Sound insulation design method for speech privacy

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ABSTRACT

In recent years, there has been increased interest in speech privacy in buildings as an important factor of sound insulation design between rooms. Speech privacy in terms of conversations transmitted through partitions can be described by the signal-to-noise ratio (SNR) of the transmitted sound. The SNR is related to the speech transmission index (STI). In this paper, a method of predicting the SNR is derived from the geometrical acoustics, which assumes a diffused sound field. Using the prediction method, we propose a sound insulation design method for speech privacy that takes into consideration the sound source characteristics, sound insulation performance of the partition, acoustic absorption state of the source and receiving rooms, and the background noise level in the receiving room. Prediction results using this method corresponded well with the measured results in an actual sound field.

INTRODUCTION

When doors and windows are installed in partitions between rooms, or the partitions are not sufficiently soundproofed, conversational privacy may become problematic. In such cases, we can evaluate the speech privacy conditions based on ASTM E 2638. The Speech Privacy Class (SPC) is calculated from the measured sound pressure level differences between rooms and background noise levels. If these parameters can be predicted, SPC can be used as a sound insulation design method for speech privacy. However, conditions governing speech privacy are determined not only by sound pressure level differences and background noise levels, but also sound source characteristics and the sound absorption conditions of the source and receiving rooms. If the speech privacy index can be estimated by taking into account the acoustic conditions of the sound sources, partitions, and rooms, then we can conduct sound insulation design for speech privacy effectively.

The speech privacy index corresponds well with the Speech Transmission Index (STI). Calculating STI values of sound transmission through a partition is equivalent to predicting speech privacy conditions.

For room acoustic design, we proposed the SNR_{stat} method as a simple STI prediction method based on geometric acoustics, which assumes a diffused sound field. In this paper, the SNR_{stat} method will be expanded to calculate the STI of transmitted speech, and we suggest a sound insulation design method for speech privacy using the SNR_{stat} method.

METHODS

SNR_{stat} method for room acoustic design

The SNR_{stat} method is based on the Lochner-Burger signal-to-noise ratio (SNR), which is calculated by:

$$SNR = 10\log\frac{\int_0^{\Delta t}\alpha_{(p,t)}p_{(t)}^2 dt}{\int_{\Delta t}^{\infty}p_{(t)}^2 dt + p_N^2 T}. \quad (1)$$

Where $p(t)$ is the sound pressure impulse response, $\alpha_{(p,t)}$ is the coefficient according to time t and sound pressure p, p_N is the sound pressure of the background noise, and T is the duration. Δt is the maximum delay time of early reflections contributing to speech intelligibility as a signal. Late-arriving reflections after Δt inhibit speech intelligibility as noise.

In reference to the concept, we proposed SNR_{stat}, which is the SNR predicted by simple formulas based on geometrical acoustics assuming a diffused sound field.

SNR_{stat} is defined as:

$$SNR_{\text{stat}} = 10\log_{10}\left(\frac{E_d + E_e}{E_r + E_{BGN}}\right). \quad (2)$$

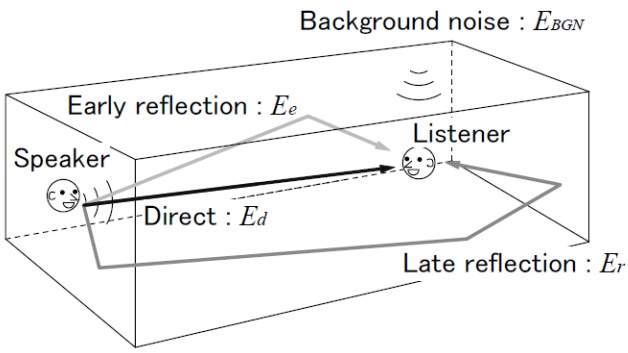


Figure 1: Calculation model of SNR_{stat} method for room acoustic design

In Eq. (2), E_d is the energy density of the direct sound, E_e is the energy density of the early reflections contributing to speech intelligibility, E_r is the energy density of the late-arriving reflections, and E_{BGN} is the energy density of the background noise. The energy densities are calculated by

$$E_d = \frac{W}{c}\frac{Q}{4\pi r^2}, \quad (3)$$

$$E_e = \frac{W}{c}\frac{4}{R}\left[1-(1-\alpha)^n\right], \quad (4)$$

$$E_r = \frac{W}{c}\frac{4}{R}(1-\alpha)^n, \quad (5)$$

$$E_{BGN} = \frac{1}{c}10^{(L_{BGN}-120)/10}. \quad (6)$$

Where W is the power of the sound source, Q is the directivity coefficient, c is the speed of sound, r is the distance from the sound source to the receiving point, R is the room constant (= $S\alpha / (1-\alpha)$), α is the average surface absorption coefficient of the room, and L_{BGN} is the sound pressure level of the background noise. n in Eqs. (4) and (5) is the maximum reflection order of the early reflections contributing to speech intelligibility and is calculated by:

$$n = \frac{r + c\Delta t}{p}. \tag{7}$$

Where Δt is the maximum delay time of early reflections (Δt =50 ms), p is the mean free path (= $4V/S$), V is the room volume and S is the room surface area.

SNR_{stat} values can be converted to STI values using the regression equation shown in Figure 3:

$$STI = \frac{SNR_{\text{stat}} + 14.8}{34.0}. \tag{8}$$

SNR_{stat} method for sound insulation design

When there is a partition between the sound source and the receiving point as shown in Figure 2, the mean free path p is given by:

$$p = \frac{4V_t}{S_t}. \tag{9}$$

Where V_t is the total volume of the two rooms and S_t is the total surface area of the two rooms. The direct sound and the early and late reflection sounds arriving at the receiving point must be transmitted through the partition. Equations (3), (4), (5) can be transformed into

$$E_d = \tau \frac{W}{c} \frac{Q}{4\pi r^2}, \tag{10}$$

$$E_e = \tau \frac{W}{c} \frac{4S}{R_1 R_2} \left[1 - (1 - \alpha_{12})^n\right], \tag{11}$$

$$E_r = \tau \frac{W}{c} \frac{4S}{R_1 R_2} (1 - \alpha_{12})^n. \tag{12}$$

Where τ is the transmission coefficient of the partition, S is the area of the partition, R_1 and R_2 are the room constants of the source room and receiving room, and α_{12} is the total average surface absorption coefficient of the two rooms. The regression equation converting SNR_{stat} values to STI values is given by:

$$STI = \frac{\tan^{-1}\{(SNR_{\text{stat}} - 2.2)/10\}}{\pi} + 0.5. \tag{13}$$

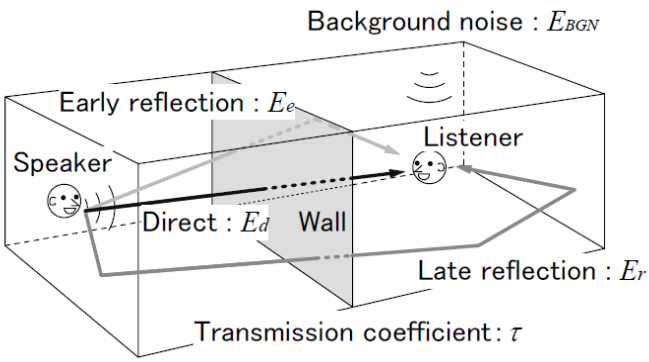


Figure 2: Calculation model for SNR_{stat} method for sound insulation design

The regression curves of Eqs. (8) and (13) are shown in Figure 3 with plots of the STI predicted by the Houtgast calculation method versus SNR_{stat} under the same conditions.

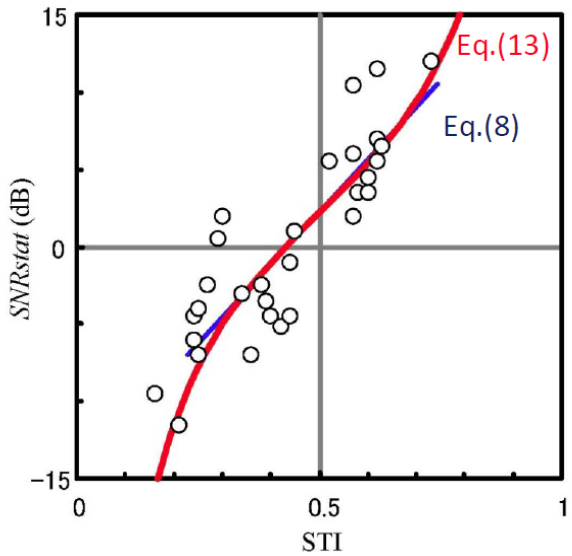


Figure 3: Relationship between SNR_{stat} and STI

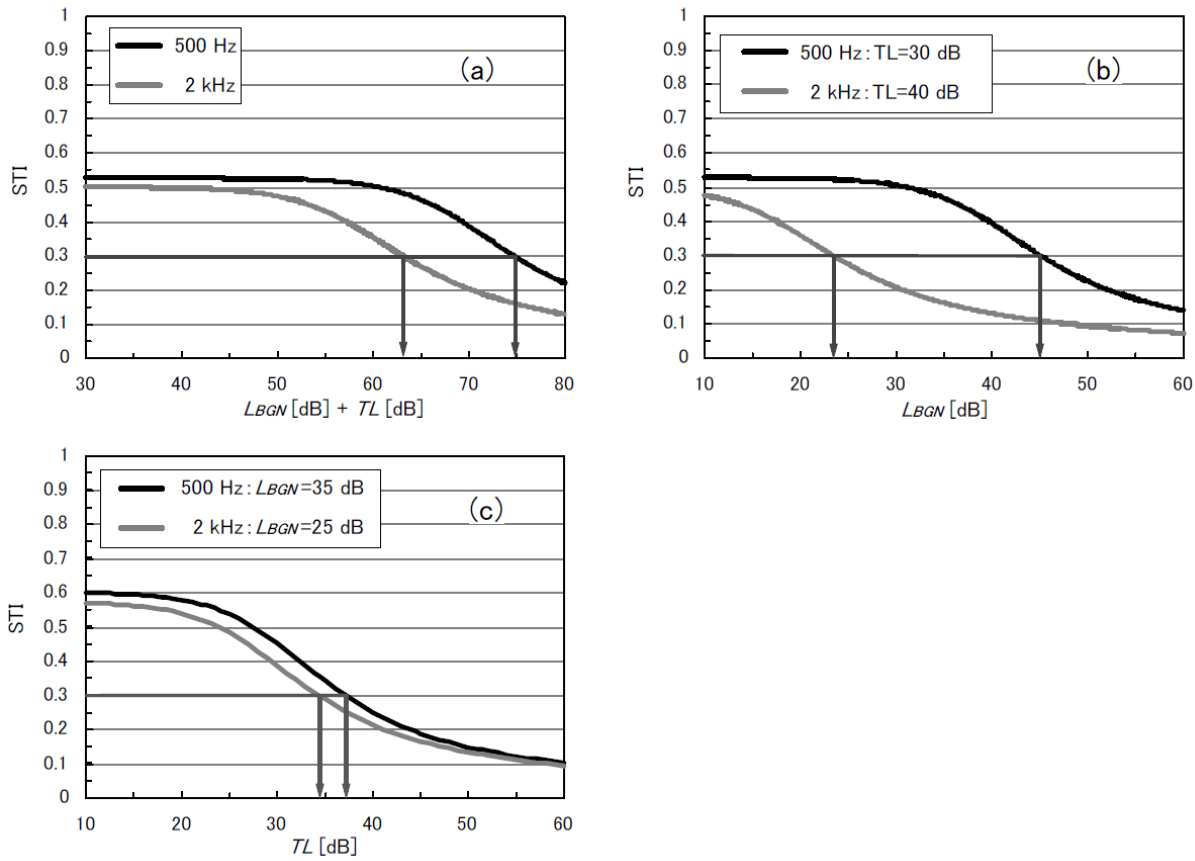


Figure 4: Sound insulation design curves for speech privacy.

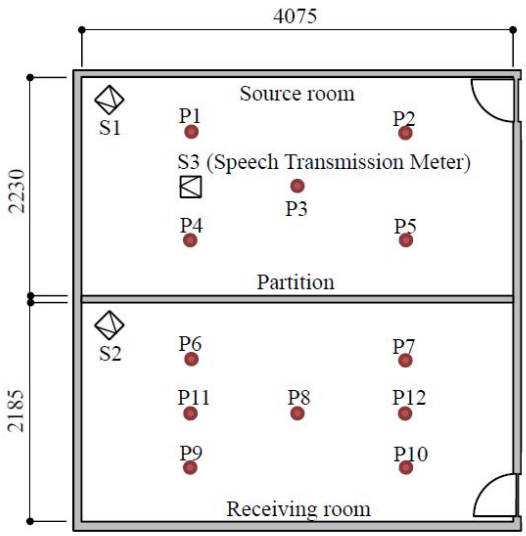
(a) L_{BGN} [dB] + TL [dB] versus STI, (b) L_{BGN} [dB] versus STI, (c) TL [dB] versus STI

Using Equations (2), (9), (10), (11), (12), (13), we can predict the STI values at the sound insulation design stage, and we can derive three types of curves for the sound insulation design. The first curve is L_{BGN} [dB] + TL [dB] versus STI as shown in Figure 4(a). This curve is very similar to the SPC concept in ASTM E 2638. The second curve is L_{BGN} [dB] versus STI as shown in Figure 4(b). This curve is used when the transmission loss of the partition has been decided and cannot be changed. The third curve is TL [dB] versus STI as shown in Figure 4(c). The curve is used when it is impossible to control masking noises systematically. The power and directivity of the source, the room constants of the two rooms, the distance from the source to the receiving point, the total volume and surface area of the rooms, and the partition area must all be known to derive these curves. These curves should be calculated at the 500-Hz and 2-kHz octave bands, to obtain RASTI values.

In sound insulation design, these curves give the appropriate transmission loss of the partition and the level of masking noise to achieve target STI values. If the target STI value is 0.3, you can get the appropriate transmission loss of the partition, the level of background noise, and their sum from the point on the curves where the STI value becomes 0.3.

EXPERIMENT

In order to confirm the accuracy of the SNR_{stat} method for sound insulation design, STI values were measured in rooms that were separated by a partition. The plan of the rooms (source and receiving rooms) is shown in Figure 5. The source points and receiving points in some measurements are described in the figure. The ceiling height of the rooms is 2.59 m.



	Source room	Receiving room	Partition wall
Volume [m^3]	23.5	23.1	-
Surface area [m^2]	50.8	50.2	10.6

	P11	P12
Distance from source S3 [m]	2.0	2.8

Figure 5: Experimental conditions

Average surface absorption coefficient

In order to obtain the average surface absorption coefficients of the rooms, the reverberation time was measured. The source points in the source room and the receiving room are S1 and S2 in Figure 5. The receiving points in the source room and the receiving room are P2, P3, P4, P7, P8, and P9. The height of these points is 1.2 m.

Apparent transmission loss

In order to obtain the apparent transmission loss induced by the partition, the sound pressure level differences between the source and receiving rooms were measured. The source point was S1 and the measurement points in the source room were from P1 to P5, and in the receiving room were from P6 to P10. The equivalent absorption area of the receiving room was calculated from the results of the reverberation measurements. The apparent transmission loss induced by the partition was calculated from the sound pressure level difference and the equivalent absorption area.

Sound source acoustic characteristics

The power level of the Speech Transmission Meter Type 3361 (B&K) was measured in a reverberation room using the reference sound source method. The directivity of the Speech Transmission Meter was measured in an anechoic room. The directivity factor was obtained by:

$$10\log_{10}(Q) = Lp_{rad}(\theta,\phi) + 10\log_{10}(4\pi r^2) - PWL\,. \tag{14}$$

Where, Q is the directivity factor for the directions of horizontal angle θ and elevation angle ϕ, r is the distance from the source to the measurement points, and PWL is the power level of the Speech Transmission Meter measured in a reverberation room.

STI

STI values of 500 Hz and 2 kHz in the octave band were measured by Speech Transmission Meter Type 3361 (B&K). The source point was S3 in the source room and STI measurement points were P11 and P12 in the receiving room. The background noise radiated from flat panel speaker systems in the walls and their sound pressure levels at the receiving points were changed.

RESULTS

Measured Parameters

The average surface absorption coefficients of the rooms, the apparent transmission loss of the partition, and the power level and directivity factor of the Speech Transmission Meter are shown in Table 1.

Table 1: Acoustic conditions of sound source and rooms

		500 Hz	2 kHz
Average absorption coefficient	Source room	0.103	0.092
	Reciving room	0.103	0.082
	Average	0.103	0.087
Apparent transmission loss [dB]		33.5	42.6
Power level of the Speech Transmission Meter [dB]		71.1	58.4
Directivity factor	P11	0.89	0.44
	P12	1.29	1.74

Sound insulation design curves and measured STI

The relationship between the measured STI values and the background noise levels is shown in Figure 8 with the L_{BGN} [dB] versus STI curve predicted under the same conditions at the 500-Hz and 2-kHz octave bands. The measured values show good correlation with the L_{BGN} [dB] versus STI curve. These results show the accuracy of the prediction theory and the curves for the sound insulation design.

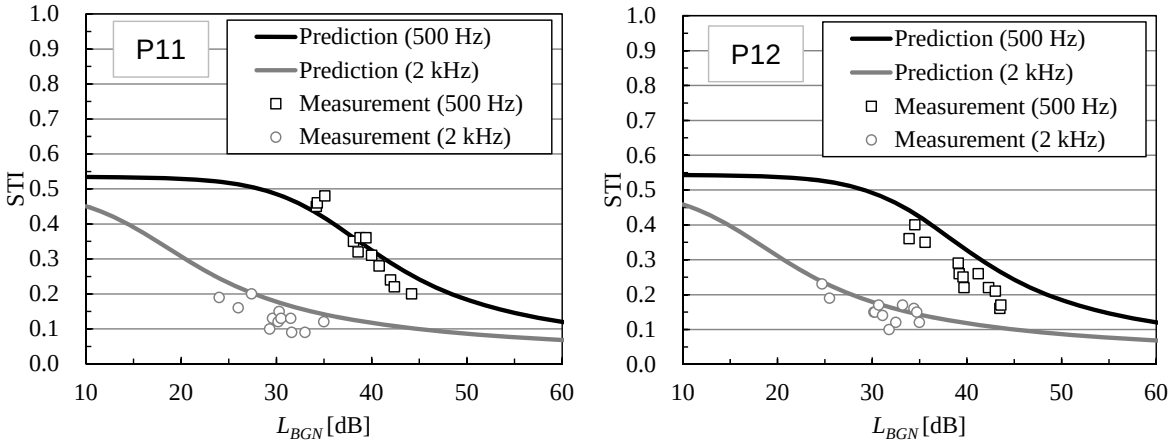


Figure 8: Experimental results

CONCLUSIONS

For effective sound insulation design for speech privacy, we proposed the SNR_{stat} method which can predict STI values from the acoustic characteristics of the sound source, the distance from the source and the receiving point, the transmission loss induced by the partition, the average absorption coefficient of the source and receiving rooms, and the sound pressure level of the background noise. As an application of the prediction method, we presented three types of sound insulation design curves.

The result of the experiment demonstrated that the sound insulation design curve on background noise level shows good agreement with the STI values measured in actual rooms separated by a partition.

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