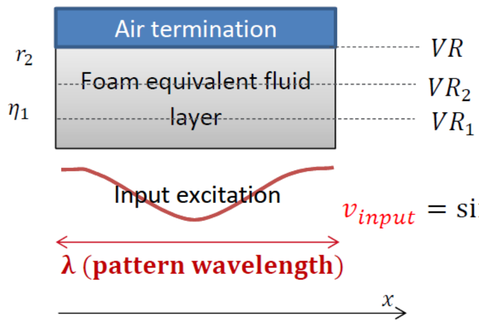
Metric definition
Breakdown of the metric

Input field patterns – sine excitation

$$VR = \frac{v_{output}}{v_{input}} = \frac{\prod \eta_i (1-r_{i+1})}{\alpha_n}$$

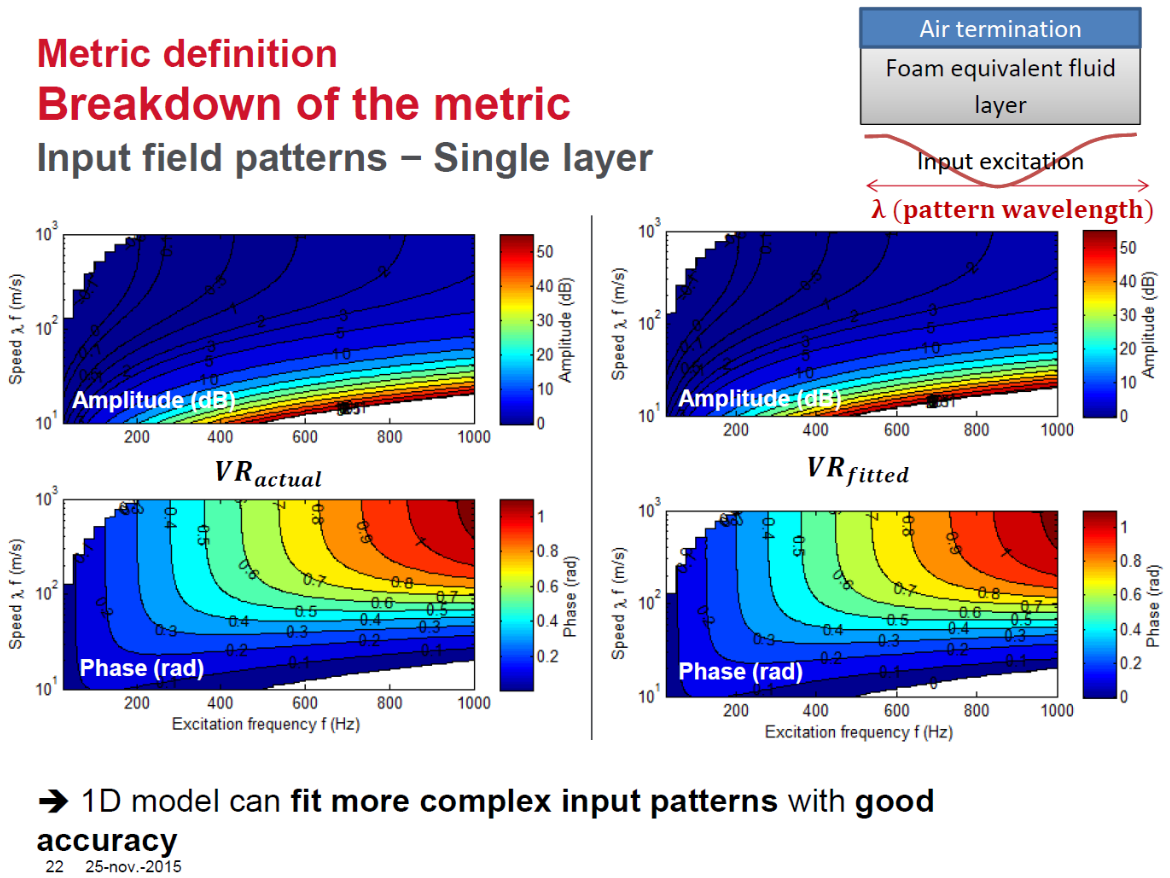
Evolution of the coefficients for more complex input fields? FE model:

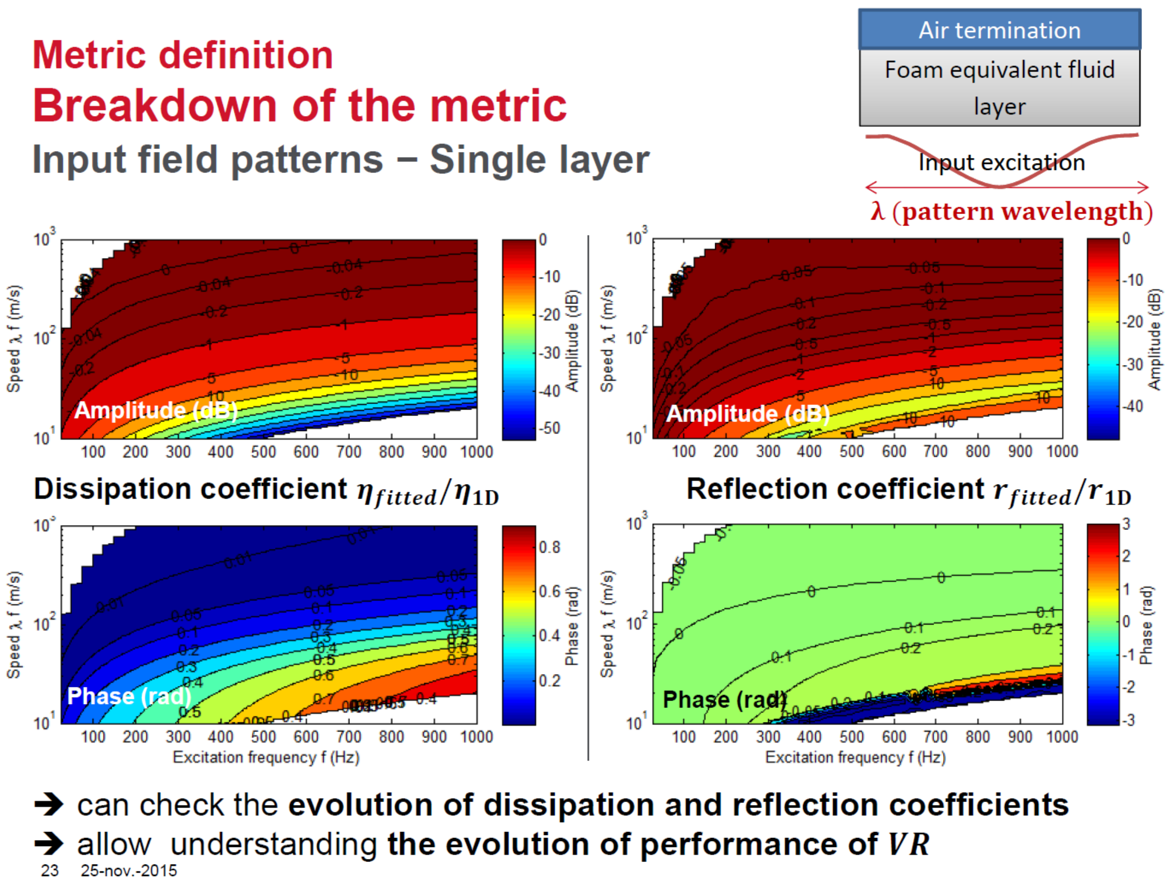
- Infinite layering
- Real sine excitation for different patterns λ
- Excitation frequencies f up to 1 kHz



Invert problem solving $\{VR_1, VR_2\} \Rightarrow \{\eta_1, r_2\} \Rightarrow VR_{fitted}$

$v_{input} = \sin(2\pi x/\lambda)$


Metric definition
Breakdown of the metric
Input field patterns – Single layer
Air termination
Foam equivalent fluid layer
Input excitation
λ (pattern wavelength)
Amplitude (dB)
Phase (rad)
Speed λ f (m/s)
Excitation frequency f (Hz)
VR actual
VR fitted
➔ 1D model can fit more complex input patterns with good accuracy
22 25-nov.-2015


Metric definition
Breakdown of the metric
Input field patterns – Single layer
Air termination
Foam equivalent fluid layer
Input excitation
λ (pattern wavelength)
Amplitude (dB)
Phase (rad)
Speed λ f (m/s)
Excitation frequency f (Hz)
Dissipation coefficient η fitted/η 1D
Reflection coefficient r fitted/r 1D
➔ can check the evolution of dissipation and reflection coefficients
➔ allow understanding the evolution of performance of VR
23 25-nov.-2015

Metric definition
Breakdown of the metric

Breakdown – Conclusions

A breakdown of the velocity ratio $VR = \frac{v_{output}}{v_{input}}$ in transmission and reflection coefficients has been introduced:

- It is exact in 1D elastic and fluid layers
- For 1D Biot porous layer, controllable discrepancies arise
- For more complex input shapes:
  - those 1D coefficients can be fitted
  - It gives good accuracy for reconstruction of the velocity ratio VR

➔ Gives a **good tool for development**:
  - Assessment of the **contribution of each layer** and **each interaction** between 2 layers in the VR
  - Assessment of the **evolution of the coefficients** for more complex input patterns

Conclusions and next steps

Conclusions and next steps
Conclusions

Mid-frequency transmission loss is too dependent:

- On output termination,
- On input fields
- On perturbation from the other panels

➔ **It cannot be used as a performance metric for the panel itself in MF**.

A new metric was introduced $ISPR = \frac{v_{output}}{p_{input}||a_{input}} = VR \frac{v_{input}}{p_{input}||a_{input}}$ and a breakdown of the velocity ratio $VR = \frac{v_{output}}{v_{input}}$ in transmission and reflection coefficients from

- Layering
  - Assessment of the **contribution of each layer / each interaction**
- Input field patterns
  - Evolution for **more complex input patterns** with low discrepancy
- Output termination
  - **Velocity** v_{output} is **less dependent** to the perturbations mentioned above

26 25-nov.-2015

Conclusions and next steps
Next steps

$$ISPR = \frac{v_{output}}{p_{input}||a_{input}} = \frac{v_{output}}{v_{input}} \frac{v_{input}}{p_{input}||a_{input}}$$

- Confirm the choice of $p_{input}||a_{input}$ as input quantities by checking the sensitivity of $\frac{v_{input}}{p_{input}||a_{input}}$ to perturbation of environment.
- Breakdown of the velocity ratio $VR = \frac{v_{output}}{v_{input}}$ due to geometry effects
  - Assessment of the evolution of reflection and dissipation coefficients near the limits

Then ISPR could be used as:

- Panel target setting
- Sensitivity analyses

27 25-nov.-2015

Acknowledgements

TOYOTA
ALWAYS A BETTER WAY
KU LEUVEN

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Vlaams Supercomputer Centrum