Subjective spatiotemporal matrix as a new measure of sound field distribution in a room

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Abstract. A new approach for representing the acoustic quality of classroom is presented in this paper. The subjective spatiotemporal measure was developed from a 3D scanning plane by using a dedicated scanning gear to measure the subjective volumetric sound field of a listener inside the room. Calculated coherence matrix is derived from spectral comparison on the appropriate scanning planes. It then could be used for indicating the subjective perception of a listener which is may differ to another listener at a different position inside the rooms.

1. Introduction
The study of subjective perception to the sound field in a room is one of important field in acoustics nowadays. A room to be said has a high acoustic quality if the sound field from any source are spread and propagate in all direction and exist in any spatial position with the same energy level refer to the particular reference point. In other words, subjective perception is close related with diffuseness of the room. It had been used for various applications including listening condition in church, music signals, and binaural room impulse response [1-3]. Head Related Transform Function (HRTF) is a function that consists of direction, distance, and frequency. It is the most common measure to show the subjectivity, which is known not only varies with the arrival direction of the sound, but with the anthropometric of the subject [4].

In case more than one source are exist in the room, then listener would hear crosstalk and also the reflected sound waves as depicted in Figure 1. In such circumstance, one must consider the binaural room response which is includes of HRTF and the room transfer function. It means that HRTF is could not yet enough to use for describing subjectivity response nor room diffuseness. Subjective perception experience can vary with listener position inside the room and also subject to the room spatial and binaural response [5-7]. This paper proposing an alternative marker for visualization both subjective spatial and temporal sound field based on volumetric scanning measurement approach that can be used in reverberant room condition. The accumulative effect of crosstalk and reflected sound waves heard by the listener are measured in four scanning planes on the front side, rear side, left and right side.

2. Method
The concept of proposing scanning technique for measuring the subjective spatiotemporal matrix can be introduced by using Figure 1. It describes a reverberant room circumstance where more than one source exists in the room in the same times. Both listeners would hear crosstalk and also reflected
sound waves from all sources within the room. By using convolution relation, the scanned sound pressure in left and right side scanning plane of listener number one are given by,

\[
\begin{bmatrix}
    r_{1L} \\
r_{1R}
\end{bmatrix} =
\begin{bmatrix}
    h_{11} & h_{12} \\
    h_{21} & h_{22}
\end{bmatrix} \ast \begin{bmatrix}
    s_1 \\
s_2
\end{bmatrix}
\]

(1)

\[ R_1 = H_{11}S_1 + H_{12}S_2 \] \hspace{1cm} (2)

The spectra for listener number two could be written as,

\[ R_2 = H_{21}S_1 + H_{22}S_2 \] \hspace{1cm} (3)

General expression for listener \( R_1 \) within a room with \( N \) speakers or sound source given by

\[ R_1 = \sum_{i=1}^{N} H_{1i}S_i \] \hspace{1cm} (4)

If there are only one sound source or speaker exist in the room, the equation (2) and (3) becomes to \( R_1 = H_1S \) and \( R_2 = H_2S \), and the response \( H_1 \) and \( H_2 \) could be written as,

\[ H_1 = \frac{R_1}{S} = \frac{R_1}{S} \ast = \frac{R_1}{S} \ast = \frac{G_{RS}}{G_{SS}} = \frac{G_{RR}}{G_{SR}} \] \hspace{1cm} (5)
\[ H_2 = \frac{R_2}{S} = \frac{R_2 S^*}{S S^*} = \frac{R_2 R_*}{S R_*} = \frac{G_{RS}}{G_{SS}} = \frac{G_{RR}}{G_{SR}} \quad (6) \]

The $R^*$ and $S^*$ are complex conjugates of the $R$ and $S$ spectra respectively. $G_{RR}$ and $G_{SS}$ are autocorrelation and $G_{SR}$ and $G_{RS}$ the cross spectrum. Hence from equation (5) and (6) one can derive a coherence factor relation $\gamma^2$ for sound field on the scanning plane of listener $R_i$ as,

\[ \gamma^2 = \frac{G_{RS} G_{SR}}{G_{SS} G_{RR} R_i} \quad (7) \]

The ratio of $\gamma^2$ for the appropriate scanning plane between the two listener $R_1$ and $R_2$ can be use for subjective comparison purpose. It is equal to the ratio between $H_1$ and $H_2$ for the same appropriate scanning plane.

The data acquisition has been conducting on a 3D scanning gear as depicted in Figure (2). The geometrical dimension of the scanning gear is 2 m in its height and 1 m for the each side. A scanning grid with the element size of 10 cm × 10 cm has been made on the four scanning plane of the scanning gear and denoted as front (F), rear (B), right (R) and left (L). The test room is a real classroom at the Physics department of Sebelas Maret University with the dimensions of 9.3 m, 5.9 m and 4 m in its length, width and ceiling’s height respectively.

![Figure 2](image1.png)

**Figure 2.** The scanning plane and position of the mannequin model inside the scanning gear.

A mannequin used as listener model. It positioned on a chair inside the scanning gear. An OmniPower B&K 4292 has been used as the sound source for generating random noise. A pair of B&K 4189 microphones attached inside the mannequin ears have been using for capturing the random noise. While another same type microphone was used for scanning purpose. The entire captured data was analysis by using the FFT and CPB analyzer module of the B&K Pulse 3160 LAN-Xi type which is a fully computer controlled system. The intensity spectra were calculated based on the captured data of the scanning microphone in respect to the left and right mannequin ears microphones as the reference.

3. Result and Discussion

Figure (3) shows the time domain sound field distribution on the four scanning plane of the listener at position number one for $t = \{0.5; 1.0; 1.4\}$ second. While Figure (4) representing the sound field of the listeners in three different positions for the $t=1$ second.
It shows from Figure (3) that the sound pressure distribution on the scanning planes is changed subject to the time and its position. Figure (3a) representing the listener at position one which is \( t = 0.5 \) for the mannequin situated on the chair in the first row, around 2.7 m from the whiteboard on the front wall. It is seen that some yellow to red area spotted on the scanning planes. The fraction area of the yellow to red spot are increased as a function of time. This phenomenon is associated with multiple reflections of the sound waves inside the classroom. Since the classroom wall constructed by painted coating brick wall without any absorbing layer, it became reverberant inside. Thus, as the sound waves are continuously radiated from the source, the portion of multiple reflections increases as well.

The spotted pattern on Figure (4b) also occurred for the same reason. It is seen that the left and right scanning plane of the second listener which is the mannequin situated on the chair at the right mid-row position are mostly spotted with the yellow to red colors. As explained above the listener receiving the highly reflected sound waves from the walls on the left and right side. It differs from the listener on position three. It is clearly indicated from Figure (5b) which is a sliced data from the sound field over the left scanning plane on time domain at three different positions on \( t=1.5 \) second. Figure (5a) representing sliced data of sound pressure on the front scanning plane for \( t=1 \) second.
Further investigation on the differences of the sound field distribution over the scanning planes also investigated on the term of the coherence matrix. The calculated value for four different frequencies is presented below to show the different sensation received by the listener on three different positions. The coherence matrix for the right scanning plane of position one and two is given by,

$$[H_{12(125)}] = \begin{bmatrix} 2,27 & 14,93 & 2,71 & 0,01 & 0,002 & 0,36 & 1,74 & 6,34 & 0,34 \end{bmatrix}$$

$$[H_{12(250)}] = \begin{bmatrix} 0,46 & 0,59 & 0,42 & 1,00 & 2,83 & 0,02 & 2,68 & 25,11 & 0,02 \end{bmatrix}$$

$$[H_{12(500)}] = \begin{bmatrix} 1,96 & 0,87 & 0,20 & 0,18 & 11,98 & 0,54 & 0,02 & 0,08 & 1,74 \end{bmatrix}$$

$$[H_{12(1k)}] = \begin{bmatrix} 0,29 & 12,54 & 0,08 & 1,93 & 0,55 & 0,87 & 9,08 & 0,19 & 0,06 \end{bmatrix}$$

The results of similar measures for position one and three is given by,

$$[H_{13(125)}] = \begin{bmatrix} 0,34 & 0,31 & 4,78 & 0,71 & 0,009 & 9,74 & 5,05 & 99,57 & 0,05 \end{bmatrix}$$

$$[H_{13(250)}] = \begin{bmatrix} 0,38 & 5,53 & 0,95 & 2,97 & 0,99 & 0,01 & 0,92 & 4,43 & 0,98 \end{bmatrix}$$

$$[H_{13(500)}] = \begin{bmatrix} 0,68 & 3,46 & 0,05 & 1,08 & 14,15 & 0,06 & 0,03 & 1,63 & 0,32 \end{bmatrix}$$

$$[H_{13(1k)}] = \begin{bmatrix} 0,53 & 0,78 & 8,65 & 1,26 & 0,25 & 0,47 & 5,73 & 0,48 & 0,09 \end{bmatrix}$$

The above values strongly indicated the sound field inside the classroom are not distributed diffusively. In the other words, the listener at a certain position is may have the different sensation to the other listeners on the other sitting positions when they listen to the same talk or sound at the same time.
time. Hence, the entire above results conclude that the coherence matrix representing subjective measures for the perception of a listener among the others inside the room. It could be used as anew measure for representing the acoustical quality of a room by using a simple equation as given by equation (7).

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