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Prediction of speech privacy between rooms

Jukka Keränen, Petra Virjonen and Valtteri Hongisto

Finnish Institute of Occupational Health, Lemminkäisenkatu 14-18 B, 20520 Turku, Finland
jukka.keranen@ttl.fi

One of the main purposes of wall structures and doors is to provide an appropriate level of speech privacy between rooms. But speech privacy does not depend only on sound reduction index but also on, e.g., background noise level, room volumes, reverberation times and speech effort. The aim of this study is to present a simple and validated model to predict the speech privacy between two arbitrary rooms when above mentioned parameters are known. Speech privacy was described using Speech Transmission Index, STI. STI can be determined when the basic parameters are known. The validation of the model was made in four cases. The model is useful when economic optimization of speech privacy is appreciated. It can lead to significant reductions or increments of general recommendations for sound reduction index, especially, when room dimensions are unusual or the rooms have special purposes. Internet software was created for the practical application of the model. The model can be used both in the design stage of the building and the diagnosis of speech privacy problems.

1 Introduction

One of the main purposes of structures is to provide an appropriate level of speech privacy between rooms. Speech privacy does not depend only on sound reduction index but also on, e.g., the background noise level, room volumes, reverberation times and speech effort.

In the following, some practical examples are presented, where the dimensioning has failed although the sound reduction index, SRI, of the partition agreed the requirements:

- the background noise level of the office room is very low and desired speech privacy is not reached with recommended SRI
- the reverberation time of the phone room is high and volume of the room is small which increases the speech level and reduces speech privacy
- volume of the atrium is very large which reduces the speech level and increases speech privacy

The aim of this study is to present a simple and validated model to predict the speech privacy between two arbitrary rooms when above mentioned basic parameters, speech effort, room dimensions, early decay times in the rooms and background noise level in the receiving room, are known.

The model is based on existing and well-known theories but it combines them in a new way which can be useful when specifications to wall structures are planned in building projects.

Speech privacy is described using Speech Transmission Index, STI. Acceptable speech privacy for typical office work is reached when STI falls below 0.17 using normal speech effort.[1] Confidential speech privacy presupposes that STI=0.00 using normal speech effort. Absolute confidentiality presupposes that STI=0.00 is reached with raised speech effort or shout.

2 Materials and methods

2.1 Materials and measurements

The model was validated in four different cases (Table 1). The cases consisted of different combinations of adjacent rooms. Case 1 consisted of two reverberation chambers. The larger room (155 m^3) was selected as receiving room because of higher reverberation time. Case 2 was performed between a small auditorium and a cafeteria. The measurement direction was from the auditoria to the cafeteria. Case 3 was done between two furnished office rooms and Case 4 between two empty office rooms.

Sound insulation was measured according to ISO 140-4 [2, 3]. STI was measured using sine sweep excitation signal and measurement software (winMLS 2004). Measurement device consisted of a measurement microphone, an omni-directional loudspeaker, an amplifier, an external sound card for signal input and output, and a laptop computer for controlling the measurements. The measurement method of STI is described in Ref. [4].

Case	transmitting room / receiving room	Room dimensions [m] Length	Width	Height	Volume [m^3]
1	reverberation chamber (empty)	6.9	4.5	3.7	113
	reverberation chamber (empty)	7.6	5.1	4.0	155
2	small auditorium (furnished)	9.0	7.0	2.4	151
	cafeteria (furnished)	8.0	8.0	2.3	147
3	office room (furnished)	4.7	3.5	2.9	48
	office room (furnished)	4.7	2.9	3.0	40
4	office room (empty)	3.8	3.6	2.5	34
	office room (empty)	4.1	3.6	2.5	37

Table 1 Validation cases.

2.2 Speech sound level

The calculations were performed at octave bands from 125 to 8000 Hz.

The speech sound level in a room can be calculated when the sound power level of the speaker, $L_{W,S}$, the dimensions of the room and the amount of room absorption, thus, reverberation time, T, is known. If sound field is assumed to be diffuse and sound source is assumed to be omni-directional the average sound pressure level in the transmitting room, $L_{p,1}$, can be calculated using equation

$$L_{p,1} = L_{W,S} - 11 + 10\lg\left(\frac{4T_1}{0.16V_1}\right) \quad (1)$$

where V_1 is the room volume and T_1 is the reverberation time of the room.

Sound power level of a male speaker exercising normal speech effort was used in this study (Fig. 1). However, the sound power level may be adjusted according to any speech spectrum.

To predict the speech level transmitted to the adjacent receiving room sound reduction index, R', of the wall must be known or estimated. Then, the speech level in the receiving room is calculated by

$$L_{p,2} = L_{p,1} - R' + 10\lg\left(\frac{S}{A_2}\right) \quad (2)$$

where $L_{p,1}$ is the sound pressure level of the speech in the transmitting room, R' is the sound reduction index, S is the surface area of the wall between the rooms [m^2] and A_2 is the total absorption area in the receiving room [m^2]. The sound field is assumed to be diffuse. The absorption area can be determined by

$$A_2 = \frac{0.16V_2}{T_2} \quad (3)$$

Typically, this model is most useful in the design stage of the building when the values are not available in octave bands. The difficulty in the application of this model can be the lack of octave band data of sound reduction index, background noise level and reverberation time *in situ*.

Reverberation time can be evaluated with sufficient accuracy using Sabine's equation if measurement data is not available.

Background noise levels can be usually obtained from HVAC-designer. If spectrum is not available, the spectrum of ventilation noise needs to be estimated. In many cases, the slope of ventilation noise is close to -5 dB per octave in the range 125 to 8000 Hz. This occurred also in this study and it is not an accident.

In most cases, the R_w-values of structures are available but frequency-dependent values of R are not. If literature cannot help either, octave band values can be estimated by applying ISO 717-1 reference curve backwards as explained in Fig. 1.

An example of predicted sound pressure levels in case 4 is presented in Fig.2.

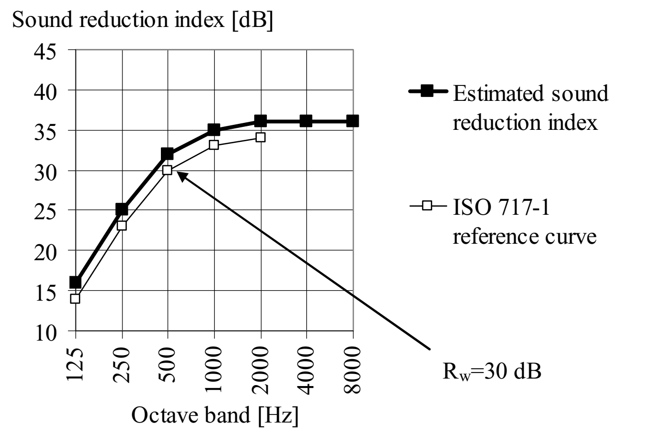
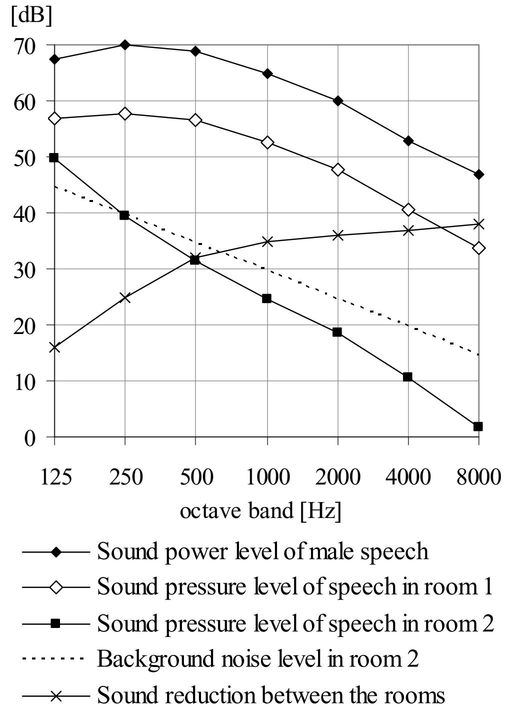


Fig. 1. The octave band values can be estimated by adding 2 dB to the octave band values of ISO 717-1 reference curve at position R_w. The values at 4 and 8 kHz are assumed to be equal with 2 kHz. The graph shows the application of the method when R_w=30 dB.



.Fig. 2. Sound power level of male speaker and predicted speech sound level in transmitting and receiving room. Sound reduction index and background noise level are also presented.

2.3 Speech Transmission Index

STI can be predicted when the sound pressure level of the speech transmitted through the wall, the background noise level, $L_{p,B}$ [dB], and the early decay time, *EDT* [s], in the receiving room are known. However, no simple and robust equation for early decay time exists. In reasonably small rooms with reasonably diffuse sound field the early decay time is typically close to reverberation time T_{20}. There is no direct sound path or early reflections from the speaker to the listener, because they are in different rooms.

In the receiving room, $L_{p,2}$, $L_{p,B,2}$, and T_2 were used to predict STI.[4] STI was calculated using modulation reduction factor

$$m(F) = \frac{1}{\sqrt{1+\left[2\pi F\frac{T_2}{13.8}\right]^2}}\frac{1}{1+10^{-L_{SN}/10}} \quad (4)$$

where L_{SN}=$L_{p,2}$-$L_{p,B2}$. The modulation frequencies F were 0.63, 0.8, 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10 and 12.5. The modulation reduction factor was calculated at octave bands 125 - 8000 Hz. The m -values were converted into an apparent signal-to-noise ratio

$$(S/N)_{app} = 10\lg\left(\frac{m}{1-m}\right)\text{dB} \quad (5)$$

The values above +15 dB were replaced by +15 dB and similarly below -15 dB by -15 dB. After that an arithmetic average of $(S/N)_{app}$ was calculated at each octave band k

$$(S/N)_{app,k} = \frac{1}{14}\sum_{i=1}^{14}(S/N)_{app,i} \quad (6)$$

The weighted average of the octave band $(S/N)_{app,k}$ value was determined by

$$\overline{(S/N)}_{app} = \sum_{k=1}^{7} w_k (S/N)_{app,k} \qquad (7)$$

where w_k was 0.13, 0.14, 0.11, 0.12, 0.19, 0.17 and 0.14. Finally, STI was determined by equation

$$STI = \frac{\overline{(S/N)}_{app} + 15}{30} \qquad (8)$$

3 Results

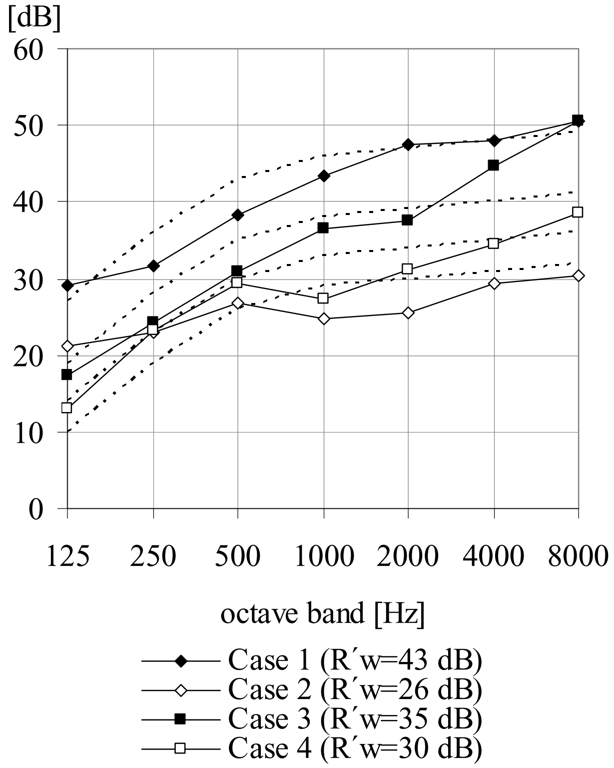
The results of sound insulation measurements are presented in Fig. 3. The measured background noise levels are presented in Fig. 4. The measured reverberation times are presented in Fig. 5.

The values used in predictions are presented in dotted lines in Figs. 2 - 4. The prediction model was validated in four cases. The measured and predicted STI values are presented with measured R'_w values in Table 2.

In these four cases, the linear correlation coefficient between STI and R'_w was 0.53 which is unacceptably low. It demonstrates the reason why the evaluation of speech privacy is important. The developed model could be useful in the design and problem solving.

Case	STI measured / predicted	R'_w [dB]
1	0.00 / 0.00	43
2	0.11 / 0.11	26
3	0.04 / 0.00	35
4	0.22 / 0.21	30

Table 2 measured and predicted STI and measured R'_w in the four cases.



.Fig. 3. Measured (full lines) and predicted (dotted) sound reduction index in the four cases.

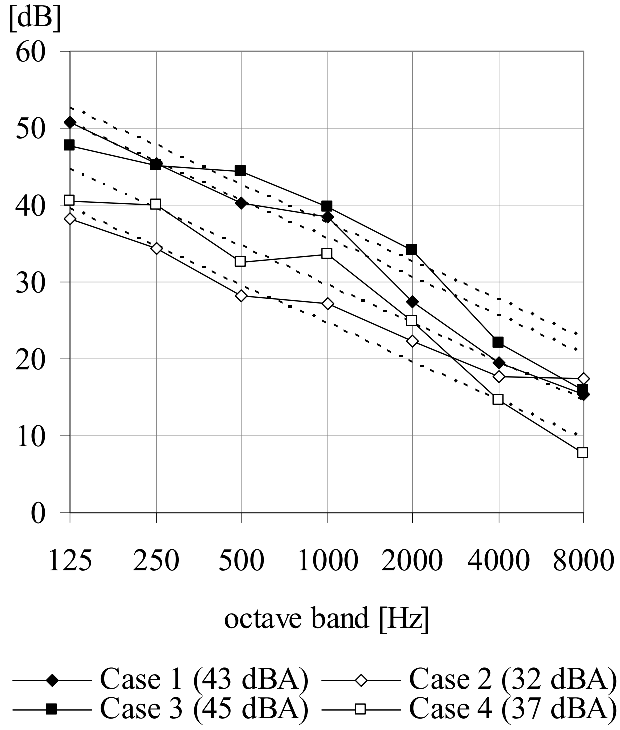
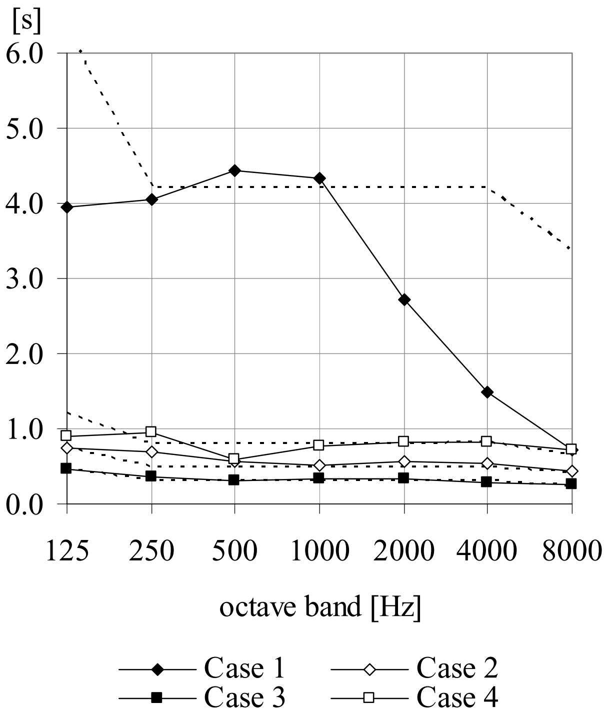


Fig. 4. Measured (full lines) and predicted (dotted) background noise level, $L_{p,B,2}$, in the four cases.



.Fig. 5. Measured (full line) and predicted (dotted) reverberation times in the receiving room, T_2.

4 Discussion

A model was introduced to predict speech privacy between rooms ("subjective sound insulation") using STI. The presented calculations are adopted from standardized procedures for sound insulation measurement and determination of speech transmission index. The approach is analytic and straightforward which enables easy implementation in various design processes.

The accuracy of the prediction results in Table 2 implies that the methods selected for the study are valid. However, in the future more thorough validation would be useful.

The cases are discussed shortly below.

Case 1. The weighted SRI was moderate, R'_w=43 dB, so that speech sound attenuated significantly. The background noise level, 43 dBA, was also high to reach a masking effect. In addition, reverberation time was large so that STI dropped to zero.

Case 2. The weighted SRI was very low, R'_w=26 dB. The background noise level was also low, 32 dBA. However, the volumes of both rooms were exceptionally large and speech privacy was almost confidential. This case shows that high sound reduction index is not always necessary between large rooms.

Case 3. The weighted SRI was typical for office rooms, R'_w=35 dB. The background noise was high, 45 dBA. There was absorption material (EN 11654 class A) on the ceiling and on the side wall so that the reverberation time was small. Predicted STI was lower than measured. Because the reverberation time was small the reason for inaccuracy must be in the difference between predicted and measured speech sound pressure level in the receiving room.

Case 4. The weighted SRI was very low, R'_w=30 dB. The rooms were empty so that the reverberation times, 0.6-0.9 s, were higher than in Case 3. The background noise level, 37 dBA, was typical for room offices. Acceptable speech privacy was not reached.

5 Internet tool

The prediction model has been programmed into a JAVA applet which is freely available in the internet.[5] The applet has a simple interface for the input parameters. Room dimensions, average reverberation times, wall surface area between the rooms and the weighted sound reduction index, R'_w, may be typed in text fields (Fig. 6). Speech effort and masking background noise level are selected using slider controls. Calculated speech sound pressure level in rooms 1 and 2, masking background noise level in room 2 and sound reduction index are presented graphically. The predicted STI is presented below the graph.

There is also an option to adjust manually reverberation times, sound reduction index and masking background noise level at the octave bands 125-8000 Hz. This option is enabled using "Edit spectra" -button.

6 Conclusion

The model for predicting speech privacy between adjacent rooms was presented. The model is useful when economic optimization of lightweight wall structures is appreciated. It can lead to major changes in conventional recommendations for R'_w value. The optimization is very easy using the internet tool.[5]

Acknowledgments

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References

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[2] ISO 140-4:1998 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 4: Field measurements of airborne sound insulation between rooms (1998)

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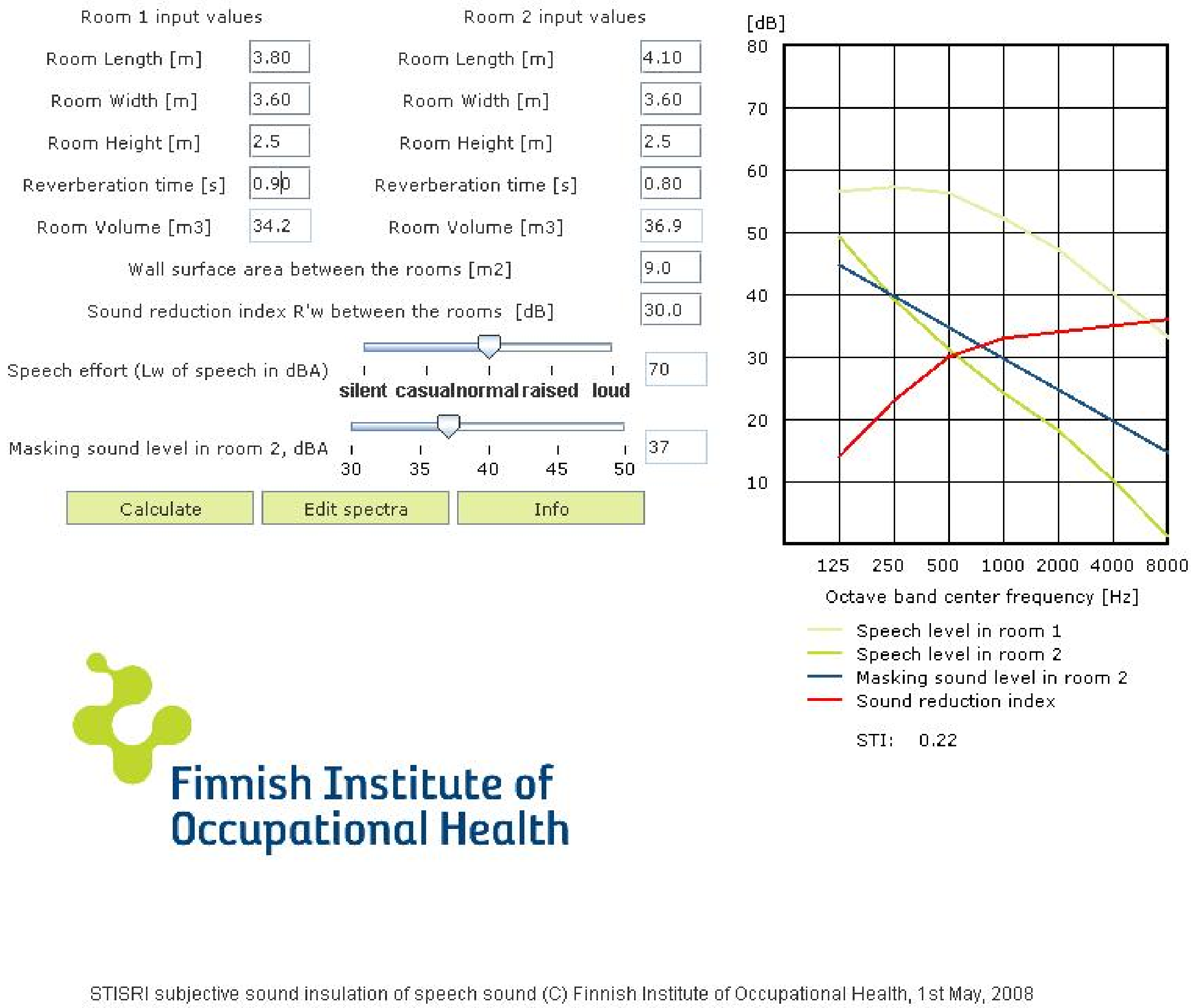

.Fig. 6. Screen capture of the internet tool during the calculation of Case 4.