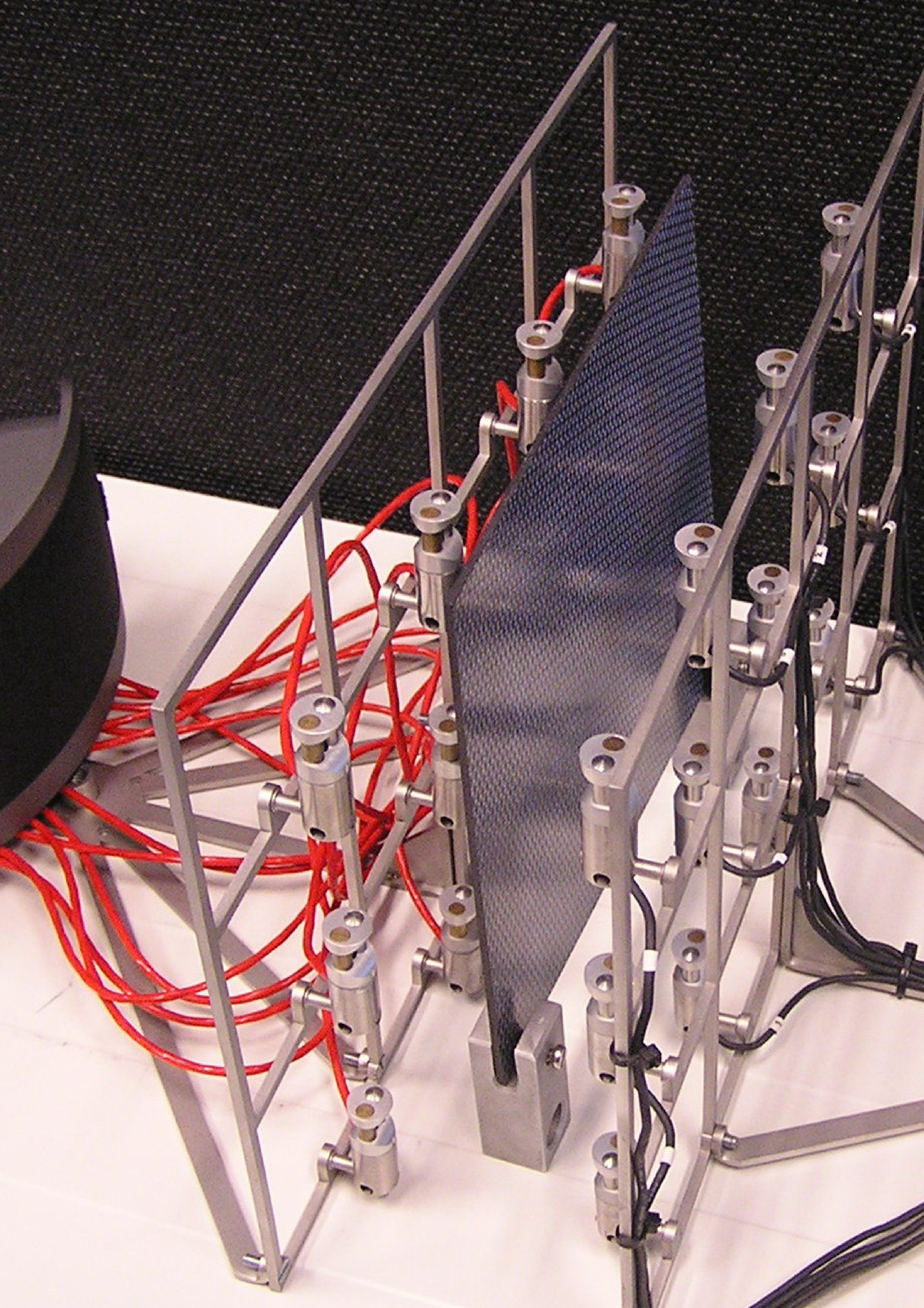

19 transmission loss measurements

Fig. 19.1 (previous page): Historical photo: experimental setup to measure the transmission loss in situ with a double array.

19.1 Introduction

The transmission loss of an acoustical material is defined as the ratio of sound intensity incident on the material (W_i) to the amount of sound energy that is transmitted through the material.

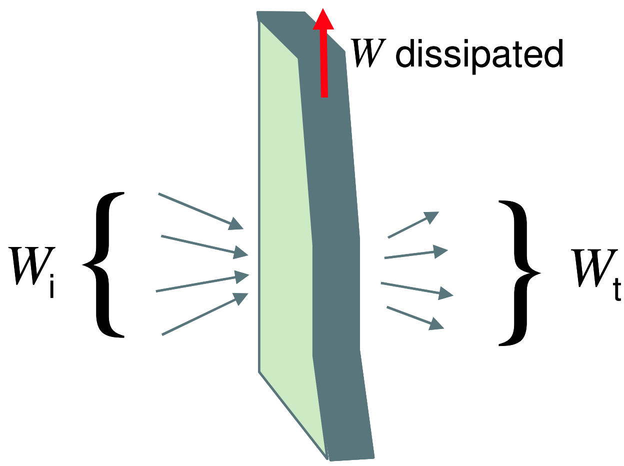

Fig. 19.2: Schematic representation of the transmission loss ingredients, from [2].

The transmission loss is defined as:

$$TL(\omega) \equiv 10\log_{10}\left(\frac{W_{\rm i}}{W_{\rm t}}\right) \qquad (19.1)$$

Most engineers and scientists who deal with these types of noise control treatments perform experiments to compare the transmission loss effectiveness of different treatment options.

Although the definition of transmission loss is very simple, the actual measurement of the transmission loss is complex. This is because the measurement of the sound energy transmitted in the material (W_i) is difficult to measure directly.

With a sound intensity probe the net intensity is measured at the side of the incident sound wave, i.e. the incident intensity minus the reflected intensity.

19.2 The standard measurement method

The standard test methods for the transmission loss measurement uses two adjacent rooms with an adjoining transmission path. The treatment under test is placed between the two rooms in the adjoining transmission path. Sound is generated in one room and measurements are taken in both the source and receiver room to characterize the transmission loss. The standard method avoids the direct measurement of the sound energy transmitted in the material by using a reverberation room.

This method is defined, time tested, and reliable. Unfortunately, implementing this testing method reliably requires large and expensive test chambers. In many situations where the transmission loss tests are necessary but infrequent, this cost and space burden is unacceptable. A transmission loss testing procedure that is less costly and requires less space would be of great interest in this situation.

The first technique utilizes sound intensity to experimentally determine the transmission loss. This method has been standardized by the American Society of Testing and Materials (ASTM) in the standard ASTM E22492.

A broadband sound source is placed in the reverberation, or source, room. The material under test is secured using an open window between the rooms. The sound intensity incident on the material (I_i) is calculated in Eq. (19.2) from the space averaged sound pressure in the source room, p, under the assumption that the sound field is diffuse. Here, ρ is the density of air and c is the speed of sound in air.

The sound intensity transmitted through the material (I_t) is then measured in the anechoic chamber, or receiver room, using a sound intensity probe. The intensity probe is positioned perpendicular to the test sample and can be scanned or moved point by point over the material surface to obtain the averaged transmitted sound intensity. The transmission coefficient is then the ratio of transmitted sound intensity to incident sound intensity and the transmission loss measurement can be computed:

$$I_i = \frac{p^2}{4\rho c} \qquad TL = 10 Log \frac{I_t}{I_i} \tag{19.2}$$

A photograph of one side of the set up is shown in Fig. 19.3. As can be seen, it is quite a large set up. Disadvantage of the set up is its size and related to this the cost of the measurement. Apart from that it is only possible to measure materials that are suited to fit in between the two rooms.

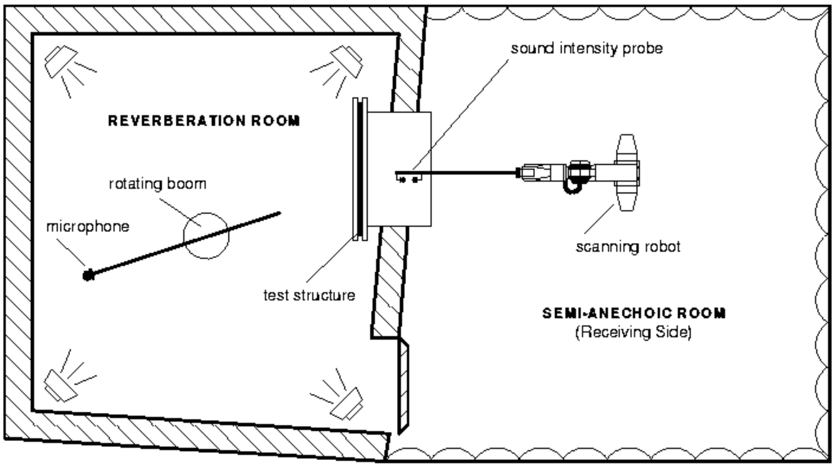

Fig. 19.3: Standard set up to measure the transmission loss of acoustic materials.

In a test at GM (Detroit) a ½" PU Microflown based intensity probe was tested in a transmission loss measurement and compared with a traditional pp probe with a spacing of 8.5mm (a small spacing to be able to reach 10kHz). As can be seen in Fig. 19.5 the PU probe an the pp probe do have a similar response apart from the frequencies higher than 4kHz.

Fig. 19.4: Standard set up to measure the transmission loss of acoustic materials.

The deviation is caused by the lower signal to noise ratio of a pu probe at these higher frequencies. If the signal is below 0dB (which is a very low level), the pu pr0obe cannot be used in straightforward way.

The reason for the extreme low levels is that the signal in the reverberation room cannot be extremely loud and that in this case a material with a very high transmission loss factor is used.

There are ways to increase the signal to noise ratio of pu probes (longer averaging, measure with a smaller bandwidth, etc).

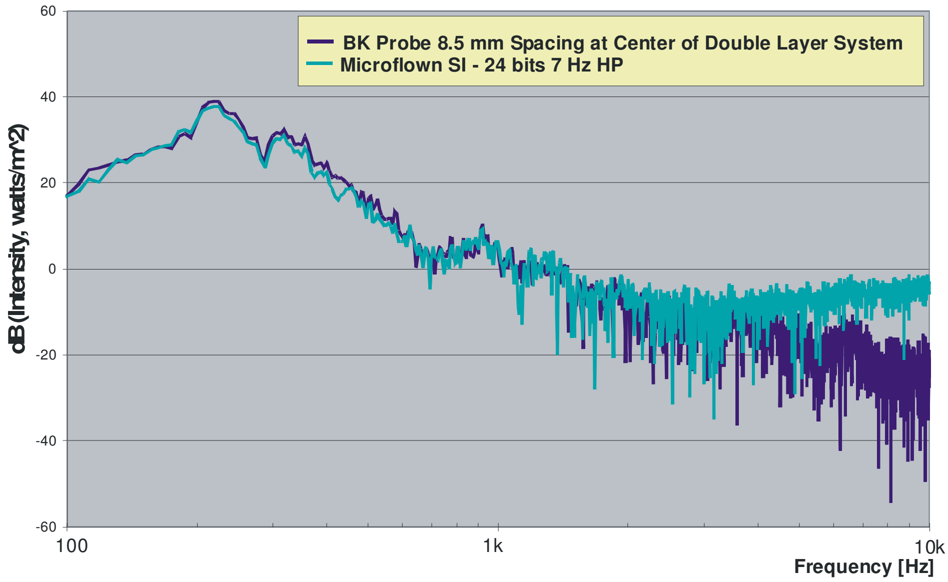

Fig. 19.5: Comparison between BK Probe and Microflown PU probe.

Under some conditions it is also possible to measure the transmission loss in a standing wave tube.

19.3 Pressure based standing wave tube methods

In a standing wave tube an acoustic sample is placed at place x=0 in the tube (not at the end). Fig. 19.6 shows a plane wave tube with a loudspeaker left, a termination to the right and a sample of test material in the middle, separating the tube in two sections. This paragraph is a summary from [2].

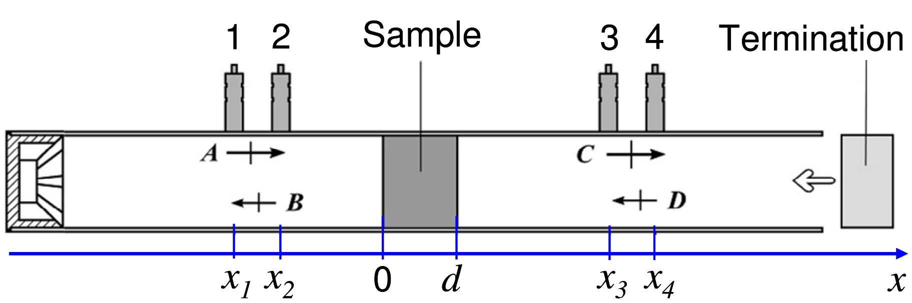

Fig. 19.6: A standing wave tube with an acoustic sample in the middle, two sets of microphones are positioned at each side (from [2]).

The sound pressure $P1$ to $P4$ at the microphone positions can be expressed in terms of the complex plane wave amplitudes A to D.

$$P_1 = (Ae^{-ikx_1} + Be^{ikx_1}) \quad P_3 = (Ce^{-jkx_3} + De^{ikx_3})$$
$$P_2 = (Ae^{-ikx_2} + Be^{ikx_2}) \quad P_4 = (Ce^{-jkx_4} + De^{ikx_4}) \tag{19.3}$$

The complex plane wave amplitudes A to D are given by:

$$A = \frac{i(P_1 e^{ikx_2} - P_2 e^{ikx_1})}{2\sin k(x_1 - x_2)}, \quad C = \frac{i(P_3 e^{ikx_4} - P_4 e^{ikx_3})}{2\sin k(x_3 - x_4)},$$
$$B = \frac{i(P_2 e^{-ikx_1} - P_1 e^{-ikx_2})}{2\sin k(x_1 - x_2)}, \quad D = \frac{i(P_4 e^{-ikx_3} - P_3 e^{-ikx_4})}{2\sin k(x_3 - x_4)} \tag{19.4}$$

The transmission loss of the sample can be derived from the plane wave amplitudes. The plane wave reflection and transmission coefficients of the sample are defined. Plane waves A and D are incident on the sample, while B and C are outgoing. The amplitudes of the outgoing waves are linear functions of the amplitudes of the incident waves, the coefficients being the reflection and transmission coefficients.

The transmission and reflection coefficients provide two linear equations that relate the outgoing waves on one side and the incoming waves on the other side.

$$C = t_{12}A + r_2 D, \; B = r_1 A + t_{21} D \; \rightarrow \; \begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} r_1 & t_{21} \\ t_{12} & r_2 \end{bmatrix} \begin{bmatrix} A \\ D \end{bmatrix} \tag{19.5}$$

Where t_{12} is the transmission coefficient from 1 to 2 and r_1 is reflection coefficient of side one, etc.

These equations can be easily re-arranged to relate the wave amplitudes in the left tube section to those in the right section. These matrices are called plane wave scattering matrices.

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix} = \begin{bmatrix} 1/t_{12} & -r_2/t_{12} \\ r_1/t_{12} & t_{21} - r_1 r_2/t_{12} \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix} \tag{19.6}$$

The transmission is given by:

$$TL_n \equiv 10\log\left(\left|\frac{A}{C}\right|^2_{D=0}\right) = 10\log\left(\left|a_{11}\right|^2\right) = 10\log\left(\left|\frac{1}{t_{12}}\right|^2\right) \tag{19.7}$$

One measurement of the complex plane wave amplitudes A to D provides two equations to determine the four matrix coefficients.

By performing two measurements with different termination conditions, represented here by $^{(a)}$ and $^{(b)}$, the four independent equations for determination of the four scattering matrix elements are obtained.

$$\begin{bmatrix} A^{(a)} & A^{(b)} \\ B^{(a)} & B^{(b)} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} C^{(a)} & C^{(b)} \\ D^{(a)} & D^{(b)} \end{bmatrix} \tag{19.8}$$

Solution of these equations provides the transmission loss.

Dividing by $C^{(a)}C^{(b)}$ in numerator and denominator we get an expression, where the denominator equals the difference between the complex reflection coefficients of the two different terminations. The estimation becomes numerically ill conditioned at frequencies where the complex reflection coefficients are identical or nearly identical.

$$a_{11} = \frac{A^{(a)}D^{(b)} - A^{(b)}D^{(a)}}{C^{(a)}D^{(b)} - C^{(b)}D^{(a)}} = \frac{R^{(b)} \cdot A^{(a)}/C^{(a)} - R^{(a)} \cdot A^{(b)}/C^{(b)}}{R^{(b)} - R^{(a)}}, \quad R^{(s)} \equiv \frac{D^{(s)}}{C^{(s)}} \tag{19.9}$$

In case the sample is symmetric in the sense that the transmission coefficient is the same in both directions (i.e. $t_{21}=t_{12}$) and the reflection coefficient is the same from both sides ($r_1=r_2$), only a single load condition needs to be measured. The reflection coefficient is then given by:

$$R_a = r_1 = \frac{a_{21}}{a_{11}} = \frac{AB - CD}{A^2 - D^2} \tag{19.10}$$

The transmission coefficient is given by:

$$TL_n = 10\log\left(\left|a_{11}\right|^2\right) = 10\log\left(\left|\frac{A^2 - D^2}{AC - BD}\right|^2\right) \tag{19.11}$$

Transfer Matrix method

This paragraph is a summary from [4]. The transfer matrix is used to relate the sound pressures and normal acoustic particle velocities on the two faces of the material under test. The sound pressure and the particle velocity in the left side of the tube (as shown in Fig. 19.6) are given by:

$$\begin{aligned} P &= (Ae^{-ikx} + Be^{ikx}) \\ V &= (Ae^{-ikx} - Be^{ikx})/\rho_0 c \end{aligned} \tag{19.12}$$

At the right side:

$$\begin{aligned} P &= (Ce^{-ikx} + De^{ikx}) \\ V &= (Ce^{-ikx} - De^{ikx})/\rho_0 c \end{aligned} \tag{19.13}$$

At the surface of the sample under test the sound pressure and particle velocity are given by:

$$P\big|_{x=0} = (A+B) \qquad P\big|_{x=d} = (Ce^{-ikd} + De^{ikd})$$
$$V\big|_{x=0} = (A-B)/\rho_0 c \qquad V\big|_{x=d} = (Ce^{-ikd} - De^{ikd})/\rho_0 c \qquad (19.14)$$

The transfer matrix **T** maps the sound pressure and particle velocity on the downstream face of the sample (x=d) onto the pressure and particle velocity on the upstream face (x=0):

$$\begin{bmatrix} P \\ V \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix}_{x=d} \qquad (19.15)$$

Just like the scattering matrices (the matrix of transmission losses en reflection coefficients), the transfer matrix characterizes the sample, independent of excitation and termination. It provides a complete two-port model of the sample and allows the transmission Loss to be determined. And as with the scattering matrices, a single measurement of complex plane wave amplitudes provides two equations for determination of the four matrix elements. Again, similar as the previous paragraph, two additional independent equations can be generated by measuring a second different termination condition.

$$\begin{bmatrix} P^{(a)} & P^{(b)} \\ V^{(a)} & V^{(b)} \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P^{(a)} & P^{(b)} \\ V^{(a)} & V^{(b)} \end{bmatrix}_{x=d} \qquad (19.16)$$

19.4 PU standing wave tube method

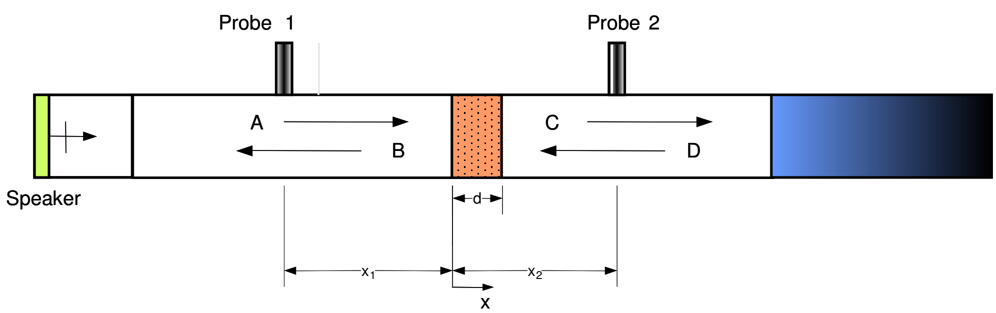

Fig. 19.7: A standing wave tube set up to measure the transmission loss of acoustic materials, (from [3]).

The complex variables are given by:

$$P_1 = (Ae^{-jkx_1} + Be^{jkx_1})e^{j\omega t} \qquad P_2 = (Ce^{-jkx_2} + De^{jkx_2})e^{j\omega t}$$
$$V_1 = \frac{(Ae^{-jkx_1} - Be^{jkx_1})e^{j\omega t}}{\rho_0 c} \qquad V_2 = \frac{(Ce^{-jkx_2} - De^{jkx_2})e^{j\omega t}}{\rho_0 c} \qquad (19.17)$$

The complex amplitude of waves is derived:

$$A = \frac{P_1 + \rho_0 c V_1}{2e^{-jkx_1}} \quad C = \frac{P_2 + \rho_0 c V_2}{2e^{-jkx_2}}$$
$$B = \frac{P_1 - \rho_0 c V_1}{2e^{jkx_1}} \quad D = \frac{P_2 - \rho_0 c V_2}{2e^{jkx_2}} \qquad (19.18)$$

19.5 PU free field method

The difficult part in the transmission loss definition is the determination of the sound energy transmitted in the material (W_i). This is because the sound intensity measured at the inward side, measures the net intensity; that is the inward intensity minus the reflected intensity.

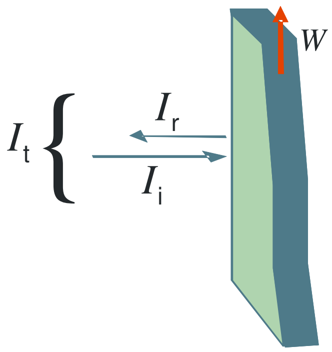

Fig. 19.8: The measured intensity is the subtraction of the inward minus the reflected intensity.

It is possible to measure the reflection coefficient in situ (which is the ratio of the inward intensity and the reflected intensity $|R|=I_r/I_i$). If this value is known, the inward intensity can be calculated from the net intensity.

If the material is highly reflective, the reflection coefficient approximates unity and the method becomes very unstable.

Another method is to take a calibrated monopole. The sound intensity of such source is given as function of place by a reference (velocity) sensor. The inward intensity is not affected by the presence of the material (only the net intensity).

The transmitted intensity is simply measured with an intensity probe. (If the source signal is used as a reference signal, the measurement is unaffected by background noise).

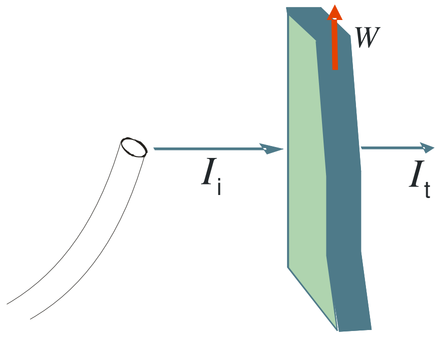

Fig. 19.9: The inward intensity is determined by the calibrated monopole. The transmitted intensity is simply measured by an intensity probe.

19.6 References

[1] Andrew R. Barnard et al., Measurement of Sound Transmission Loss Using a Modified Four Microphone Impedance Tube, NOISE-CON 2004

[2] O. Olivieri, J.S. Bolton and T. Yoo, Measurement of transmission loss of materials using a standing wave tube, Internoise, 2006.

[3] Taewook Yoo and J. Stuart Bolton, private discussions

[4] Bryan H. Song and J. Stuart Bolton, A transfer-matrix approach for estimating the characteristic impedance and wave numbers of limp and rigid porous materials, JASA 2000