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EFFECTS OF DIRECTIVITY OF A SOUND SOURCE ON SPEECH INTELLIGIBILITY IN THE SOUND FIELD

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ABSTRACT
In room acoustics, optimum reverberation time varies with the variation in the use of the room. For example, relatively long reverberation time is set for a hall for music, while for speech or hall broadcasting including an emergency, high distinctness is required. In a general conference room and lecture room, ensuring of the intelligibility with a moderate reverberation time is a high-priority issue. For the measure of this problem, loudspeakers with non-uniform directivity (for example column speakers) are generally used, and the effect of directivity depends on the acoustic condition of the room. Also, our voice has somewhat directivity, due to this directivity the intelligibility of speech in a room may depend on the listening position. In this report, from the view point of speech intelligibility, a method for simulation of the room response including the effect of directivity of the sound source is proposed, which enables us to estimate quantitatively the relation between the sound field and the source directivity. By means of this method with the measure of Speech Transmission Index (STI), the discussion is given to the degree of change in speech intelligibility with the change in the degree of directivity.

INTRODUCTION
For investigation into the basic characteristics of sound fields, generally, the sound source is assumed to be nondirectional. Any sound source, however, has some kind of directivity with frequency dependence. Due to this directional property, listening condition at audience seats may change depending on the degree of directivity. The relation between the directivity of musical instruments and characteristics of the sound field has been investigated by Meyer[1], Marshall[2], Matsui[3], for the purpose of effect evaluation for musical performance. In the case of sound field having a sound source, intelligibility of sound at certain receiving point strongly depends on not only the reverberation time but also the source directivity with the positional relation of the source and receiver.

In room acoustics, optimum reverberation time changes according to the use of the room. For example, a hall for music performance, relatively long reverberation time is required, while in the case of announcements including an emergency, high distinctness is required. Also for a hall for music, there is a requirement of speech use. In a general conference room and lecture room, ensuring of the speech intelligibility with a moderate reverberation time is a high priority issue. For the measure of such a problem, loudspeakers with directivity (column speakers or sound in beam named Audio Spotlight) are often used. In these cases, it becomes important to evaluate appropriately the effect of source directivity on speech intelligibility.

In this report, from the view point of speech intelligibility, a method for simulation of the impulse response including the effects of both frequency dependence of reflection and the source directivity is proposed by means of a basic form of the image method. The discussion is given to the effect of directivity on the speech intelligibility using Speech Transmission Index (STI).

IMPULSE RESPONSE FROM THE IMAGE METHOD

All information regarding the time structure of the response at a receiving point, generated from a sound source, is aggregated in the impulse response. By using an image method, basically, the impulse response is obtained as a train of pulses having variation in amplitude and the time delay corresponding to the geometrical path length and the reflectivity of the boundary surface. In the case of reflection from a perfectly rigid surface, the reflection pulse $p(t)$ normalized by the direct pulse is given by

$$p(t) = \frac{d_0}{d}\delta(t - t_d), \qquad t_d = \frac{d - d_0}{c_0}, \tag{Eq.1}$$

where δ is the Dirac delta function, d_0 and d are the distance from the source and reflection path-length, and c_0 as the speed of sound. While in the case of reflection from the surface with the reflection coefficient $r_p(f)$ having frequency dependence, the reflection wave can be expressed, from the convolution in the frequency domain, as

$$\begin{aligned} p(t) &= \Im^{-1}\left\{ r_p(f) \cdot \Im\left\{ \frac{d_0}{d}\delta(t - t_d) \right\} \right\} \\ &= \Im^{-1}\left\{ \frac{d_0}{d} r_p(f) e^{-i2\pi f t_d} \right\}, \end{aligned} \tag{Eq.2}$$

where $\Im$ and $\Im^{-1}$ mean the Fourier transform and the inverse transform, respectively. From (Eq.2), the contribution of an image source generated in the nth-order of reflection is written in the form [4].

$$p(t) = \Im^{-1}\left\{ \frac{d_0}{d} r_{p1}(f) \cdot r_{p2}(f) \cdots r_{pn}(f) e^{-i2\pi f t_d} \right\} \tag{Eq.3}$$

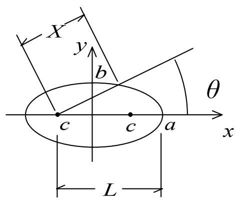

Figure 1.-Configuration of the source-directivity model

Introduction of the source directivity

In the present study, the simplest case is assumed, in which the directional property of a source is modelled as a spheroid with frequency independence, which is shown in Figure 1. The sound pressure p_θ in the direction of an angle θ from the principal axis of a spheroid is given in the form

$$p_\theta = p_0 10^{D_L/20}, \tag{Eq.4}$$

where p_0 is the sound pressure in the direction of the principal axis, and D_L is the directional index[dB] in the direction of θ. In the case of dynamic range 40dB for example, the directional index is written as

$$D_L = 40\left(\frac{X}{L} - 1\right), \qquad \frac{X}{L} = \frac{(b/a)^2\left[1 + (c/a)\cos\theta\right]}{\left[\sin^2\theta + (b/a)^2\cos^2\theta\right](1 + c/a)}, \tag{Eq.5}$$

where b/a is the ellipticity, which is used as a parameter for evaluating the degree of the source directivity. Figure 2 shows the example of application to the image method.

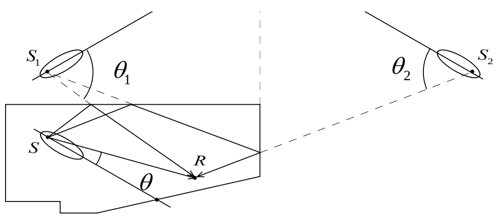

Figure 2.-Application of the source-directivity model to the image method

As can be seen from this figure, the directional intensity of the direct pulse can be specified by the use of θ alone. In the same way, the nth-order of reflection is specified by θ_n. The amplitude of each pulse at each stage of reflection can be calculated from (Eqs.4 and 5) with the data of the reflection angle of each image source.

EVALUATION OF SPEECH INTELLIGIBILITY

The extent to which speech can be understood is evaluated by Speech Transmission Index (STI) [5]. In the sound field, where the effect of the background noise is negligible, STI can be calculated directly from the impulse response. In this case, the calculation needs relatively long time response to attenuate enough, because STI has a close relation to the reverberation time. By using the image method, however, it is almost impossible to calculate up to high orders of reflection corresponding to fully attenuate region of the response. Then any method to add the later part of reflections should be adopted, in which securing of identity of early reflections (from the image method) and later reflections (reverberation tail) becomes primary issue. Regarding this matter, some artificial methods for adding the reverberation tail have been proposed [6,7]. The choice of the method, however, depends on the purpose of use of the impulse response. In the present study, the case where a directional loudspeaker system is introduced to an existing hall to improve the speech intelligibility is assumed as an example of the technique.

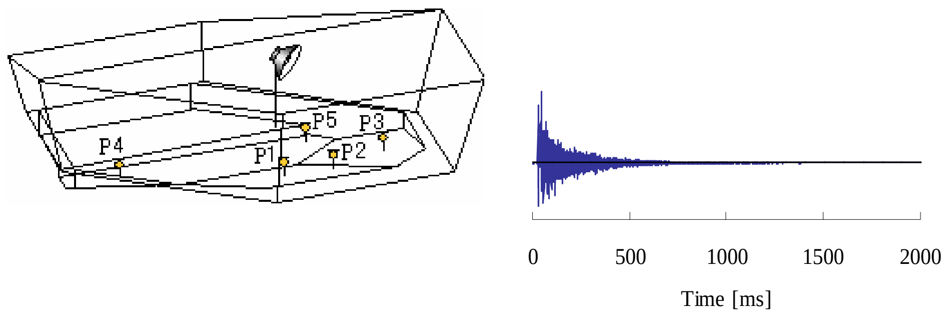

Figure 3.-A simple model of a hall, and an impulse response used in the calculation

Figure 3 shows the targeted hall, which is a simple model of an existing hall in about 500 seats disregarding a detailed roughness. An impulse response measured at some location of source and receiver is used, which is also shown in Figure 3. From this response, mean absorption coefficient (corresponding to the mean reflection coefficient $r_p(f)$ of (Eq.3)) of 1/1- or 1/3-octave band interval is derived by means of Sabine reverberation formula. By using (Eq.2) with the frequency variations in the reflection coefficient $r_p(f)$, each reflected wave can be calculated from the data of the image method. In the calculation, interpolation was used for arbitrary frequency. One example of the response is shown in Figure 4(a), in which the sampling frequency is 24kHz.

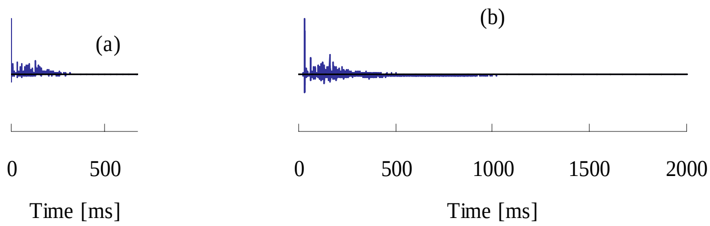

Figure 4.-Impulse response from the image method (a), and combined impulse response filtered at mid frequencies (b)

For connecting two parts, early reflections in Figure 4(a) and the later part of Figure 3, it is important to connect smoothly to one another. For this purpose, it is necessary to set appropriate values of both the time of connection and the data compression rate for the reverberant part. The former value should be taken as long as possible, and for the latter case, the method for estimating the value taken here is to evaluate the linearity of the decay curves of the connected response: i.e., the data compression rate is decided in order that the decay rate of the early part and the later part reaches same value at mid frequencies (500-2kHz). An

example of the combined impulse response filtered at mid frequencies is shown in Figure 4(b), in which the time of connection is 300ms.
The value of STI can be calculated directly from the impulse response. The results of the calculated STI for the case shown in Figure 3 (source and receiving points P1-P5) are shown in Figures 5 and 6, with the variable of ellipticity and the parameter of the reverberation time. The source is located 7m in height from the floor, and each receiver is located 1m height, and the principal axis of the directional source is oriented in the direction P1. The ellipticity, which is the parameter of the source directivity, is changed between 1.0 and 0.5. The relation between the ellipticity and the directivity index is shown in Figure 7. It should be noted that the directivity is here assumed to be constant over the frequency range of interest; this situation differs from the loudspeaker systems actually used.

It is well known that the speech intelligibility is greatly affected by the reverberation time. Then it is important to discuss the effect of the source directivity with consideration of the variation of the reverberation time. The impulse response measured at a receiving point in an existing hall is shown in Figure 3, and the characteristics of the reverberation time (RT15) used in the calculations are shown in Figure 8 including some different types of reverberation (RT07, 10 and 20), which are modified corresponding to the reverberation time (at mid frequencies) of 0.7, 1.0 and 2.0, respectively.

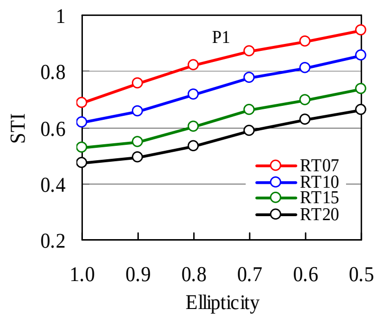

Figure 5.-STI variation at a point P1 with a parameter of the reverberation time

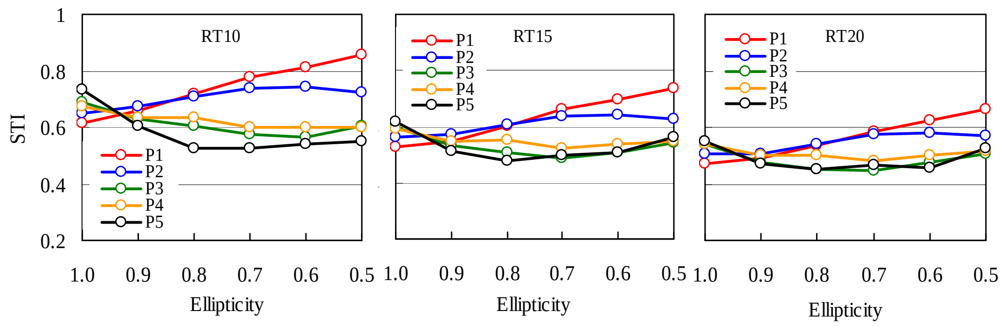

Figure 6.-Effects of difference in receiving point on STI

Figure 5 shows the results of P1 on the principal axis of directivity. It is seen from this figure that STI increases with decreased reverberation time. For example, in the change from RT20 to RT10, almost equal intelligibility can be secured by changing the directivity (ellipticity) from 1.0

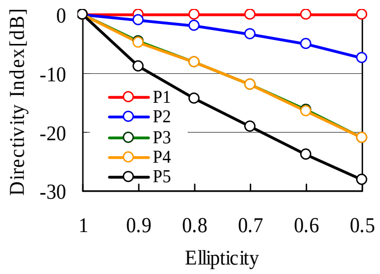

Figure 7.-Relation between the ellipticity and Directivity Index

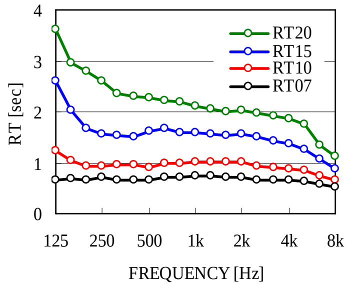

Figure 8.-Characteristics of the reverberation time used in the calculation

to 0.6. In the case of RT15, changing the directivity from 1.0 to 0.8 changes the evaluation of intelligibility from ‘FAIR’ to ‘GOOD’. It can be seen also that the sound field with a smaller value of reverberation time receives a greater influence from the early stage of variation of the directivity, i.e., a big effect can be expected by changing a slight difference of the directivity. In the case of receiving points lying on the principal axis of directivity (like a point P1), decreasing the ellipticity means increase of the direct sound. One example is shown in Figure 9 for the impulse response (point P1with RT15) of early reflections and the ellipticity of 1.0 and 0.5.

It is easy to understand the change in intelligibility due to this type of change in the directivity. Other receiving points, however, may suffer from the inverse effect due to change in the directivity, i.e., these points are at risk for decreasing the intelligibility. An example (point P3 with RT15 and the variation in ellipticity 1.0 and 0.5) is also shown in Figure 9. To discuss this effect, the variation in STI with the change in receiver location is shown in Figure 6, in which the direction of the principal axis of the directivity fixed at P1. It is seen from this result that there is no one-sided tendency for degradation of intelligibility due to decrease of the ellipticity. For the variation in the reverberation time, at below 0.8 of the ellipticity, all cases of STI continue to be flat. Moreover the intelligibility slightly heads for the direction of the improvement with increased directivity. Also it can be seen that STI has slightly stronger dependence of the directivity in the case of decreased reverberation.

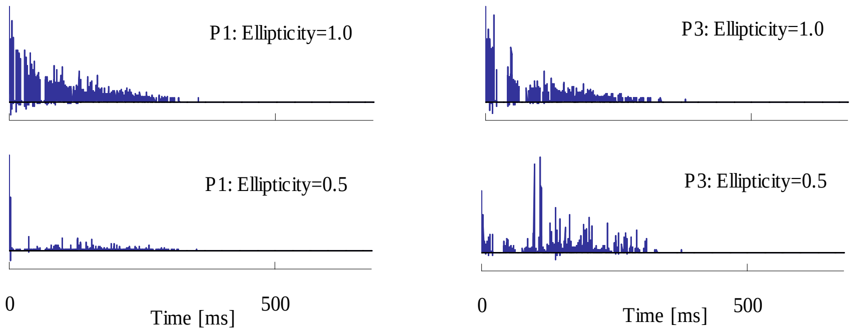

Figure 9.-Effecs of source directivity on the impulse response

CONCLUSIONS

A method for simulation of the impulse response including the effect of both frequency dependence of reflection and directivity of the sound source was proposed with a basis of an image method. The reverberation tail was added ensuring consistency with early reflections with respect to time structure of the response. Speech Transmission Index (STI) calculated from this response was discussed in relation to the reverberation time for evaluation of the effect of the source directivity on intelligibility of the sound field. The results are summarized as follows: At receivers on the principal axis of the source directivity, as the directivity increases, increase of the intelligibility can be expected. In the sound field with the smaller value of reverberation time, improvement of intelligibility can be expected by means of changing the source directivity. At receivers off the principal axis of directivity, the intelligibility becomes worse with some decrease of the direct component of the response, however, which does not suffer one-sided deterioration.

From these findings, it may be expected to improve the intelligibility by using some directional-loudspeaker systems with some different directions of the axis.

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