Expansion of an individual equalization method for binaural signals

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1. Introduction

When binaural signals are recorded with a dummy head and then reproduced through headphones, equalization is required to cancel the duplicate frequency characteristics of external ears while recording and reproduction [1,2]. In these studies the PTF (headphone transfer function), which is the transfer function from the terminal of the headphone to the eardrum, is compensated for by assuming that the frequency characteristics of the dummy head's external ears are identical to those of a listener. The author has proposed an equalization method to compensate for the individual differences in the external ear characteristics as well [3,4]. While the recording point was restricted to the entrance of the ear canal in our studies [3–5], a microphone is usually embedded in the dummy head where a listener's eardrum would be. This article expands our method to recording points other than the entrance of the ear canal.

2. Derivation of individual equalization [2–4]

2.1. Terminology definitions

According to the literature [2], the frequency domain representations of sound pressure observed for a listener are defined as follows:

P_1: sound pressure in the middle of the head with the listener absent in the original sound field
P_2: sound pressure at the entrance of a blocked ear canal in the original sound field
P_3: sound pressure at the entrance of an open ear canal in the original sound field
P_4: sound pressure at the eardrum in the original sound field
P_5: sound pressure at the entrance of a blocked ear canal when wearing a headphone
P_6: sound pressure at the entrance of an open ear canal when wearing a headphone
P_7: sound pressure at the eardrum when wearing a headphone.

"Blocked" means that the ear canal is physically blocked, for instance, with an earplug. Each sound pressure that is observed for a dummy head is denoted with a prime. Since P_1 is measured without a listener, $P_1 = P'_1$.

The transfer functions (including sensitivity and a frequency response) of a microphone are defined as follows:

M_1: transfer function of Microphone No. 1 used to record a signal with the dummy head in the original sound field
M_2: transfer function of Microphone No. 2 used to measure the PTF with a listener.

In this article, Microphone No. 2 is placed at the entrance of a listener's open ear canal to record P_6.

The voltage of a headphone- or microphone-terminal is defined as follows:

E_{hp}: voltage of the input terminal of the headphone
E_{mic}: voltage of the output terminal of Microphone No. 2

where $E_{mic} = P_6 \cdot M_2$ in this article since Microphone No. 2 is located as described above.

2.2. Individual equalization for signals recorded at the entrance of an open ear canal [2–4]

Figure 1 shows a block diagram of the binaural recording/reproduction system where G represents the equalization filter. In the original sound field, the signal is recorded at the entrance of the dummy head's open ear canal as P'_3. According to the literature [2], the total transfer function from the original sound field, P_1, to the sound pressure at the eardrum, P_7, is

$$\frac{P'_3}{P_1} \cdot M_1 \cdot G \cdot \frac{P_7}{E_{hp}}. \tag{1}$$

This should be equal to P_4/P_1, which is the transfer function from P_1 to the sound pressure at the eardrum in the original sound field, P_4, so that G is given by

$$G = \frac{P_4}{P'_3} \cdot \frac{E_{hp}}{M_1 \cdot P_7} \tag{2}$$

$$= \frac{P_3}{P'_3} \cdot \frac{E_{hp}}{M_1 \cdot P_6} \tag{3}$$

$$= \frac{P_3}{P'_3} \cdot \frac{M_2}{M_1} \cdot \frac{E_{hp}}{E_{mic}}. \tag{4}$$

Equation (3) is derived from Eq. (2) using the relationship of $P_4/P_3 = P_7/P_6$, which indicates that the transfer function from the entrance of the ear canal to the eardrum is the same during recording and reproduction [2]. Equation (4) is derived from Eq. (3) using $E_{mic} = P_6 \cdot M_2$. G is calculated separately for the right and left channels as shown in Fig. 1.

Equation (4) implies that the transfer functions of the two microphones must be calibrated by measuring M_1 and M_2. If Microphone No. 2, which measures sound pressure at the entrance of the ear canal, P_6, is the same as Microphone No. 1, then $M_1 = M_2$. Thus, $M_1 = M_2$ and Eq. (4) result in

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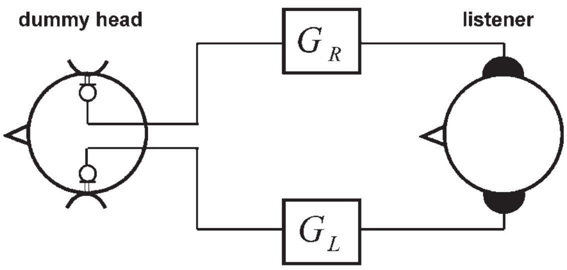

Fig. 1 Block diagram of a binaural system.

$$G = \frac{P_3}{P'_3} \cdot \frac{E_{hp}}{E_{mic}}. \tag{5}$$

The first term, P_3/P'_3, is the individual equalization [3,4], and the second term, E_{hp}/E_{mic}, compensates for the PTF [2].

As above, since the relationship of $M_1 = M_2$ is the key for realizing the individual equalization, the same microphone must be used for both recording in the original sound field and for measuring the PTF. This is the reason that the recording point was restricted to the entrance of the ear canal in our studies [3–5].

3. Expansion of the individual equalization

3.1. Recording at the entrance of an open ear canal

As shown in Eq. (5), if $M_1 = M_2$, the microphones do not need to be calibrated. Incidentally, Eq. (4) can be rearranged as follows:

$$G_B = \frac{P_3 \cdot M_2}{P'_3 \cdot M_1} \cdot \frac{E_{hp}}{E_{mic}} \tag{6}$$

where suffix B corresponds to "Method B: recording at the entrance of the open ear canal" in the literature [2]. This equation means that the condition of $M_1 = M_2$ can be ignored and the microphones do not need to be calibrated. In other words, calibration is unnecessary if Microphone No. 2, which was originally introduced to measure P_6, is also used for recording P_3. This is because the numerator and denominator of the first term, $(P_3 \cdot M_2)/(P'_3 \cdot M_1)$, represent the output signals of the microphones for the listener and the dummy head, respectively. It is noteworthy that we do not directly observe sound pressure but the output voltage of the microphone. Thus, the transfer functions of the microphones, M_1 and M_2, do not be needed to calculate $(P_3 \cdot M_2)/(P'_3 \cdot M_1)$.

3.2. Recording at the eardrum

Equation (6) indicates that different types of microphones can be used to record signals for a listener and a dummy head. Thus, a microphone embedded at the position of the dummy head's eardrum can be used for binaural recording. Even in this case, recording for the listener is done at the entrance of the open ear canal since it is difficult to place a microphone at the eardrum of the listener. The equalization characteristic called G_A corresponds to "Method A: recording at the eardrum" in the literature [2]. The total transfer function from the original sound field, P_1, to sound pressure at the eardrum, P_7, is

$$\frac{P'_4}{P_1} \cdot M_1 \cdot G_A \cdot \frac{P_7}{E_{hp}} \tag{7}$$

while it should still be P_4/P_1. When they are equal, G_A is given by

$$G_A = \frac{P_4}{P'_4} \cdot \frac{E_{hp}}{M_1 \cdot P_7} \tag{8}$$

$$= \frac{P_3}{P'_4} \cdot \frac{E_{hp}}{M_1 \cdot P_6} \tag{9}$$

$$= \frac{P_3 \cdot M_2}{P'_4 \cdot M_1} \cdot \frac{E_{hp}}{E_{mic}}. \tag{10}$$

Equation (10) is also derived using the relationships of $P_4/P_3 = P_7/P_6$ and $E_{mic} = P_6 \cdot M_2$. This equation demonstrates that the individual equalization is available for binaural signals recorded at the eardrum without calibrating the microphones.

3.3. Recording at the entrance of a blocked ear canal

Møller [2] indicated that recording at the entrance of a blocked ear canal is attractive since the recorded signals contain minimal individual information. However, sound pressures P_2 (for a listener) and P'_2 (for a dummy head) are different although the ear canals are blocked. Thus, our individual equalization is required.

The equalization characteristic called G_C corresponds to "Method C: recording at the entrance of the blocked ear canal" in the literature [2]. The total transfer function from the original sound field to sound pressure at the eardrum is

$$\frac{P'_2}{P_1} \cdot M_1 \cdot G_C \cdot \frac{P_7}{E_{hp}} \tag{11}$$

while it should again be P_4/P_1. Thus, G_C is given by

$$G_C = \frac{P_4}{P'_2} \cdot \frac{E_{hp}}{M_1 \cdot P_7} \tag{12}$$

$$= \frac{P_3}{P'_2} \cdot \frac{E_{hp}}{M_1 \cdot P_6} \tag{13}$$

$$= \frac{P_3 \cdot M_2}{P'_2 \cdot M_1} \cdot \frac{E_{hp}}{E_{mic}}. \tag{14}$$

This equation indicates again that the individual equalization is available without calibrating the microphones.

4. Summary

Equations (6), (10), and (14) are summarized as

$$G = \frac{P_3 \cdot M_2}{P'_i \cdot M_1} \cdot \frac{E_{hp}}{E_{mic}} \tag{15}$$

where i is 2, 3, or 4. The individual equalization is available regardless of the recording points on a dummy head and the microphones do not need to be calibrated. Consequently, the individual equalization method was successfully expanded.

However, there is a constraint on Eq. (15) since it contains P_3. Thus, a listener must visit the original sound field at least once to measure the equalization characteristics. Studies how to resolve this constraint condition are currently underway [5,6].

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