Acoustic contrast sensitivity to transfer function errors in the design of a personal audio system

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Abstract: An analytic means to evaluate the error sensitivity of a personal audio system is proposed. The personal audio system, which focuses acoustic energy into a zone of interest using multiple loudspeakers, is subject to various errors when implemented. The performance of a personal audio system, defined as an energy ratio between the zone of interest and the rest, is inevitably influenced by errors. Thus the ability to predict performance change at the design stage is crucial when building a robust personal audio system. The dependence of the energy ratio change on various types of errors is formulated.

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1. Introduction

Personal audio systems[1,2] are used to produce private or isolated sound zone without disturbing other listeners. To achieve this goal, a personal audio system utilizes an array of loudspeakers and controls the radiation of sound from each loudspeaker such that the distribution of acoustic potential energy is concentrated over a selected zone through the constructive and destructive interferences of sound waves. Therefore the function that describes sound radiation from each loudspeaker, often denoted as the transfer function, plays a crucial role in determining the control signals of loudspeakers. In practice, transfer functions of loudspeakers are either modeled or measured; hence, modeling or measurement errors always exist. When a personal audio system is driven by control signals that are calculated from the modeled transfer function, performance change can occur due to the discrepancy between the modeled and actual transfer functions.

The performance degradation[3] has been investigated in case of the distortion of the calculated control signals due to the randomly distributed transfer function errors. A number of robust control methods[4] have been proposed to reduce the performance degradation due to the transfer function error. Although these studies can inform the nature of the system and improve the robustness of a system against the arbitrary or random error distribution, the fundamental behavior of a system subjected to the specific type of error has not been addressed well. For example, there can be various sources of errors, such as the loudspeaker position mismatch, the measurement microphone mismatch, or even the gain and phase of each loudspeaker can be different. In this regard, the performance sensitivity of a personal audio system to various types of errors is investigated.

The performance of a personal audio system can be represented by the ratio of acoustic energies from two different zones. It is noteworthy that there are always two different types of zones involved with the concept of the personal audio; one is the bright zone in which a louder sound is desirable than in the surrounding area. The other zone is the dark (quiet) zone in which the sound pressure level needs to be

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minimized. For instance, Choi and Kim[5] proposed the use of the acoustic energy ratio of bright and dark zones, which is termed as acoustic contrast, as a measure of performance and as an objective function. In view of all these, the sensitivity of the acoustic contrast against the error can be a useful indicator of system's robustness.

The measured transfer functions include both the electro-acoustic response of the transducers and the characteristics of acoustic wave propagation between the loudspeaker and microphone positions. For instance, the acoustic propagation responses between loudspeakers and microphones may vary if there is the physical presence/movement of a listener or the change of the reflection boundary. The effect of such variations in acoustic responses, however, depends on the characteristics of the scatterer or the reflection boundary such that it should be studied for case by case. Thus two different types of errors have been considered here: The magnitude and phase error due to the electro-acoustic response mismatch and the errors that arise due to the position mismatch. Those mismatches in transducers may be important issues when there are model mismatches between the actual product and experimental prototype or manufacturing variances. Herein, the sensitivities of acoustic contrast in response to the errors that arise from electro-acoustic and position mismatches are formulated, respectively. An exemplary analysis, which uses a linear array of loudspeakers, explains which parameter has to be precisely controlled and which can be regarded as less important, in the design of a personal audio system.

2. Problem definition

2.1 Sound field controlled by multiple loudspeakers

Consider a personal audio system consisting of L loudspeakers and driven by a single frequency ω. Control signals $q^{(l)}(l = 1, 2, \ldots, L,$: Number of loudspeakers) are fed into each loudspeaker located at a position $\vec{r}_s^{\,(l)}$. Microphones located at $\vec{r}_m^{\,(n)}(n = 1, \ldots, N,$ N: Number of measurement points) measure the generated sound pressure $p(\vec{r}_m^{\,(n)})$. The pressure field that is generated by the control signals and measured at various microphone positions can be expressed as

$$\mathbf{p} = \mathbf{H}\mathbf{q}, \tag{1}$$

where $\mathbf{p} = [\, p(\vec{r}_m^{\,(1)}) \quad p(\vec{r}_m^{\,(N)})\,]^T$, $[\mathbf{H}]_{n,l} = h(\vec{r}_m^{\,(n)}|\vec{r}_s^{\,(l)})$, and $\mathbf{q} = [\, q^{(1)} \cdots q^{(L)}\,]^T$. Here $h(\vec{r}_m^{\,(n)}|\vec{r}_s^{\,(l)})$ is a transfer function between the lth loudspeaker and the nth microphone.

2.2 Pressure perturbation due to the transfer function errors

When the measured (or modeled) transfer function differs from the actual transfer function of the real loudspeaker, the difference between the two can be considered as the transfer function error. In general, a transfer function that includes errors can be expressed as

$$\tilde{\mathbf{H}} = \mathbf{H} + \delta\mathbf{H}, \tag{2}$$

where $\delta\mathbf{H}$ is a matrix representing the transfer function error $[[\delta\mathbf{H}]_{n,l} = \delta h(\vec{r}_m^{\,(n)}|\vec{r}_s^{\,(l)})]$, and $\tilde{\mathbf{H}}$ denotes the transfer function matrix with errors. The pressure perturbation $\delta\mathbf{p}$ that arises from the transfer function errors then can be expressed as follows:

$$\delta\mathbf{p} = \delta\mathbf{H}\mathbf{q}. \tag{3}$$

The mathematical expression of $\delta\mathbf{p}$ depends on the source of errors.

2.2.1 Electro-acoustic mismatch

In the case of electro-acoustic mismatch, the transfer function errors incur as the magnitude or phase variation of frequency response, which can be formulated[6] as

$$\tilde{h}(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) = (1+a_s^{(l)})e^{j\phi_s^{(l)}}(1+a_m^{(n)})e^{j\phi_m^{(n)}}h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}), \tag{4}$$

where $a_s^{(l)}$ and $\phi_s^{(l)}$ are the magnitude and phase errors of a transfer function for the lth loudspeaker, and $a_m^{(n)}$ and $\phi_m^{(n)}$ denote the errors for the nth microphone, respectively. The errors are all real valued variables ($a_s^{(l)}$ and $a_m^{(n)} \geq -1$). Assuming small magnitude and phase errors, such that $(1+a)e^{j\phi} \approx 1 + a + j\phi$, the perturbed transfer function can be approximated as

$$\tilde{h}(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) \approx h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) + [(a_s^{(l)} + j\phi_s^{(l)}) + (a_m^{(n)} + j\phi_m^{(n)})]h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}). \tag{5}$$

Equation (5) yields the transfer function error in matrix form as

$$\delta\mathbf{H} = \mathbf{H}\mathbf{E}_s + \mathbf{E}_m\mathbf{H}, \tag{6}$$

where the errors in loudspeakers and microphones are expressed by diagonal matrices: $\mathbf{E}_s = \mathrm{diag}[(a_s^{(1)} + j\phi_s^{(1)}), \ldots, (a_s^{(L)} + j\phi_s^{(L)})]$ and $\mathbf{E}_m = \mathrm{diag}[(a_m^{(1)} + j\phi_m^{(1)}), \ldots, (a_m^{(N)} + j\phi_m^{(N)})]$. With magnitude and phase errors only in the lth loudspeaker, the error matrix $\mathbf{E}_s$ can be written by $\mathbf{E}_s = \mathrm{diag}[\boldsymbol{\delta}_l](a_s^{(l)} + j\phi_s^{(l)})$, where $\boldsymbol{\delta}_l$ denotes the Kronecker delta vector the sole nonzero element of which equals 1 in the lth entry. Then the pressure perturbation $\delta\mathbf{p}$ can be expressed as

$$\delta\mathbf{p} = \mathbf{H}\mathbf{E}_s\mathbf{q} = \mathbf{h}^{(l)}(a_s^{(l)} + j\phi_s^{(l)})q^{(l)} = (a_s^{(l)} + j\phi_s^{(l)})\mathbf{p}^{(l)}, \tag{7}$$

where $\mathbf{h}^{(l)}$ represents the lth column of $\mathbf{H}$, and $\mathbf{p}^{(l)} = \mathbf{h}^{(l)}q^{(l)}$ denotes the pressure field of the lth loudspeaker. It is noteworthy that the pressure perturbation due to the electro-acoustic mismatch of a loudspeaker is proportional to the loudspeaker's transfer function, $\mathbf{h}^{(l)}$. When the electro-acoustic mismatch exists only in the nth microphone such that $\mathbf{E}_m = (a_m^{(n)} + j\phi_m^{(n)})\mathrm{diag}[\boldsymbol{\delta}_n]$, the pressure perturbation is expressed as

$$\delta\mathbf{p} = \mathbf{E}_m\mathbf{H}\mathbf{q} = \mathbf{E}_m\mathbf{p} = (a_m^{(n)} + j\phi_m^{(n)})p(\vec{r}_m^{(n)})\boldsymbol{\delta}_n. \tag{8}$$

2.2.2 Position mismatch

When there are position mismatches at $\vec{r}_s^{(l)}$ and $\vec{r}_m^{(n)}$ with $\delta\vec{r}_s^{(l)}$ and $\delta\vec{r}_m^{(n)}$, respectively, the transfer function can be expressed as

$$\tilde{h}(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) = h(\vec{r}_m^{(n)} + \delta\vec{r}_m^{(n)}|\vec{r}_s^{(l)} + \delta\vec{r}_s^{(l)}). \tag{9}$$

If it is assumed that $|\delta\vec{r}_m^{(n)}|$ and $|\delta\vec{r}_s^{(l)}|$ are small compared to the wavelength, Eq. (9) can be approximated[6] as

$$\tilde{h}(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) \approx h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) + \nabla_s h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) \cdot \delta\vec{r}_s^{(l)} + \nabla_m h(\vec{r}_m^{(n)}|\vec{r}_s^{(l)}) \cdot \delta\vec{r}_m^{(n)}, \tag{10}$$

where ∇_s and ∇_m are gradient operators with respect to the source position $\vec{r}_s$ and the microphone position $\vec{r}_m$. The transfer function's error of Eq. (10) can be written in matrix form as

$$\delta\mathbf{H} = \nabla_s\mathbf{H} \cdot \vec{\mathbf{T}}_s + \vec{\mathbf{T}}_m \cdot \nabla_m\mathbf{H}, \tag{11}$$

where $\vec{\mathbf{T}}_s = \mathrm{diag}[\delta\vec{r}_s^{(1)}, \ldots, \delta\vec{r}_s^{(L)}]$ and $\vec{\mathbf{T}}_m = \mathrm{diag}[\delta\vec{r}_m^{(1)}, \ldots, \delta\vec{r}_m^{(N)}]$ denote the translations of the loudspeakers and the microphones, respectively. If the position mismatch is present only at the lth loudspeaker ($\vec{\mathbf{T}}_s = \delta\vec{r}_s^{(l)}\mathrm{diag}[\boldsymbol{\delta}_l]$), the pressure perturbations can be expressed as

$$\delta\mathbf{p} = \nabla_s\,\mathbf{p}^{(l)} \cdot \delta\vec{r}_s^{(l)}. \tag{12}$$

From Euler's equation, the gradient of a pressure field $\nabla\mathbf{p}$ is related to the velocity field $\vec{\mathbf{u}}$ by $\nabla\mathbf{p} = j\rho_0\omega\,\vec{\mathbf{u}}$, where ρ_0 is the medium's density. Because the gradient is usually evaluated with respect to the observer's position, the reciprocal velocity field $\vec{\mathbf{u}}_s^{(l)}$, generated by the lth loudspeaker, can be defined ($\nabla_s \mathbf{p}^{(l)} = j\rho_0\omega\,\vec{\mathbf{u}}_s^{(l)}$). Hence, we have

$$\delta\mathbf{p} = j\rho_0\omega\vec{\mathbf{u}}_s^{(l)} \cdot \delta\vec{r}_s^{(l)}. \tag{13}$$

On the other hand, if position mismatch is present only at the nth microphone, the pressure perturbation is written as

$$\delta\mathbf{p} = [\delta\vec{r}_m^{(n)} \cdot \nabla_m p(\vec{r}_m^{(n)})]\ \boldsymbol{\delta}_n = j\omega\rho_0[\delta\vec{r}_m^{(n)} \cdot \vec{u}(\vec{r}_m^{(n)})]\ \boldsymbol{\delta}_n, \tag{14}$$

where $\nabla_m p(\vec{r}_m^{(n)}) = j\omega\rho_0\vec{u}(\vec{r}_m^{(n)})$ from Euler's equation.

2.3 Perturbation of acoustic contrast due to pressure perturbation

The acoustic contrast[6] is defined as the space-averaged acoustic energy ratio between the bright and dark zones. That is,

$$\beta = (\mathbf{p}_b^H\mathbf{p}_b/N_b)/(\mathbf{p}_d^H\mathbf{p}_d/N_d), \tag{15}$$

where the subscripts "b" and "d" in Eq. (15), respectively, denote the bright zone (V_b) and the dark zone (V_d). From the first order approximation of $\delta\mathbf{p}$, the relative contrast perturbation can be expressed as

$$\delta\beta/\beta \approx 2(\mathrm{Re}[(\mathbf{p}_b^H/||\mathbf{p}_b||)(\delta\mathbf{p}_b/||\mathbf{p}_b||)] - \mathrm{Re}[(\mathbf{p}_d^H/||\mathbf{p}_d||)(\delta\mathbf{p}_d/||\mathbf{p}_d||)]). \tag{16}$$

The operator Re[ ] denotes the real part of a variable. The term inside of [ ] in Eq. (16) represents the relative energy perturbation in a zone. Therefore the acoustic contrast perturbation is determined by the difference of energy perturbations in the bright and dark zones, each of which is given by the real part of the inner product of two vectors $\delta\mathbf{p}/||\mathbf{p}||$ and $\mathbf{p}/||\mathbf{p}||$.

3. Acoustic contrast sensitivity with respect to transfer function errors

3.1 Electro-acoustic mismatch of a loudspeaker

The contrast perturbation can be formulated in terms of the acoustic contrast sensitivity by substituting Eq. (7) into Eq. (16). Specifically,

$$\delta\beta/\beta = K_{s,mag}^{(l)}a_s^{(l)} + K_{s,phs}^{(l)}\phi_s^{(l)}, \tag{17}$$

$$K_{s,mag}^{(l)} = 2(\mathrm{Re}[(\mathbf{p}_b^H/||\mathbf{p}_b||)(\mathbf{p}_b^{(l)}/||\mathbf{p}_b||)] - \mathrm{Re}[(\mathbf{p}_d^H/||\mathbf{p}_d||)(\mathbf{p}_d^{(l)}/||\mathbf{p}_d||)]), \tag{18}$$

$$K_{s,phs}^{(l)} = (-2)(\mathrm{Im}[(\mathbf{p}_b^H/||\mathbf{p}_b||)(\mathbf{p}_b^{(l)}/||\mathbf{p}_b||)] - \mathrm{Im}[(\mathbf{p}_d^H/||\mathbf{p}_d||)(\mathbf{p}_d^{(l)}/||\mathbf{p}_d||)]), \tag{19}$$

where $K_{s,mag}^{(l)}$ and $K_{s,phs}^{(l)}$ represent contrast sensitivities due to the magnitude and phase errors in the lth loudspeaker, respectively. The contrast sensitivity depends on the inner product of the total pressure $\mathbf{p}$ and the pressure of the lth loudspeaker $\mathbf{p}^{(l)}$. Therefore in general, the loudspeaker that contributes more to the total pressure field has greater contrast sensitivity. However, the final contrast sensitivity is determined by the real part of the inner product for the magnitude mismatch, and the imaginary part for the phase mismatch.

3.2 Electro-acoustic mismatch of a microphone

In the case of electro-acoustic mismatch of nth microphone, unlike the case of the loudspeakers, the pressure perturbation only occurs at the position of the nth microphone. From Eqs. (8) and (16), the contrast sensitivity can be described as

$$K_{m,mag}^{(n)} = \begin{cases} 2|p(\vec{r}_m^{(n)})|^2/||\mathbf{p}_b||^2 & (\vec{r}_m^{(n)} \in V_b) \\ -2|p(\vec{r}_m^{(n)})|^2/||\mathbf{p}_d||^2 & (\vec{r}_m^{(n)} \in V_d), \end{cases} \tag{20}$$

$$K_{m,phs}^{(n)} = 0, \tag{21}$$

where $K_{m,mag}^{(n)}$ and $K_{m,phs}^{(n)}$ are the contrast sensitivities for magnitude and phase errors at the nth microphone, respectively. From Eq. (20), it can be seen that the contrast sensitivity to the magnitude error is given by the ratio between the energy measured by the nth microphone and the total sound energy in a zone. Consequently, the microphone located at the position with higher pressure level is more sensitive to the magnitude error than other microphones. An additional interesting aspect of the microphone phase error is that the contrast sensitivity is always zero [Eq. (21)] because the measured pressure is squared during the energy calculation. Therefore it can be concluded that as far as the acoustic contrast is concerned, the phase calibration is unnecessary.

3.3 Position mismatch of a loudspeaker or microphone

When there is a mismatch only at the lth loudspeaker position, from Eqs. (13) and (16), the contrast perturbation can be calculated as

$$\delta\beta/\beta = \vec{K}_{s,pos}^{(l)} \cdot \delta\vec{r}_s^{(l)}, \tag{22}$$

$$\vec{K}_{s,pos}^{(l)} = -2\omega\rho_0(\mathrm{Im}[(\mathbf{p}_b^H/||\mathbf{p}_b||)(\vec{\mathbf{u}}_{sb}^{(l)}/||\mathbf{p}_b||)] - \mathrm{Im}[(\mathbf{p}_d^H/||\mathbf{p}_d||)(\vec{\mathbf{u}}_{sd}^{(l)}/||\mathbf{p}_d||)]), \tag{23}$$

where $\vec{K}_{s,pos}^{(l)}$ is the contrast sensitivity vector due to the lth loudspeaker's position mismatch. The contrast sensitivity vector for loudspeaker's position mismatch depends on the inner product[7] between the total pressure field $\mathbf{p}$ and velocity field of the lth loudspeaker $\vec{\mathbf{u}}_s^{(l)}$ and the imaginary part given by Eq. (23) is proportional to the reactive intensity generated by the total pressure field and the velocity field.

For the position mismatch of the nth microphone, the contrast sensitivity vector $\vec{K}_{m,pos}^{(n)}$ can be derived by substituting Eq. (14) into Eq. (16). Specifically,

$$\vec{K}_{m,pos}^{(n)} = \begin{cases} 2\omega\rho_0 \mathrm{Im}[p(\vec{r}_m^{(n)})\vec{u}(\vec{r}_m^{(n)})^*/||\mathbf{p}_b||^2] & (\vec{r}_m^{(n)} \in V_b) \\ -2\omega\rho_0 \mathrm{Im}[p(\vec{r}_m^{(n)})\vec{u}(\vec{r}_m^{(n)})^*/||\mathbf{p}_d||^2] & (\vec{r}_m^{(n)} \in V_d). \end{cases} \tag{24}$$

The contrast sensitivity for the microphone position mismatch can be evaluated from the reactive intensity at the microphone location. This implies that the contrast sensitivities for both the loudspeaker and microphone position mismatches can be expressed in terms of the reactive intensity.

4. Analysis of acoustic contrast sensitivity

4.1 Exemplary design of a personal audio system

We now evaluate the contrast sensitivity of a personal audio system and demonstrate how this method of analysis can be used practically. As an example of the personal audio system, a linear array with nine equally spaced loudspeakers the aperture size L_s of which is 0.34 m is considered[2] [see Fig. 1(a)]. The bright and dark zones are sampled with equal spacing ($\Delta_m = 0.02$ m) in x and y direction by 1000 ($=(B_tD_t - BD)/\Delta_m^2$) microphones. For this simulation, under the free field (or anechoic) condition, the loudspeakers are considered to be monopole sources the control signals of which are determined by the acoustic contrast maximization.[5] The pressure field at 3 kHz, generated by the system, is depicted in Fig. 1(b).

4.2 Contrast sensitivity map with respect to transfer function errors

Figures 2 and 3 depict the contrast sensitivities with respect to the electro-acoustic/position mismatches of microphones/loudspeakers, which are termed *the contrast sensitivity map*.

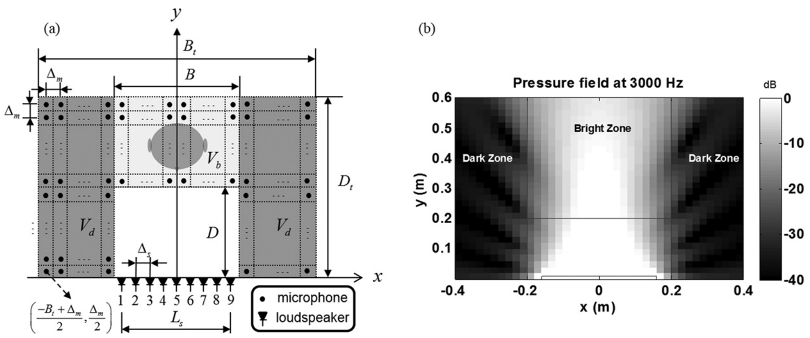

Fig. 1. (a) Configuration of a personal audio system; the bright zone (V_b) is the region that includes the assumed user location, and the dark zone (V_d) is configured near the bright zone ($B_t = 0.8\,\mathrm{m}$, $B = 0.4\,\mathrm{m}$, $D_t = 0.6\,\mathrm{m}$, $D = 0.2\,\mathrm{m}$, and $\Delta_m = 0.02\,\mathrm{m}$); nine monopoles are assumed as control loudspeakers ($L_s = 0.32\,\mathrm{m}$, $\Delta_s = 0.04\,\mathrm{m}$). (b) Pressure field (magnitude) generated by the contrast maximization [normalized by the pressure at $(x, y) = (0\,\mathrm{m},\ 0.4\,\mathrm{m})$].

The contrast sensitivity map reveals which loudspeaker or microphone is sensitive to the errors when the personal audio system is driven by the pre-determined control signals.

In Fig. 2, it can be observed that the microphone with higher pressure level [see Fig. 1(b)] is more sensitive (either in positive or negative direction) than the others. Therefore both in the bright and dark zones, the magnitude calibration of a microphone in the high amplitude region should be performed more carefully. The contrast sensitivity against the phase error of a microphone is always zero, and hence is not shown.

Meanwhile, the contrast sensitivity of the loudspeakers attains the value of zero for all loudspeakers (not shown). Zero contrast sensitivity is the peculiar feature of the personal audio system controlled by the acoustic contrast maximization, i.e., the contrast sensitivity may not be zero when loudspeakers are controlled by other control schemes. The acoustic contrast maximization chooses the stationary point of the acoustic contrast ($\partial\beta/\partial\mathbf{q} = 0$) as the optimal solution satisfying the relation $(\mathbf{H}_b^H\mathbf{H}_b/N_b)\mathbf{q} = \beta(\mathbf{H}_d^H\mathbf{H}_d/N_d)\mathbf{q}$,[5] which draws the zero contrast sensitivity. However, this does not mean that the acoustic contrast does not change irrespective of the loudspeakers' error. If the small error assumption of Eqs. (5) and (10) is not valid, the second-order terms of the contrast perturbation cannot be neglected; $\delta\beta/\beta = (||\mathbf{p}_b^{(l)}||^2/||\mathbf{p}_b||^2 - ||\mathbf{p}_d^{(l)}||^2/\,||\mathbf{p}_d||^2)\{(a_s^{(l)})^2 + (\phi_s^{(l)})^2\}$.

The distribution of contrast sensitivity vectors is marked with arrows in Fig. 3. The direction of each arrow indicates the direction that is most sensitive to the microphone/loudspeaker position mismatch, and the length of the arrow reflects the modulus of

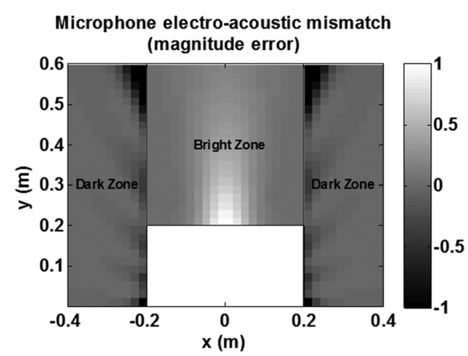

Fig. 2. Contrast sensitivity map (frequency at 3 kHz) with respect to the electro-acoustic mismatch of a microphones ($K_{m,mag}^{(n)}$). The positive/negative sign of sensitivity represents the increase/decrease of the contrast, and for each case, the sensitivities are normalized by the overall maximal sensitivity ($|K_{m,mag}^{(n)}|_{\max} = 6.3 \times 10^{-6}$).

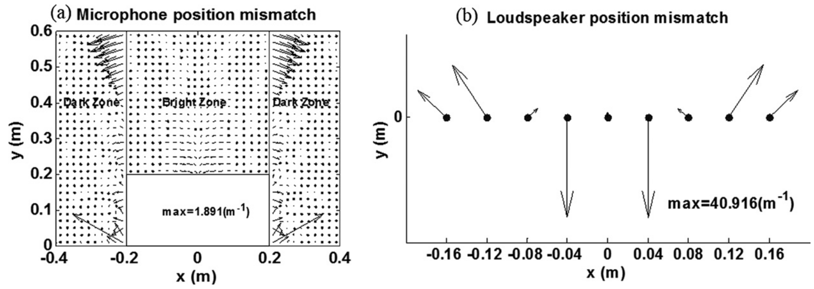

Fig. 3. Contrast sensitivity map (drawn for a single frequency of 3 kHz) with respect to the position mismatch of (a) microphones ($\vec{K}^{(n)}_{m,pos}$) and (b) loudspeakers ($\vec{K}^{(l)}_{s,pos}$) in m^{-1}. The length of arrows is normalized by the overall maximum modulus of sensitivity vector for each case.

contrast sensitivity vector. The resultant contrast perturbation is determined by the inner product of the contrast sensitivity vector and the position mismatch vector ($\delta\vec{r}^{(l)}_s$ or $\delta\vec{r}^{(n)}_m$).

5. Conclusions

The change in the performance of a personal audio system is investigated for various transfer function errors. To this end, the sensitivity of acoustic contrast is defined and mathematically expressed in terms of the degree of pressure perturbation with an assumption that the error or perturbation in the transfer function is so small that its higher order terms can be neglected. The contrast sensitivity is examined for the electro-acoustic mismatch of microphones and loudspeakers, as well as for their position mismatches.

To visualize the distribution of contrast sensitivity for various types of errors, a contrast sensitivity map is introduced, and the results for an exemplary case of a line array of loudspeakers are explained. It is demonstrated that the analysis on the acoustic contrast sensitivity can be a useful guide in the realization of a robust personal audio system.

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References and links

[1]S. J. Elliott and M. Jones, "An active headrest for personal audio," J. Acoust. Soc. Am. **119**(5), 2702–2709 (2006).

[2]J.-H. Chang, C.-H. Lee, J.-Y. Park, and Y.-H. Kim, "A realization of sound focused personal audio system using acoustic contrast control," J. Acoust. Soc. Am. **125**(4), 2091–2097 (2009).

[3]J.-Y. Park, M. Song, J.-H. Chang, and Y.-H. Kim, "Acoustic brightness/contrast control performance due to transfer function errors," in *Proceedings of 16th International Congress on Sound and Vibration*, Kraków, Poland (July 5–9, 2009).

[4]S. J. Elliott, J. Cheer, J.-W. Choi, and Y. Kim, "Robustness and regularization of personal audio systems," IEEE Trans. Audio, Speech, Lang. Process. **20**(7), 2123–2133 (2012).

[5]J.-W. Choi and Y.-H. Kim, "Generation of an acoustically bright zone within an illuminated region," J. Acoust. Soc. Am. **111**(4), 1695–1700 (2002).

[6]K.-U. Nam and Y.-H. Kim, "Error due to sensor and position mismatch in planar acoustic holography," J. Acoust. Soc. Am. **106**(4), 655–1700 (1999).

[7]J.-W. Choi and Y.-H. Kim, "Manipulation of sound intensity within a selected region using multiple sources," J. Acoust. Soc. Am. **116**(2), 843–852 (2004).