24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

ON THE IN-SITU MEASUREMENT OF TRANSMISSION LOSS USING THE LOCAL PLANE WAVE METHOD

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Acoustic transmission loss of partitions can be measured by a two-room method or using a sound intensity technique. In any case, these methods rely on specific sound fields used in the experiment. For instance, the two-room method relies heavily on the diffusivity of the incident sound field, as well as the full absorption in the receiving room. In the actual application in which the partition is used however, the sound field may be very different from the idealized sound fields used in the laboratory experiment. As the acoustic boundary conditions in the sending and the receiving room affects the transmission, a method that shows this dependency would be much more appropriate.

The local plane wave (LPW) family of methods have been successfully applied to measure sound absorption [1, 2]. Using the LPW method, one is able to split the total sound field into estimates of the incident field (a wave traveling in one direction) and the reflected field (a wave traveling into the opposite direction). Therefore, as the method does not require any assumptions about the global sound field, it can be used to approximate the sound absorption coefficient of a sample in any practical situation. Based on that very specific feature of the LPW method to separate incoming from reflected sound waves, in this paper, we will demonstrate the ability of the method to measure in-situ transmission loss. The method is explained by means of a numerical (finite element) fluid-structure interaction model.
Keywords: (transmission, measurement, finite element methods)

1. Introduction

The measurement of sound transmission loss of partitions, i.e. the reduction of the incident sound power over the partition (in dB), is important in a large number of fields. For instance in the field of building acoustics, one would like to know how much noise produced in one room can be heard in the other room. Also in the automotive industry, e.g., the construction separating the engine bay from the passengers compartment needs to block noise effectively.

Transmission loss measurements are usually performed in a laboratory setting. The partition is positioned in a window-like construction between a sending room and a receiving room. According to the ISO standards [3, 4, 5], a diffuse sound field is then generated in the sending room. For this diffuse sound field, the incident intensity (and hence power) can be evaluated. In addition to the diffuse sound field, the receiving room is required to be anechoic. This is done because for the anechoic room, the transmitted power is equal to the active power flowing into the receiving room. This transmitted power can therefore be measured using an intensity probe by scanning just behind the partition on the receiving room side.

An obvious drawback of the ISO setup is the required (expensive) experimental setup. Furthermore, a true diffuse sound field is very difficult to accomplish (especially at lower frequencies) and generally requires specially designed diffusers. More importantly however, the effective transmission loss of the partition, i.e. the transmission loss of the partition in the application, will depend on the in-situ (acoustic) environment. In other words, it does depend on how the partition is attached to the enclosing construction and also on the acoustic properties of, both, the sending and receiving room. Hence, the transmission loss measured in the laboratory setup, in general, is not representative for the transmission of sound through the partition in the actual application.

In this paper, we would like to show that an estimate of the in-situ transmission loss can actually be measured using a so-called local plane wave (LPW) assumption and in fact, is not difficult to do. As the LPW method does not require an a priori known given incident sound field, nor does it impose restrictions on the sending or receiving room, nor on any type of fixation of the partition, we can approximate the effective transmission loss of the partition in its actual application. Perhaps unnecessary, the LPW method can of course be used to measure transmission loss in the ISO (diffuse/anechoic) laboratory setup as well. This comparison will be documented elsewhere.

2. Theory

We will illustrate the use of the LPW method for transmission by means of an example of sound transmission through a flexible aluminium plate (the partition). The studied configuration is shown in Fig. 1. We assume a small acoustically hard sending room of 1x1 $[m]$, in which a point source is positioned in the lower left corner of the room. Sound is transmitted through a $3[mm]$ thick aluminium panel, which is clamped on both top and bottom of the panel. In the receiving room of 1x1 $[m]$, a plane wave impedance ρc is assumed on all boundaries, approximating an anechoic receiving room.

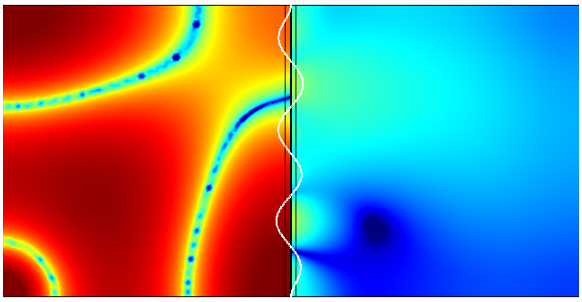

Figure 1: Sound pressure level distribution of the reference example; a sending room (left), an aluminium partition and an anechoic receiving room (right).

The transmission loss of the partition is defined by:

$$TL = -10 \log_{10} \frac{P_{tr}}{P_{in}}, \quad (1)$$

where P_{tr} is the transmitted power through the partition and P_{in} the incident power.

Based on the LPW method, the incident and reflected sound intensity (and resulting power) can easily be approximated. For this, we measure/scan the pressures of 8 microphones in a small spherical array, positioned just in front of the partition and just after the partition. Based on these signals, we deduce the pressure and particle velocity in each point of an evaluation line/area in front and after the partition. For the example case given above, these evaluation lines are shown in Fig. 1. According to the local plane wave assumption (LPW), *an assumed local incident plane wave of amplitude* $A(\mathbf{r})$ *impinging normally to the surface and an assumed local reflected plane wave of amplitude* $B(\mathbf{r})$ *emitting normally from the surface at position* $\mathbf{r}$*, both, result in the measured pressure* $P(\mathbf{r})$ *and the* *normal component of the particle velocity* $\mathbf{U}(\mathbf{r}) \cdot \mathbf{n}$. Hence, the amplitude $A(\mathbf{r})$ of the incident plane wave is, using an $e^{i\omega t}$ convention,:

$$A(\mathbf{r}) = \frac{1}{2}(P(\mathbf{r}) + \rho c\mathbf{U}(\mathbf{r}) \cdot \mathbf{n}), \tag{2}$$

where $\mathbf{n}$ is normal to and pointing into the measuring surface. The associated incident intensity is then equal to:

$$I_{in}(\mathbf{r}) = A(\mathbf{r})\bar{A}(\mathbf{r})/(2\rho c). \tag{3}$$

The amplitude $B(\mathbf{r})$ and reflected intensity are, respectively, $B(\mathbf{r}) = \frac{1}{2}(P(\mathbf{r}) - \rho c\mathbf{U}(\mathbf{r}) \cdot \mathbf{n})$ and $I_{refl} = B(\mathbf{r})\bar{B}(\mathbf{r})/(2\rho c)$. The incident and reflected powers can then be evaluated by integrating the incident and reflected intensities over the given surface:

$$P_{in} = \int I_{in}(\mathbf{r})dS \tag{4}$$

and $P_{refl} = \int I_{refl}(\mathbf{r})dS$.

Similarly, the sound intensity transmitted (emitted) from the partition to the receiving room can be estimated by the local plane wave method as well. The local amplitude $C(\mathbf{r})$ of the assumed local plane wave emitting normally from the surface at point $\mathbf{r}$, is then:

$$C(\mathbf{r}) = \frac{1}{2}(P(\mathbf{r}) - \rho c\mathbf{U}(\mathbf{r}) \cdot \mathbf{n}). \tag{5}$$

The associated intensity and power are then equal to, respectively:

$$I_{tr}(\mathbf{r}) = C(\mathbf{r})\bar{C}(\mathbf{r})/(2\rho c) \tag{6}$$

and

$$P_{tr} = \int I_{tr}(\mathbf{r})dS. \tag{7}$$

An interesting feature of this approach is that we are also able to account for possible reflections from the receiving room. The amplitude $D(\mathbf{r})$ of the assumed local plane wave due to these reflections is equal to $D(\mathbf{r}) = \frac{1}{2}(P(\mathbf{r}) + \rho c\mathbf{U}(\mathbf{r}) \cdot \mathbf{n})$ and the intensity and power are, respectively, $I_{refl*}(\mathbf{r}) = D(\mathbf{r})\bar{D}(\mathbf{r})/(2\rho c)$ and $P_{refl*} = \int I_{refl*}(\mathbf{r})dS$.

A well-known estimate of the transmission loss is given by the so-called mass law, being the transmission loss if stiffness effects are neglected, see [6]. It is given by:

$$TL_{ml} = 20\log_{10}\frac{\rho_m t\pi f}{\rho c}, \tag{8}$$

where ρ_m denotes the plate's density, t its thickness and f denotes the frequency. We will use the mass law for reference and comparison.

3. Examples

3.1 Reference example

For the reference model described above, the transmission loss obtained using the LPW method as well as the mass law are given in Fig. 2.

The transmission loss curve calculated using the LPW method is seen to have all known characteristic features. A stiffness controlled region in the low frequency region (transmission loss reducing with frequency), a mass controlled region for high frequencies (transmission loss increasing with frequency) and so-called 'coincidence' dips of very low transmission loss at the eigen-frequencies of the coupled fluid-structure interaction problem. It is seen that the transmission loss and mass law curve

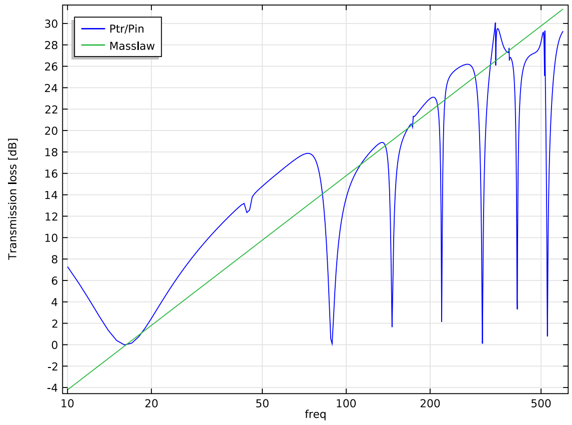

Figure 2: Transmission loss according to LPW for the reference example (blue line) and the mass law (green line). The point source is situated in the bottom-left corner in the sending room.

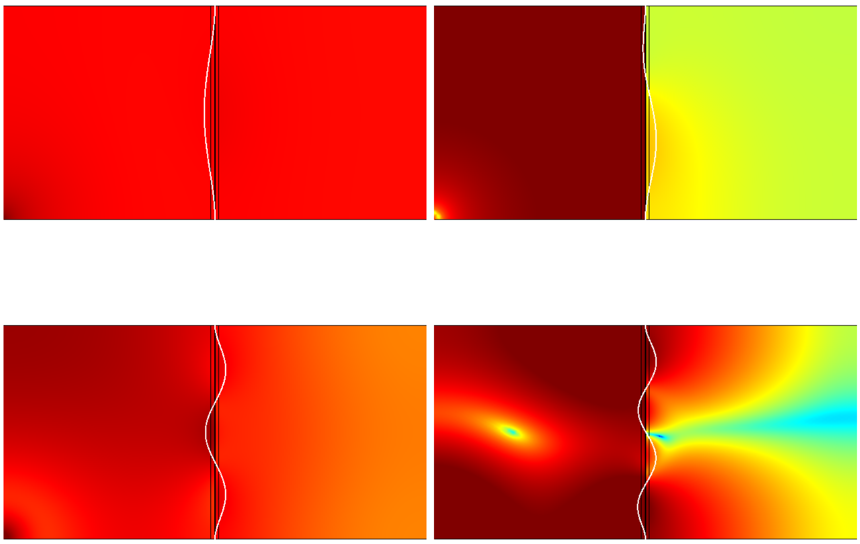

Figure 3: SPL for the reference example at 16 Hz (top, left), 44 Hz (top, right), 89 Hz (bottom, left) and 146 Hz (bottom, right). The point source is situated in the bottom-left corner of the sending room.

match quite well in the region where the mass law is applicable; the transmission loss based on LPW being more accurate in the sense that stiffness effects are accounted for. As an illustration, the sound pressure level and plate mode shapes are shown in Fig.3 for some interesting frequencies. Indeed, it can be seen that for 16 Hz, the transmission loss is close to zero and the SPL in the sending and receiving room are almost equal. The plate's deflection shape closely resembles the first eigen-mode, explaining the low transmission loss. At 44 Hz, a frequency close to the second eigen-frequency of the plate, one would also expect a small transmission loss. However one only observes a small dip in the curve. At this frequency, the acoustic wave length is large compared to the structural wavelength. Hence, the acoustic load on the plate is almost uniform, incapable of exciting the second eigen-mode and thus explaining the absence of a coincidence dip. At 89 and 146 Hz, the coincidence dips are prominent again.

The small variations in the transmission loss curves at 173 and 344 Hz are also noteworthy. These frequencies are resonance frequencies of the coupled fluid-structure interaction problem which are associated with the acoustic resonance frequencies of the sending room. Fig. 4 shows the intensity vectors in the sending and receiving room at these frequencies, showing ’recirculation cells’ of intensity vectors.

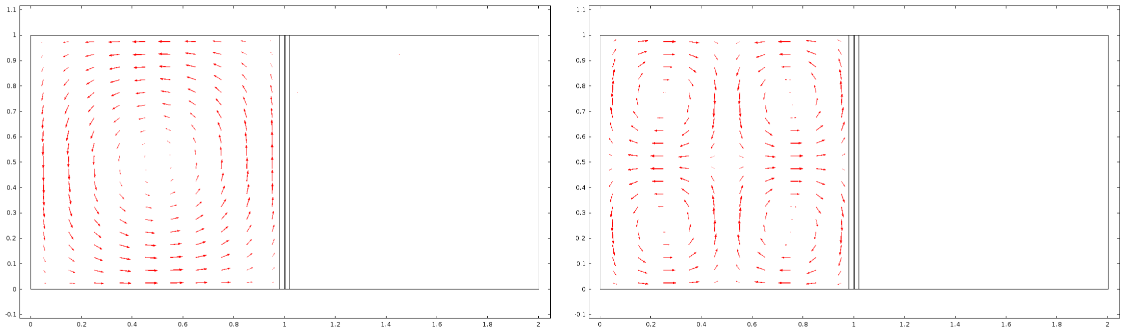

Figure 4: Intensity vectors for the reference example at 173 Hz (left) and 344 Hz (right).

3.2 Changing the source position

To show that transmission loss actually depends on the in-situ sound field, just as an example, the position of the point source has been changed to the center of the left wall. This makes the model symmetric about the horizontal symmetry-axis. The calculated transmission loss curve and the transmission curve of the reference example are shown in Fig. 5.

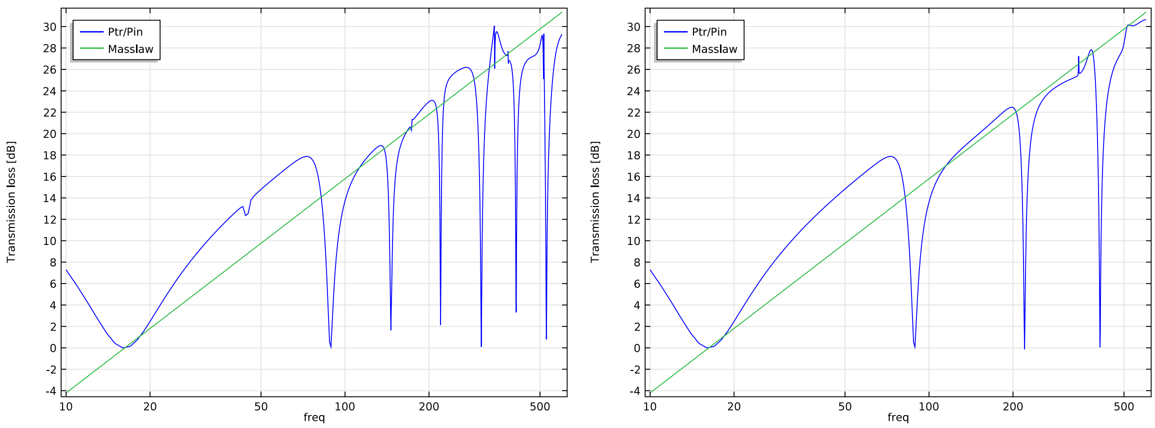

Figure 5: Transmission loss according to LPW (blue line) and the mass law (green line) for the reference example (left) and the example of a changed source position (right).

In Fig. 5, the coincidence dips at 44, 146 and 308 Hz in the example of a changed source position are now seen to be completely absent. Since the mode shapes of the aluminium plate, at these frequencies, are all anti-symmetric, the now symmetric acoustic loading prevents excitation of these modes. As a result, the coincidence dip is therefore not seen. An illustration of the sound pressure level at 89 and 146 Hz is given in Fig. 6, where the large difference between the 146 Hz solution and the 146 Hz solution in Fig. 3 is noteworthy.

3.3 Changing the receiving room

To illustrate the dependency of the transmission loss on the acoustic properties of the receiving room, the reflection from the receiving room has been successively increased. First, by assuming the receiving room floor to be acoustically hard and, secondly, assuming the receiving room floor and right wall to be acoustically hard, see Fig. 1. The calculated transmission loss curves and the curve from the reference example are shown in Fig.7.

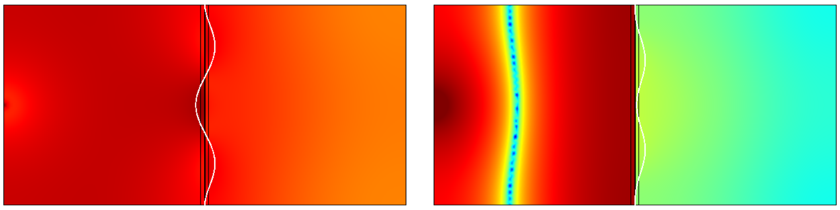

Figure 6: SPL at 89 Hz (left) and 146 Hz (right). As opposed to the reference example, the point source is located in the center of the left wall.

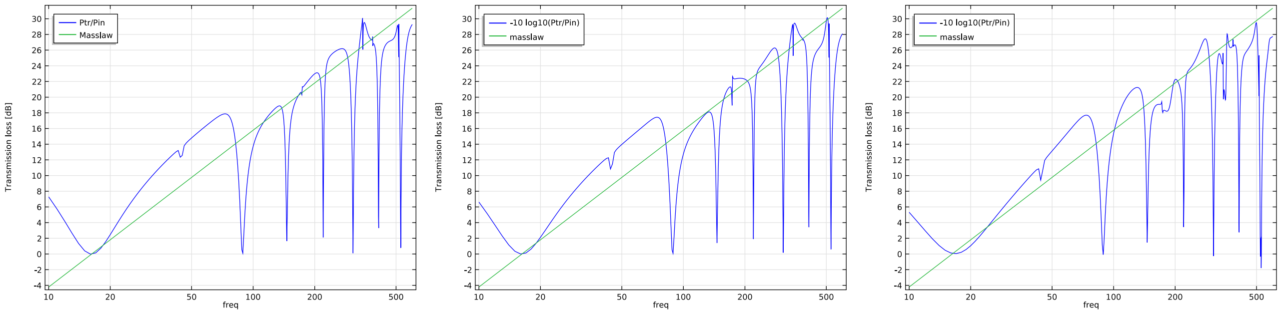

Figure 7: Transmission loss according to LPW (blue line) and the mass law (green line). Anechoic receiving room (left), rigid floor (middle), rigid floor and rigid right wall (right).

From the figures, one can first conclude that the overall transmission loss is, for the current setup, quite similar for all three cases. The difference in transmission loss of the partition is, by enlarge, not much affected by the receiving room. A good estimate of the anechoic transmission loss can thus be obtained from measurements with a non-anechoic receiving room. One does however see that the transmission loss is affected, especially at the eigen-frequencies associated with the receiving room, i.e. near 173 and 344 Hz in Fig. 7.

3.3.1 Absorption coefficient/Radiation efficiency

The LPW method provides additional insight in the acoustic behavior of the partition. For instance, as explained in [2], the absorption coefficient of the partition can be approximated by:

$$\alpha = \frac{P_{ac}^{in}}{P_{in}} = \frac{P_{in} - P_{refl}}{P_{in}}, \tag{9}$$

where P_{ac}^{in} denotes the active (i.e. the net time-averaged) power on the sending side of the partition. The absorption coefficient is defined as the percentage of the incoming power being absorbed by the surface; the value ranging from 0 for no absorption, to unity for full absorption. Note that in this case, as the dissipation in the partition is absent, the 'absorption' is just due to the sound power being transmitted through the partition and passed to the absorbing boundaries in the receiving room.

Equivalently, on the receiving room (emitted) side, the radiation efficiency, defined as:

$$\epsilon = \frac{P_{ac}^{tr}}{P_{tr}} = \frac{P_{tr} - P_{refl*}}{P_{tr}}, \tag{10}$$

where P_{ac}^{tr} is the active power on the receiving/emitted side of the partition, can now be evaluated. The radiation efficiency is defined as the percentage of the emitted power (P_{tr}) which radiates to the far field (P_{ac}^{tr}). Due to the reflection of the receiving room but also due to the plates radiation impedance, this efficiency is a number between 0 for no net power emission to unity for most efficient radiation, i.e. all emitted power radiates to the far field.

Both the absorption coefficient and radiation efficiency are shown in Fig. 8 for the different receiving rooms (anechoic, rigid floor, and rigid floor and rigid right wall).

The first, maybe counterintuitive, observation is the increase in absorption coefficient at the low frequencies, while the absorption of the receiving room is reduced. This may seem erroneous but can be explained by the observed increase in radiation efficiency at the emitted side of the partition. As the radiation efficiency increases, a larger fraction of the emitted sound power is actually emitted to the far field (the radiation impedance has increased). Hence, the emission of sound power of this partition is more efficient, if the receiving room is less absorbing, which explains the increase in absorption coefficient.

In addition, one observes the absorption coefficient to be always less than the radiation efficiency. Although this is beyond the scope of this paper, for non-dissipative partitions, one could state that the capability of a plate to 'absorb' sound power is limited by the radiation efficiency of that same plate to emit sound power.

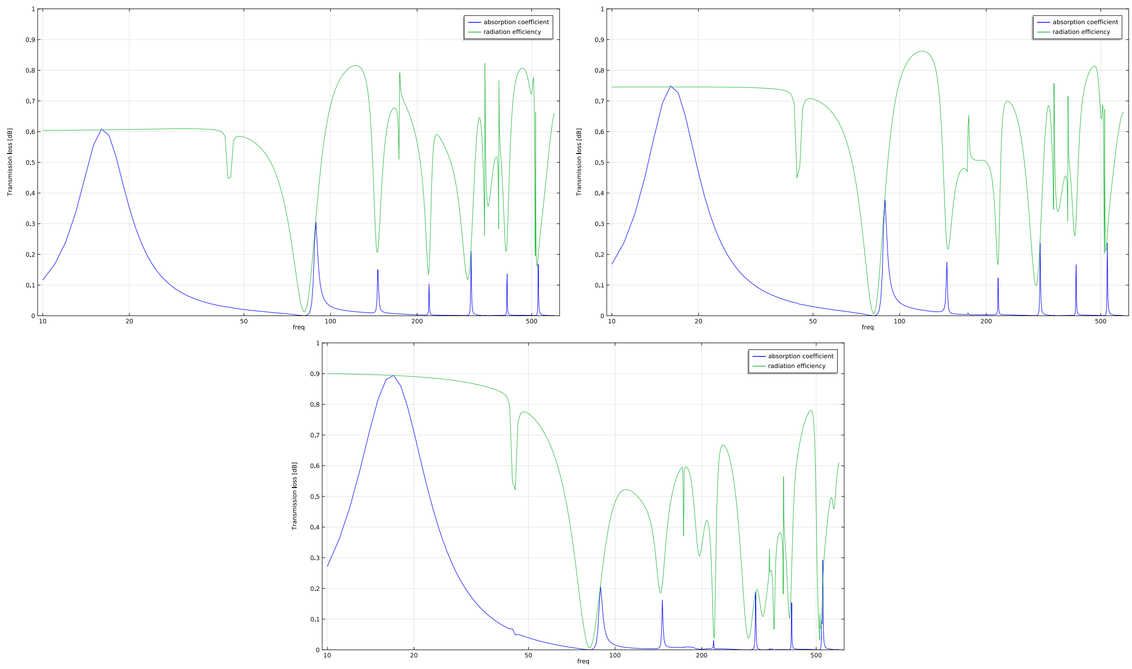

Figure 8: Absorption coefficient (blue line) and radiation efficiency (green line) according based on the LPW method for the anechoic receiving room (top left), rigid floor (top right), rigid floor and rigid right wall (bottom).

3.4 Changing the partition

As a last example, the effect of changing the thickness of the partition itself from 3 to 2 to $1.5[mm]$ is illustrated in Fig. 9. The transmission loss curves based on the LPW method are in accordance to the mass law. The clear decrease in transmission loss with thickness is similar to the prediction of the mass law.

4. Conclusion

The local plane wave method can be used to approximate the incoming and transmitted sound power through a partition, by measuring pressures at, at least, 2 nearby locations (or the pressure and particle velocity at one location) in front and after the partition. Based on these powers, the effective,

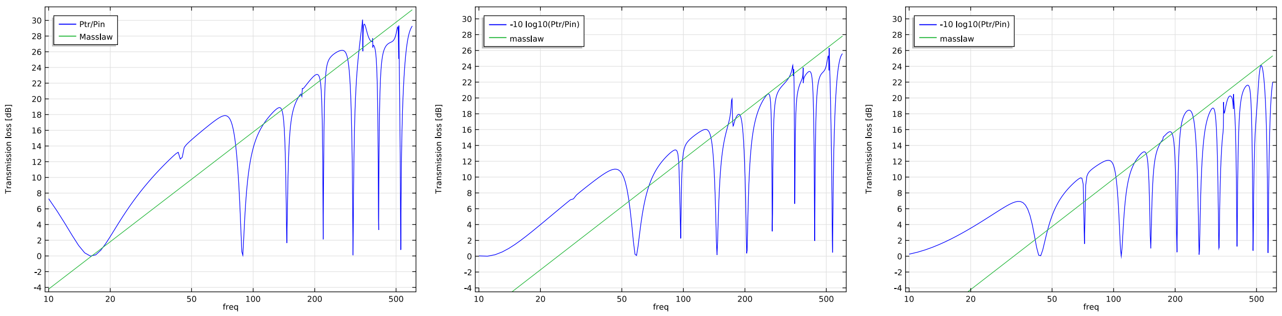

Figure 9: Transmission loss according to LPW (blue line) and the mass law (green line). Thickness of the partition $t = 3[mm]$, $t = 2[mm]$ and $t = 1.5[mm]$.

i.e. in-situ, sound power transmission loss can easily be approximated. It has been shown that the, thus obtained, transmission loss closely follows, but is different from, the mass law. All characteristic features of a transmission loss curve are observed in this curve; a stiffness dominated decreasing transmission loss at low frequencies, an increasing transmission loss for higher frequencies and the coincidence dips at the eigen-frequencies of the coupled fluid-structure interaction problem. This has been illustrated by a number of numerical examples in which the source position in the sending room, the boundary conditions of the receiving room and the thickness of the partition have been changed.

REFERENCES

1. Y.H.Wijnant, E.R. Kuipers and A. de Boer, *Development and application of a new method for the in-situ measurement of sound absorption*, Proc. of ISMA 31, Leuven, Belgium, (2010).

2. Kuipers, E. *Measuring sound absorption using local field assumptions*, PhD Thesis, University of Twente, (2013).

3. ISO 15186, *Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity.*, – Part 1: 2000, Laboratory measurements. – Part 2: 2003, Field measurements. – Part 3: 2002, Laboratory measurements at low frequencies.

4. ISO 10140-5, *Acoustics – Laboratory measurement of sound insulation of building elements* – Part 5: "Requirements for test facilities and equipment.

5. ISO 3745, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure*, – Precision methods for anechoic rooms and hemi-anechoic rooms.

6. D.T. Blackstock, *Fundamentals of physical acoustics*, A Wiley-Interscience publication, 2000.