VARIATIONS IN THE ACOUSTIC MEASUREMENT OF EARBUD EARPHONES IN AN ANECHOIC CHAMBER DUE TO CHANGES IN THE EARPHONE PLACEMENT IN EAR CONCHA

S. J. Pawar*[1], Y. C. Liu†[2] and Jin H. Huang‡[3]
[1]Department of Applied Mechanics, Motilal Nehru National Institute of Technology Allahabad,Prayagraj INDIA,
[2]Bachelor's Program in Precision System Design, Feng Chia University, Taichung, Taiwan, Republic of China,
[3]Department of Mechanical and Computer-Aided Engineering, Feng Chia University, Taichung, Taiwan, Republic of China,

Résumé

La croissance des produits électroniques grand public, encouragés par les innovations, a stimulé le développement persistant des écouteurs pour une reproduction sonore de haute qualité. L'écouteur bouton est situé dans le pavillon de l'oreille humaine en face du conduit auditif. Le placement des écouteurs dans le pavillon de l'oreille joue un rôle remarquable dans la réponse du niveau de pression acoustique d'un écouteur. Dans cette étude, dix écouteurs ont été testés pour la réponse en fréquence et la distorsion harmonique totale en utilisant un simulateur de tête et de torse dans une chambre anéchoïque. Trois positions et deux orientations d'écouteurs dans le pavillon de l'oreille ont été identifiées pour la mesure. Sur la base des réponses de tous les écouteurs à toutes les orientations et positions, il est conclu qu'il existe une variation de la réponse en fréquence et de la distorsion harmonique totale. Même si la variation est de faible ampleur, son effet sur la perception du son, l'exposition au son et le seuil d'audition est phénoménal. Sur la base de la proposition présentée dans ce travail et de l'exposition sonore quotidienne sûre, il a été suggéré que la variation de la réponse en fréquence affecte la sonorité perçue de la musique/du son et peut provoquer des différences significatives dans la limite d'exposition sonore quotidienne pour un être humain.

Mots clefs : écouteur bouton, réponse en fréquence, oreille humaine, niveau de pression acoustique, distorsion harmonique totale

Abstract

The growth of consumer electronic products is encouraged by innovations and has stimulated the persistent development of earphones for high-quality sound reproduction. Earbud earphone is located in the concha of the human ear facing an ear-canal. The placement of earphones in the concha plays a remarkable role in the sound pressure level response of an earphone. In this study, ten earphones were tested for frequency response and total harmonic distortion using head and torso simulator in an anechoic chamber. Three positions and two orientations of earphones in the concha were identified for measurement. Based on the responses of all earphones at all orientations and positions, it is concluded that there is a variation in the frequency response and total harmonic distortion. Even though the variation is small in magnitude, its effect on sound perception, sound exposure, and the hearing threshold is phenomenal. Based on the proposition presented in this work and the safe daily sound exposure, it has been determined that the variation in the frequency response affects the perceived loudness of sound and can cause significant differences in the daily sound exposure limit for a human being.

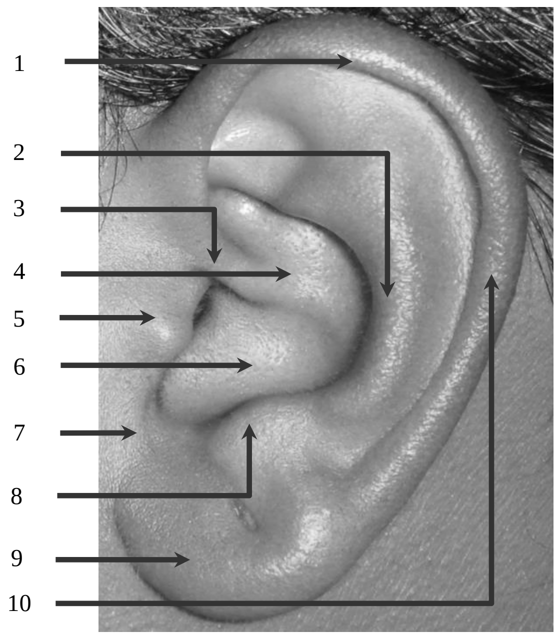
Keywords: earbud earphone, frequency response, human ear, sound pressure level, total harmonic distortion

1 Introduction

The growth of 4C products (i.e., computer, communication, consumer electronics, and car electronics), or the consumer electronic products, has encouraged new developments in the electroacoustic community worldwide. The relentless evolution of earphone has stimulated a cache of innovations in the field of electroacoustic transducers. The earphone is intended not only for the delivery of high-quality sound but is required to be stylish, slim, portable, and aesthetic. High-fidelity sound reproduction over a wide frequency range has explored "Research Avenue" in earphone design and development for the electroacoustic community. The typical earbud earphone (EE) rests within the concha (Figure 1) facing an ear-canal [1]. The EE is subjected to-sound leakage across its interface with concha due to the human ear anatomy. The frequency response (sound pressure level (SPL)) of EE depends on the parameters associated with both the earphone and ear. The earphone parameters involve a miniature loudspeaker, earphone size, earphone shape, earphone enclosure volume, vent, and sound holes in the enclosure. The parameters associated with an ear are an ear-canal and its transfer function, shape & size of the concha, and leakage across earphone-concha interface. The placement of an earphone in the concha plays a significant role in the earphone's SPL response and total harmonic distortion (THD). The SPL, the localized pressure fluctuations created by sound-producing device over the atmospheric pressure attributes to the range of frequencies that the sound-producing device can reproduce. The THD is owed to the loudspeaker nonlinearity that generates additional signal components from the loudspeaker and associ-

* sjpawar@mnnit.ac.in
† ycliu@ fcu.edu.tw
‡ jhhuang@fcu.edu.tw

ated electronic hardware, which causes output signal distortion. Thus, the THD may deteriorate the sound quality of an earphone.



1. Helix
2. Anti helix
3. Anterior notch
4. Crus helias
5. Tragus
6. Cavum (concha)
7. Tragal notch
8. Anti tragus
9. Lobule
10. Pinna

Figure 1: Anatomy of an external ear.

An acoustic performance estimation and measurement of telecommunication equipment by an artificial ear has been given in ITU-T Recommendations P.57 [1]. B&K developed a Head and Torso Simulator (HATS), known as Type 4128 [2], for an in-situ acoustic evaluation and performance estimation of audio products. An International Electrotechnical Commission (IEC) coupler (IEC-60711) [3] and B&K measurement microphone are housed in the HATS. Wojcik and Cardinal (1999) [4] discussed uncertainties in the measurement by the HATS. Riederer and Niska (2002) [5] carried out measurement and simulation of 3D sound with insert headphones. The ear-tip of earphone allows the exact positioning of the earphone in the concha, which results in the attenuation of background noise 15-20 dBSPL as reported. Ćirić and Hammershøi (2006) [6] addressed the measurement of earphones by ear using a standard coupler and found that individual ears have detected significantly different levels of SPL. Tikander (2007) [7] provided a lumped element model to simulate the sound of transmission path from the surrounding environment into the ear-canal. Additionally, an air leakage due to the cloth (sponge) had been modeled. In an attempt to calibrate headphones and earphones by KEMAR for psychoacoustic experimentation, Zhiwen *et al.* (2009) [8] reported a significant change of sound pressure on the tympanic membrane due to small change in the location of an earphone in the concha. Liu (2008) [9] explained the ergonomic design and development of ear-related products by providing anthropometric dimensions of an outer ear. Erber (1968) [10] investigated the influence of an outer ear configuration on the acoustic stimulus by a supra-aural headphone on the tympanic membrane. Zwislocki *et al.* (1988) [11] reported unpredictability in the audiometric applications of an earphone due to the variability associated with an acoustic coupling between the sound source and an eardrum. Kulkarni and Colburn (2000) [12] pointed out that the performance of supra-aural headphones varies with the positioning of the headphone cushion during normal usage by KEMAR measurements. A significant effect of middle ear pathologies on the sound pressure variation in the ear-canal has been indicated by Voss *et al.* (2000) [13]. Ruiz *et al.* (2005) [14] reported issues during the measurement of electro-acoustic instruments during the calibration of audiometric and psychoacoustic tests. For uncertainty in the response of circum-aural earphones, The effects of temperature and placement were quantified by measurements. The sound leaks to the surrounding, from the rear side of EE in two ways, first, through the soundhole and second from the interface of EE casing and concha surface. Due to the leakage of the sound, the SPL detected by eardrum changes [15]. The modeling and measurement of EE has been carried out in our previous publication [16]. The field studies [17-19] were done for investigating the use of portable audio devices and the hearing health of customers.

Liu (2008) [9] performed an extensive data collection and analysis for understanding the human ear anthropometry for effective design of ear-related products. It is evident that the anthropometric dimensions of the outer ear for different demographic data, including gender, age, etc. plays a significant role in mass customization and collaborative ear-related product design. Three dimensions of the outer ear (earhole length (L_a), ear connection length (L_b), and pinna length (L_c)) were decided (Figure 2) as significant. Two hundred subjects (20-59 years of age) were grouped into four age groups for ear dimensions determination by the superimposed grid photographic technique. The outer ear plays a prime role in the collection of sound from the environment and transmission of same to the middle ear. The outer ear collects the sound and transmits it to the tympanic membrane (diaphragm) through the auditory canal (ear-canal).

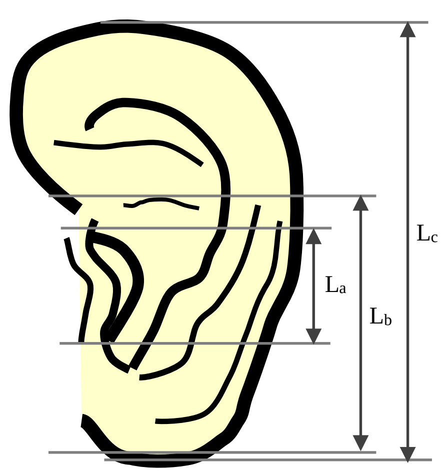


Figure 2: Three critical dimensions of human ear [9].

The average values of ear dimensions were measured and L_a was found to be larger in males (15.6 mm vs. 14.5 mm), also L_b is appreciably higher in males (47.5 mm vs. 42.2 mm), and L_c is also significantly similarly larger in males (58.4 mm vs. 53.9 mm). These facts establish gender dependence on the dimensions, however, show no significant difference across different age groups. The dimension analysis of both the ears show a strong correlation between the right and left ears, revealing their asymmetry. It is concluded that the right ear had larger dimensions than the left ear.

Erber (1968) [10] reported that mean hearing sensitivity for young subjects differ. Young females of 18-24 years of age demonstrate better hearing than males of that age. There have been anatomical dissimilarities of auditory systems (viz. skull, pinna, ear-canal dimensions, quantity, and quality of external hair) and hair along with cerumen content of the ear-canal. Besides, studies reveal that acoustic stimulus created by earphones at the tympanic membrane can be affected by factors like voltage applied to the earphone, force applied on the earphone, earphone cushion-pinna seal, ear-canal volume, earphone and cushion type, etc. Middle ear pathologies alter the impedance of the middle ear, and also every deviation in the anthropometric dimension of the ear can change the impedance. Lee *et al.* (2016) [20] carried out detailed anthropometric dimensions of the outer ear for the design of ear-related products. The outer ear consists of three main parts (pinna, concha, and external auditory canal). Figures 3 (a-c) shows some significant anthropometric dimensions of the human ear, focusing mainly on the earbud earphone as L_{aa} = Cavum concha length, L_{ab} = Cavum concha width (also L_{bb}), L_{ac} = Centre of concha to anterior cymba concha length, L_{ba} = Ear-canal length, L_{ca} = Cavum concha depth, L_{cb} = Ear-canal depth (also L_{cd}), and L_{cc} = Pinna flare angle.

In confirmation with the anatomy of an average human ear and according to ITU-T recommendations, the diameter of EE should be less than 25 mm for proper fitting in the concha cavity. The diameter of earphones available in the market varies from 12-20 mm. The miniature-loudspeaker (Figure 4 (a)) is housed in an aesthetically shaped casing of earphone (Figure 4 (b)). The EE generates sound from the front and back. Also, there are two sound leakages from EE to its backside. One through the vent holes in the under-yoke of the loudspeaker to earphone cavity which further leaks to the backside via the sound-hole in an earphone cover. Another sound leakage is from the rear side of an earphone through an earphone circumference and the concha interface.

The B & K Type 4128 is typical HATS, it consists of an artificial head mounted on a torso extending to the waist. It lets an accurate simulation of an acoustic field around a human head and a torso for airborne acoustic measurements. The HATS consists of a removable silicone rubber pinna, an occluded ear-simulator, and a 1/2” microphone with a preamplifier. The placement of EE in the pinna (concha cavity) is in definite relation to the ear reference point (ERP) and an ear-canal entrance point (EEP) [1]. A schematic of B & K HATS with EE resting in a concha cavity is given in Figure 4 (c). In a human ear, EE rests against the cavum (concha) and is supported by the crus helias, tragus, and anti-tragus (Figure 1). Besides, the tragal notch assists in the placement

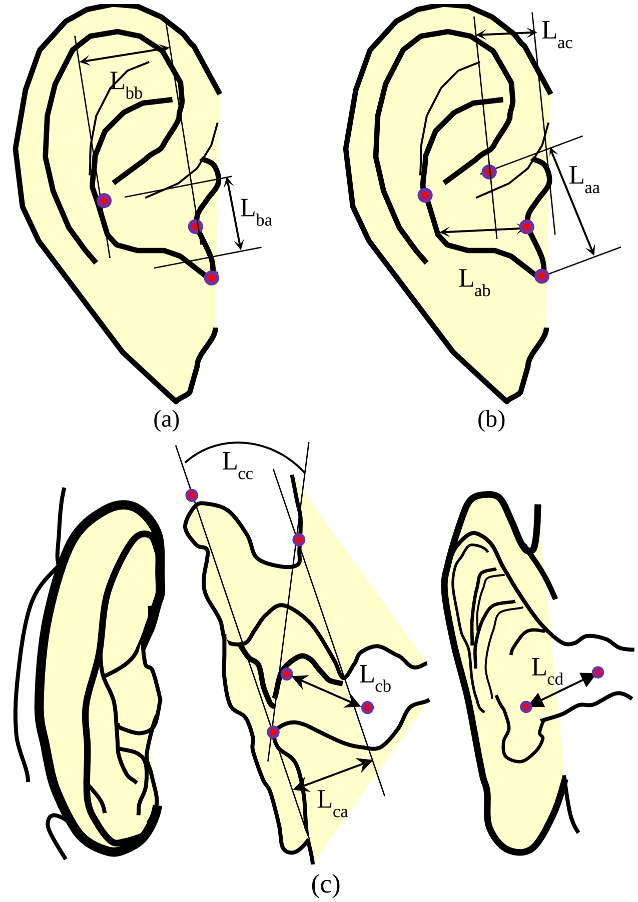


Figure 3: Some significant anthropometric dimensions of human ear [20].

of EE so that it should not loose during regular uses. Due to the variations in the anatomy of a pinna, it is difficult and impracticable to fit EE in the concha cavity perfectly. As a result, some sound leaks through the EE circumference and concha interface (Figure 4 (c)), shown by arrows from the top and bottom of EE. However, majority of the sound is directed towards an ear-canal opening and reaches to the pinna external cavity. Moreover, the sound goes to the pinna circular cavity and finally enters the IEC-60711 coupler and is detected by the microphone housed in IEC coupler.

The SPL or the frequency response of a loudspeaker is a vital characteristic to quantify the behavior of loudspeaker. In a perfect condition, the curve should be flat over the working range of a loudspeaker. The THD of a signal is a measurement of the harmonic distortion in an output which is the ratio of sum of the powers of all harmonic frequency components to the power of fundamental frequency. The THD characterizes the linearity of audio system, loudspeaker, amplifier, microphone, etc. Generally, the THD is expressed either in decibel or in percentage. It is nonlinearity, resulting in addition of unwanted signals to the input signal that is harmonically related to it. Hence the spectrum of the output shows some added frequency components at 2x, 3x, 4x, 5x, and so on of an original signal.

Klippel, in a series of papers [21-24], discussed the nonlinear behavior of loudspeakers. The loudspeaker generates a nonlinear signal component in the output along with the orig-

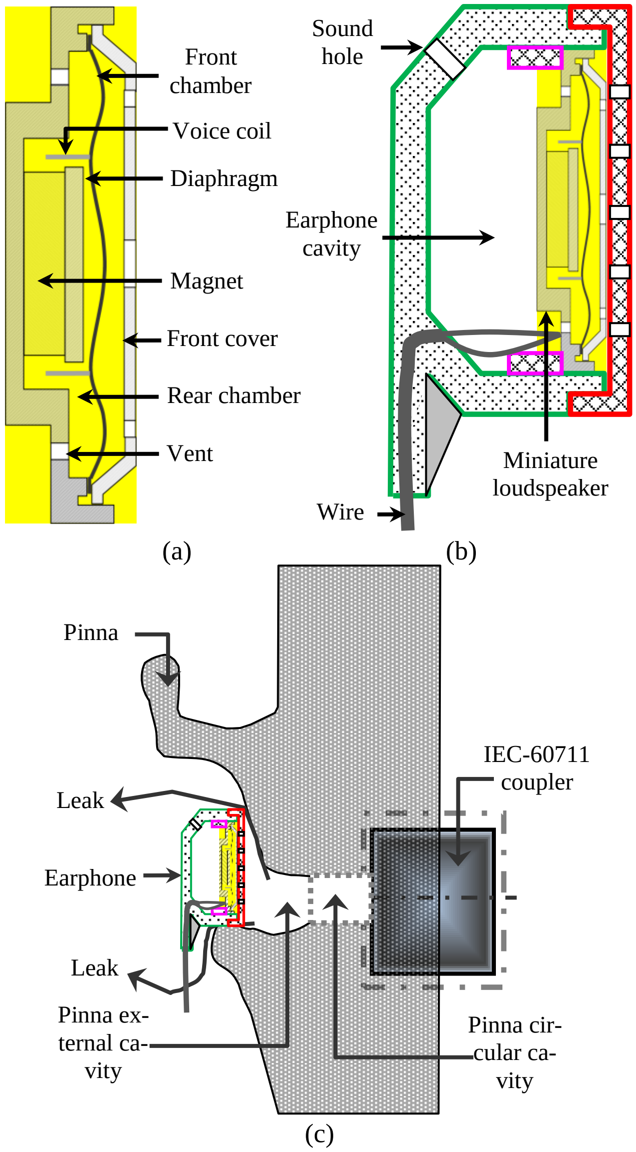


Figure 4: Schematic of (a) Miniature loudspeaker, (b) Earbud earphone, and (c) B&K HATS with earphone in concha.

inal signal when driven at high input level. In most cases, the nonlinear signal components are unwanted; but, are inherent due to nonlinearity of the electro-dynamic loudspeaker and cannot be avoided. Motor and suspension nonlinearities are two dominant causes of loudspeaker nonlinearities. The distortions can also be categorized as a regular and irregular. The nonlinear properties of loudspeaker design cause regular distortions and are usually dominating 2nd to 5th harmonics as well as THD [25]. Irregular distortions are due to defects, manufacturing process artifacts, aging, and other external impacts (overload, climate, etc.) during the life cycle of the loudspeaker. A rubbing voice coil, buzzing parts, loose particles in the gap, and air leaks are some common loudspeaker defects. The regular distortions are significant at low frequency; and, irregular distortions are usually broadband. Much smaller amplitude irregular distortions are masked by the lower order regular distortions. In our earlier efforts [26, 27], an effect of the nonlinear suspension stiffness on the SPL and THD has been simulated, experimented, and validated for a circular and an elliptical miniature loudspeaker, respectively. Analogously, an effect of a nonlinear force factor on the SPL and THD of a circular and an elliptical miniature loudspeaker has also been simulated, experimented, and validated by our group [28, 29], respectively.

In continuation with the various field studies [17-19], an extensive logistic about human ear, human hearing, etc. were documented. Enormous capabilities of the human ear have been explored in terms of the frequency range covered, sound pressure sustained, and sound energy handled. The remarkable abilities of the hearing system have been highlighted, along with challenges and risks [30]. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) in 2008 gave a detailed report and advisory advised on the potential health risks of exposure to noise from personal music players and mobile phones. The inability to hear sounds below certain thresholds is the most common form of hearing impairment. It is reported that exposure to excessive noise is a significant cause of hearing disorder worldwide. Nearly 16% of the hearing loss disabilities in adults are due to occupational noise. The personal music players now play not only music but provide podcasts of various activities, which are listened through ear-bud and insert types of EEs producing a range of maximum SPL around 80-115 dB(A). Remarkably, the difference in EE type may increase the SPL by 7-9 dB, specifically, the ear-bud creates the highest levels of about 120 dB(A) in the worst-case scenario it is caused by the insertion depth of the ear-bud in the ear-canal [31]. World Health Organization in 2015 [32] published a review related to the hearing loss due to recreational exposure to loud sounds. The report gave a comprehensive account of human hearing and the effect of noise. Additionally, the treatment of the noise-induced hearing loss is suggested along with prevention. Strategies are proposed by the use of legislation, social media, intervention, education conservation, etc.

Based on the variations of anthropometric dimensions of the human ear, the sound perception by different individuals from the same earphone shall be different. The effect of various factors like earphone shape, earphone size, earphone position in the concha, earphone orientation in the concha, earphone circumference and concha surface seal, earphone force on concha surface, etc. are also prominent. This study proposes and establishes that the sound perception by individuals from the same earphone shall be dissimilar due to different orientations and positions of EE in the concha. Alongside, the sound impression by the right and left ear of the same individual shall also differ. The study infers that the prolonged usages of EE may change the orientation, position, force, earphone circumference and concha surface seal, etc. which may cause variation in the SPL generated across the tympanic membrane.

2 Materials and Method

As an extension of our previous work [15], two distinct EE orientations have been identified (Figure 5) in this work. At position 1, the earphone's front surface is placed directly against the concha bottom surface and is supported along the circumference by the tragus, anti-tragus, and crus helias. The tragus sometimes covers the EE, based on the anatomy of the ear. As shown in Figure 5, positions 2 and 3 are similar to position 1; but differ slightly due to the placement of EE wire. The earphone wire is located along the tragal notch, anti-tragus, and an anterior notch for positions 1, 2, and 3, respectively. At position 1, the anthropometric notch of ear assists in perfect fit of the earphone with minimum sound leakage and least pinna external cavity volume. At position 2, due to projection of anti tragus, wire of the earphone gets lifted and extra volume is created in the pinna external cavity, along with the possibility of a higher sound leakage through the tragal notch. Similarly, at position 3, anterior notch assists the earphone wire placement in different ways, which is dependent on the anthropometry of the ear. This position affects sound leakage and pinna external cavity volume. Two different orientations of earphones are also identified as given in Figure 5. In orientation 1, earphone is directly supported against the concha bottom surface of the concha. On the contrary, the earphone is inclined (roughly 10-45° depending on the anatomy of a human ear) against the concha bottom surface in orientation 2 so that the front surface of the earphone faces the auditory canal opening. Based on the orientations mentioned above, a direct exposure of EE to the ear-canal opening varies, which implies different pinna external cavity shapes and volume, different leakage levels, and different positions of the sound sources about ERP. Hence, it is anticipated that there may be variation in SPL and THD responses of earphones when the position and orientation of EE are changed.

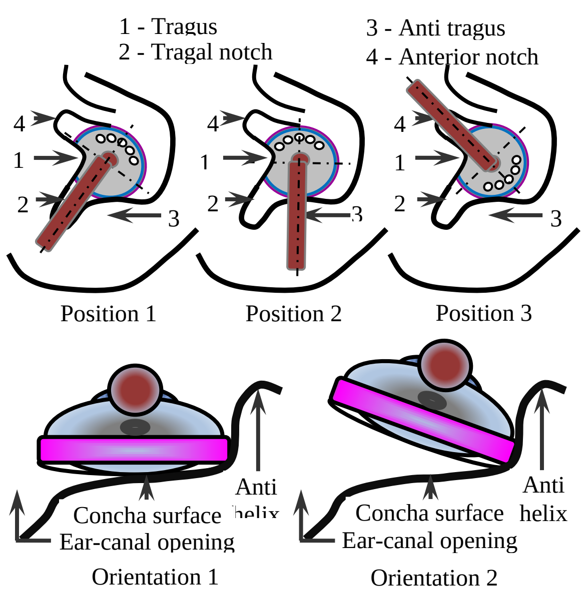


Figure 5: Schematic of earphone placement in concha for measurement.

The schema of the anechoic chamber measurement of frequency response and THD of EE is given in Figure 6. An earphone is positioned in the concha of the HATS. The software (SoundCheck® 8.1, Listen Inc. Boston, MA, USA) generates a test signal for the earphone via an amplifier. The microphone of the IEC-60711 coupler receives the sound pressure generated by the earphone and finally communicates it back to the software for further processing. In this study, the measurements are carried out for SPL and THD for each position and orientation (total of six combinations) for ten earphones, designated as E1 to E10.

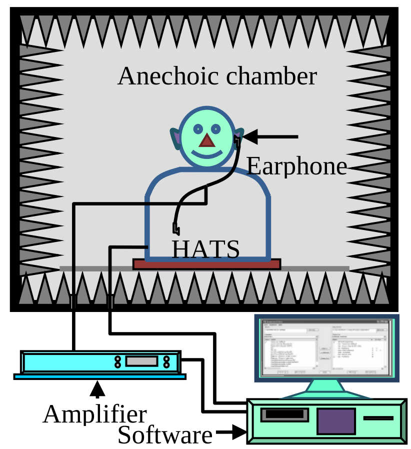


Figure 6: Measurement setup for an earbud earphone with B&K HATS.

The design and development of electroacoustic transducers like the loudspeakers, miniature loudspeakers, and earphones (like earbud and insert) are done extensively for getting consistent simulated performances. However, electroacoustic transducers are prone to manufacturing artifacts and no two loudspeakers may perform identically. There is a possibility of variation in the performance of the loudspeaker (SPL, THD, intermodulation distortion, rub & buzz, etc.) due to various factors. These factors might be defects, manufacturing variabilities, material discrepancies (compositional and structural), and service condition (working) histories (duration of sound production, mishandling, the amplitude of input signal, etc.). It is a general practice to observe the THD response of EE to identify the distortion and frequency response to see how the EE produces the sound of different frequencies. The high-fidelity sound reproduction is severely affected by the distortion in an output signal. In this study, the SPL and THD responses are measured for ten earphones (arranged in order of increasing price) available in the Taiwan market (May 2011) at three positions and two orientations. Minimum five readings are taken for each EE at a particular position and orientation for consistency in results. The details of earphones, dimensions and specifications are given in Table 1 and Table 2.

3 Results

The SPL and THD responses for earphones E1-E10 at position 1 and orientation 1 are given in Figure 7. The top plots indicate SPL responses and the bottom plots indicate corresponding THD responses. For better visibility and understanding, the left-side plots show the result of earphones E1 to E5, and the right-side plots show the result of earphones E6 to E10. The average reading of SPL and THD is given in all figures. Even though supplied with the same input signal, one can see that the SPL response of earphone E1 is lower-than the remaining EEs; however, SPL responses of remain

Table 1: The dimensions of earbud earphones.

EE	Price range	Dimension (mm)		
		Diameter	Width/thickness	Openings/slits
E1	< US$ 3.0	16.5	W = 13.5	3 slits (opening) of diff. Length, Slit 3.3 x 0.5 (big)
E2		16.6	14	No hole in earphone cavity cover
E3	US$ 3.0~5.0	16.25	14.3	5 holes, d = 0.9
E4		16.5	15.0	2 slits, 1.5 x 0.3
E5	US$ 5.0~7.0	16.6	13.5	1 central oval hole a = 1.5, b = 1.0
E6		16.5	15.8	1 big slit, 4.5 x 0.8
E7	US$ 7.0~9.0	16.8	10.8	Annular slit 5.8 x 2.6 at the back along annular position
E8		16.5	13.8	1 central hole to earphone cavity cover
E9	US$ 9.0~11	15.7	14.6	1 central hole to earphone cavity cover
E10		16.2	13.0	Small annular slit, 3.5 x 0.5

D – Diameter of an earphone.
W – Width/thickness of an earphone.

Table 2: The specifications of earbud earphones.

EE	Specifications			
	Frequency Range (Hz)	Sensitivity (dB/mW) (SPL)	Impedance (Ω) at 1 kHz	Power handling capacity (mW)
E1	12~22000	108	16	50
E2	10~25000	100	16	40
E3	20~22000	105 ± 6 dB	16	5
E4	20~20000	104 ± 4 dB	16 ± 15 %	4 and 10
E5	14~22000	104 dB	16	50
E6	20~20000	105 ± 6 dB	16	5
E7	12~22000	106 dB	16	50
E8	20~20000	104	17	40
E9	16~20000	108	16	200
E10	12~22000	102 dB	16	50

ing EEs appear unique and nearly similar. The fundamental frequency of earphone E1 is higher than other EEs. Specifi cally, it is 630 Hz for E1 and 530 Hz for E10; however, the same is falling between 170-300 Hz for all other EEs. The highest and lowest SPL of the fundamental frequency is observed for E8 (129.9 dB) and E1 (99.9 dB), respectively, and for the remaining EEs, it lies between 109.9-122.0 dB. So, it concludes that the low-frequency response of earphones E2 to E10 may be carefully tuned by the design of the EE enclosure to get a high-fidelity bass response. All EEs show a spiky response after 1.7-3 kHz with a sufficient spectral component. The THD response of EEs illustrates that earphone E1 has high THD (~61.5% at 30 Hz). This response suggests the possibility of a significant nonlinear regular distortion, which may be due to the magnetic motor and suspension nonlinearities. Additionally, a peak (~8.2%) in THD at about 300 Hz is seen, which may be due to the rub & buzz or to some extent due to the manufacturing defect in the miniature loudspeaker of the earphone E1. Reduced SPL in the low-frequency region for earphone E1 can be correlated with an enhanced THD. Some small peaks ~0.1-1.6% THD are also observed at 1.6 kHz, 3.5 kHz, 4.75 kHz, and 7.1 kHz, which can be attributed to other irregular loudspeaker distortions. Based on the THD response, negligible high-frequency distortions are seen for an earphone E1. The SPL response of E5 shows enhanced spurious resonances than other EEs at 1.5 kHz, and THD response shows an observable peak (7.7%) at 85 Hz. Similarly, E6 and E8 THD response shows a noticable peak of 6.9% (560 Hz) and 18.4% (710 Hz), respectively, which may be due to manufacturing defects and rub & buzz. The acceptable frequency response should be flat over the required frequency range, and the THD will be 10% below 20 dB so that the main signal can mask it. The SPL responses for E6-E9 are approximately similar in magnitude and pattern. They show the fundamental frequency in the range of 200-300 Hz, and the spurious resonance starts after 2-3 kHz. However, there is an appreciable difference in their low-frequency (below 200 Hz) THDs. Due to the low THD over the complete frequency range, earphone E10 is found as best designed. The earphones E2 and E3 show negligible low-frequency THD and few insignificant mid to high-frequency peaks. The earphone E4 shows a climb of 12.3% THD at 112 Hz. Similarly, an earphone E5 shows a prominent ridge of 16.5% THD at 2.5 kHz. The earphone E8 shows the highest THD (~18.4%) at 710 Hz, earphone E9 shows a hill in THD (~14.3%) at 85 Hz, and earphone E6 shows a somewhat reduced THD (~10%) between 20-70 Hz. Another earphone E7 shows 16.1% THD in the range of 20-70 Hz.

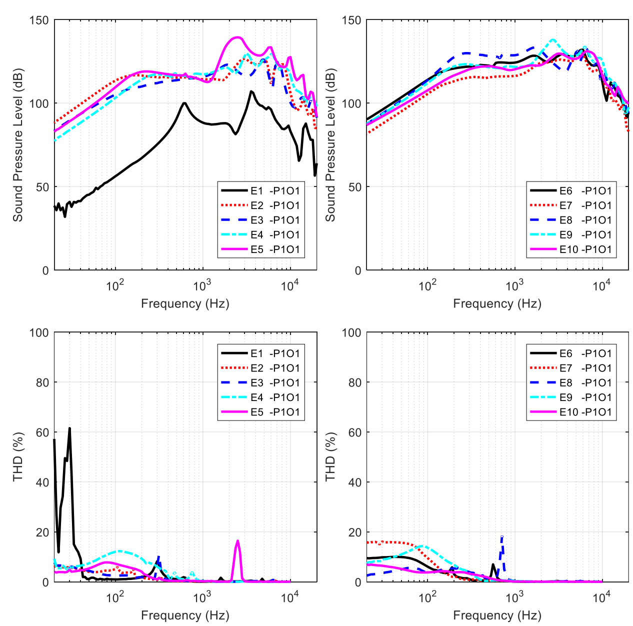


Figure 7: Frequency and THD response of Earphones 1-10 at position 1 and orientation 1.

For convenience, position 1 and orientation 1 is taken as reference (characteristic signature) for comparison of SPL and THD responses, which is widespread EE placement in the concha cavity. Figure 8 shows the SPL and THD responses of earphones E1-E10 at position 1 and orientation 2. Due to the change in orientation of EEs, there is a monotonous rise (except an initial dip at 22.4 Hz (Figure 7)) in the SPL of earphone E1 by 20-30 dB without affecting the characteristics of the curve. The changes in the SPL are due to a change in the position of the sound source about ERP, the increased volume of the cavity between EE surface and ERP, and circumferential support to the inclined earphone by the tragus. However, this may lead to sound leakage from the anterior notch and the tragal notch. This position change allows a smooth passage of the sound from EE to the tympanic membrane (eardrum) through an ear-canal. Most of the SPL responses (except E3) shows an increase from orientation 1 to orientation 2. For earphones E2 and E8, the SPL reduces by 7-12 dB and reaches up to 1.7 kHz. Similarly, for earphones E9 and E10, the SPL reduces by 5-10 dB up to 1.7 kHz. On the contrary, for an earphone E3, the SPL enhances by 5-10 dB up to 1.9 kHz. There is no significant variation in SPL of earphone E4 to E7. Above mentioned observation shows that the SPL depends on the orientation of EEs for the same position till the start of spurious resonances. For all earphones, the SPL response remains same after the start of spurious resonances For all earphones, the SPL response after the start of spurious resonances remains nearly the same and a spikier response after the second resonance analogous to Figure 7. The SPL responses of E6-E10 remains almost similar to Figure 7.

Based on the THD curve, it is found that the low-frequency THD peak is affected due to a change in the position of earphone E1, which results in an excessively large THD as a characteristic of E1. The THD response of E1 rises to 87.9% at 30 Hz with a small split peak of 47.7 dB at 25 Hz; however, mid and high-frequency THD almost remains the same. For remaining EEs, there are insignificant changes in the THD from orientation 1 to orientation 2, except for earphone E9, which shows a new peak of 5.4% THD at 2.8 kHz. It is found that EEs E1, E4, E6, E7, and E10 demonstrates noticeable low-frequency THDs at both the orientations, and is attributed to the higher sound leakage to the rear side of the earphones due to slits (openings that are bigger than sound holes) in the cavity cover. Based on the above hypothesis, one can conclude that the SPL responses are dependent on the orientations; however, it does not affect THD of EEs by a significant amount.

Figure 9 shows the SPL and THD responses of all EEs at position 2 and orientation 1. There is a monotonous rise in the SPL of earphone E1 without affecting the characteristics of the curve. More irregular SPL is found below 75 Hz. The low-frequency response of E1 is improved in magnitude on comparing with Figure 7. However, a significant change is found in the low-frequency THD trend and magnitude below 40 Hz. Thus, a strong correlation between SPL and THD is established with this behavior. The remaining THD curve remains the same. The responses of all other EEs remains similar but higher than that of E1. When compared with Figure7,

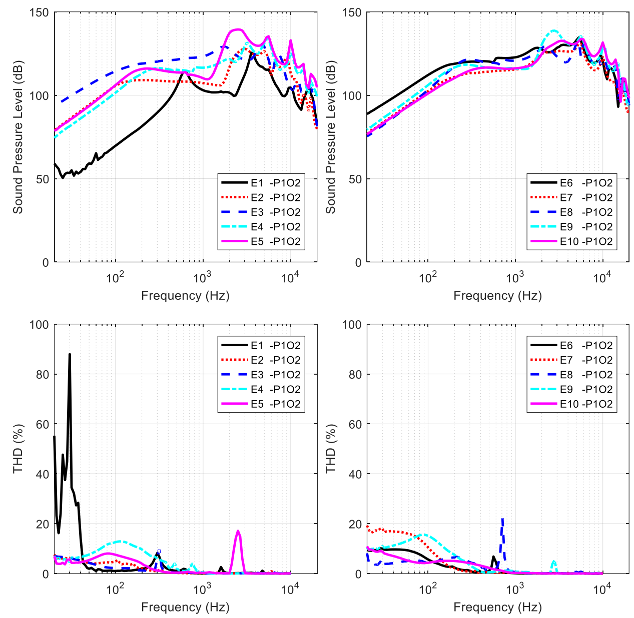


Figure 8: Frequency and THD response of Earphones 1-10 at position 1 and orientation 2.

for earphone E2, there is a reduction in the SPL by 15 dB till 1.7 kHz. For earphones E4 and E8, the decrease in SPL by 3-7 dB is found up to 1.9 kHz. Similarly, for earphones E5 and E6, reduction in SPL by 5-10 dB is observed until 1.9 kHz. On the contrary, there is no significant change in the SPL below the start of spurious resonances for earphones E3, E9, and E10. After the start of spurious resonances, the SPL response does not change by a significant amount. Some peaks are found in the THD responses viz. 10.4% at 315 Hz for E3, 3.9% at 475 Hz and 3.3% at 750 Hz for E3, 13.4% at 2.5 kHz for E5, 5.6% at 560 Hz for E6, and 19.9% at 710 Hz for E8. Except for E5 and E8, the rest of the THD peaks are insignificant. Also, some observable variations are found in the low-frequency THD responses for E7, which might be due to the biggest slit in the earphone cavity cover. The rest of earphones exhibits no change in their THD.

The SPL and THD responses of all earphones at position 2 and orientation 2 are given in Figure 10. The SPL response of earphone E1 mimics its SPL response observed in Figure 8. However, a significant change in the low-frequency THD can be found. A considerable variation in the magnitude of THD is observed as compared to Figure 9 and high THD is found below 40 Hz. For all the remaining EEs, the SPL responses below the start of spurious resonances reduce than their responses in Figure 7. Specifically, the SPL response of earphone E2 reduces by 6.1-8.3 dB in the 100 Hz-1.7 kHz. The SPL responses of E3 and E4 is lowered by an insignificant amount, similarly for E5 and E6 it lowers by 6-9 dB, and that of E7, E8, E9, and E10 drops by 0-2.4 dB, 8.8-12 dBSPL, 7-8.6 dB, and E10 3-7.1 dB, respectively. The THD responses of all EEs remains the same except for earphone E1. For earphone E1, besides the original peak, two distinct peaks are visible at 25 Hz and 37.5 Hz having 75.4% and 87.9% THD, respectively. The rest of the THD response of earphone E1 remains unaffected. Some observable variations in THD response are also found for E7. E9 also shows a new peak of 4.6% THD at 2.8 kHz. The rest of EEs do not show any deviation across the complete measurement range (Figure 7).

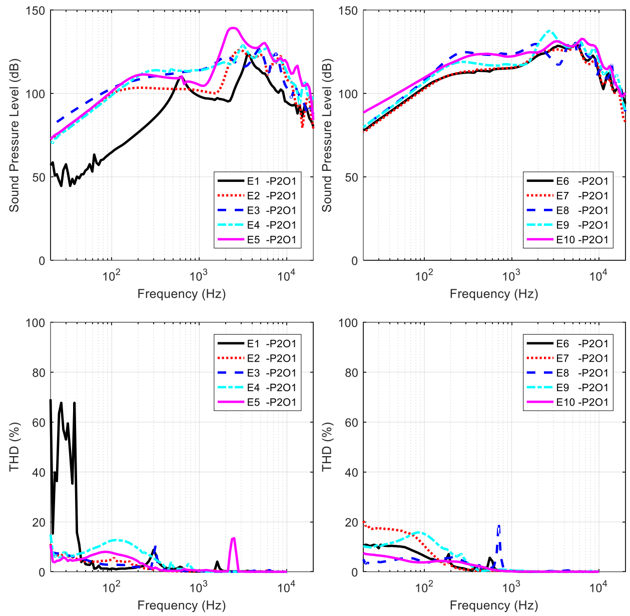


Figure 9: Frequency and THD response of Earphones 1-10 at position 2 and orientation 1.

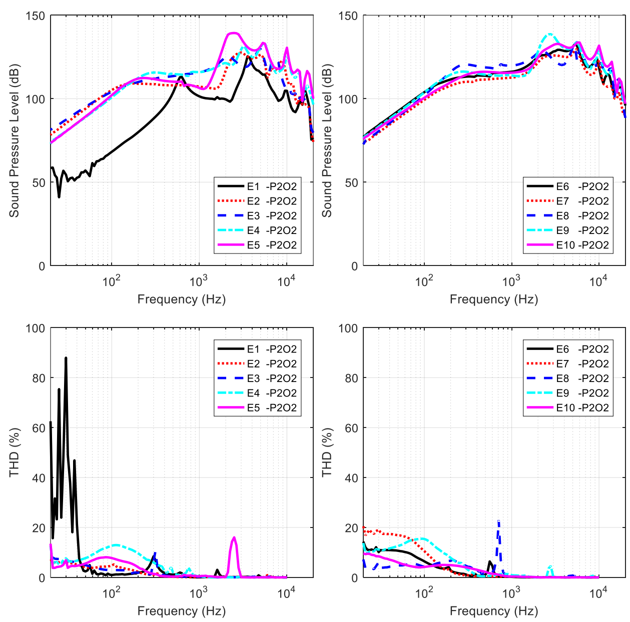


Figure 10: Frequency and THD response of Earphones 1-10 at position 2 and orientation 2.

The SPL and THD responses of all EEs at position 3 and orientation 1 are presented in Figure 11. The highest SPL response is seen for earphone E1. Also, its low frequency (20-60 Hz) irregular response became straight with a constant slope. It indicates that during this position of earphones, the sound source remains on axis with the opening of an ear-canal. This highest SPL response shows the corresponding lowest THD response as expected. Only one THD peak (47.3% 30 Hz) is observed, however the THD response over 40 Hz remains unaffected. For E2 to E10, after the start of spurious resonances, no variations are observed in the SPL responses ; however, below it, differences are found. The significant finding of these readings is that the highest SPL responses are seen for all earphones. The SPL response improves by 2-3 dBSPL for E2 and E8. Similarly, the SPL response improves by 7-10 dB for E3 and E10. Nearly 4-5 dBSPL improvement in the SPL response is also found for E5, E6, and E9. The most significant improvement in SPL response (8-15 dB) is observed for E4. Surprisingly, a decline by 2-5 dB in the SPL response is found for E7. The THD responses of all remaining earphones (E2-E10) remains unchanged when compared with Figure 7.

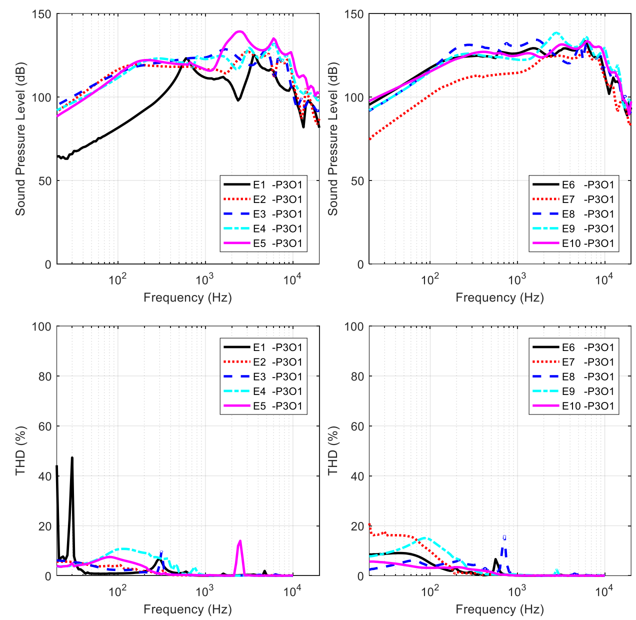


Figure 11: Frequency and THD response of Earphones 1-10 at position 3 and orientation 1.

The SPL and THD responses of all ten earphones at position 3 and orientation 2 are given in Figure 12. There is a monotonous rise in the SPL of E1, but with a slight reduction in the magnitude and with more low-frequency irregularities than given in Figure 11 without affecting the characteristics of the curve (Figure 7). The reduction in the SPL responses of E2, E8, and E9 by 2.4-11 dB is seen below the start of spurious resonances. The SPL responses of E3 and E10 exhibits insignificant variations in Figure 7. Additionally, the SPL responses of E4, E5, E6, and E7 shows a reduction by 2-3 dB, 5-6 dB, 3-5 dB, and 6-10 dB, respectively, with their responses (Figure 7). Significantly, the responses remain invariant after the start of spurious resonances for all EEs. The THD responses of all other EEs remain unchanged.

4 Discussion

Based on the relevant studies of human ear and variations in the anthropometric dimensions of ear it is expected that sound perception by different individuals from the same earphone shall be different. Some parameters like earphone shape, earphone size, earphone position in the concha, earphone orientation in the concha, earphone circumference and concha surface seal, earphone force on concha surface, etc., also contribute towards it. Extending further, this study proposes and establishes that the sound perception by the sameindividuals from the same earphone shall be different due to different orientations and positions of EE in the concha. The sound impression by the right and left ear of the same human being shall also be prone to differ due to dimensional variations. This study also infers that the prolonged usages of EE may also cause to change the orientation, position, force, earphone circumference and concha surface seal, etc. which may cause variation in the SPL generated across the tympanic membrane.

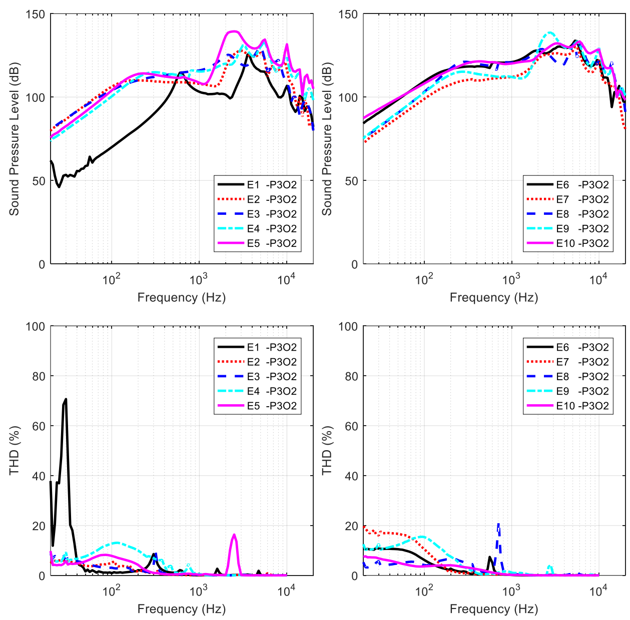


Figure 12: Frequency and THD response of Earphones 1-10 at position 3 and orientation 2.

The effect of the position of earphones in the concha cavity is explicitly seen in previous sections. In position 1, the earphone is placed firmly against the concha surface, and its wire lies along with the tragal notch. Hence, the front of the earphone remains closest to the concha and the ear-canal opening. Due to which the shape of the pinna external cavity gives reduced volume, along with small or no space for the sound leakage through space near the earphone wire. At this position, the miniature loudspeaker of the earphone might not remain close to the ERP, and the concha surface proximity due to reduced pinna external cavity volume shall provide resistance to the sound transmission through the air. Additionally, the volume across the tragal notch shall add in the pinna external cavity volume.

Similarly, at position 3, the earphone is placed firmly against the concha surface, and its wire lies along with the anterior notch. The anatomy of the tragal notch and anterior notch is different. Hence, a possibility that the front surface of the earphone remains firmly placed against the concha surface. However, at this position, the earphone casing firmly presses against the concha and possibly closes the volume across the tragal notch. Such anatomical dissimilarities result in variation in the earphone surface with an ear-canal opening and ERP. This results in the shape of a pinna external cavity that gives the least volume, along with small or no space for the sound leakage through the space near earphone wire and anterior notch.

At position 3, the earphone is placed so that its wire lies across anti tragus. The anatomy of anti tragus in reference to the anterior notch and tragal notch is different. The anti tragus is the projected portion, which results in the lifting of earphone wire from the concha surface. This position of earphone moves earphone front surface (diaphragm of a miniature loudspeaker) away from the ear-canal opening and ERP, but at the same time, there shall be an increase in the volume of the pinna external cavity.

The frequency responses of earphones were checked at 3 positions and 3 variations and found that the sound pressure variations are found without any deviation in the trend (shape) of the curve. Specifically, for E1, the lowest SPL is found at P1O1, and the highest SPL is found at P2O1 and the variation in the range of 20-25 dB across the complete measurement range. For E2, the lowest SPL is found at P2O1, and highest SPL is found at P3O1 and the variation in the range of 18-22 dB up to 1.07 kHz, for the remaining frequency range, all responses remain within 2-5 dB. E3 generates the lowest SPL at P2O1 and highest at P3O1 and the variation in the range of 10-15 dB up to 1.08 kHz, while responses remain within 2-5 dB for remaining frequency range. For E4, the response remains in 5-8 dB over the complete range at all positions and orientations except for P3O1, which is above all other responses by 10-20 dB up to 1.06 kHz. The frequency response of E5 indicates that at P2O1, the lowest SPL is observed, and at P3O1, the highest SPL is seen with the difference of 15-20 dB up to 1.02 kHz. However, the rest of the response remains in 3-5 dB. The E6 shows the lowest SPL at P2O1 and the highest SPL at P3O1 in the range of 15-20 dB up to 1.06 kHz, with the rest of the response in 3-5 dB range. The least variation in the response is observed for E7. The lowest SPL is found at P3O2 and the highest SPL at P1O1 with a range of 3-10 dB. The responses of E8, E9, and E10 are similar to E3.

It is estimated that the change of SPL by 3 dB is analogous to the change of sound intensity by a factor of 2. Similarly, 6 dB variation in SPL is equivalent to sound pressure variation by a factor of 2. An increase in the SPL by 10 dB corresponds to the sensation of doubling in volume (loudness) of sound. The perception of sound by a human ear is a very subjective process. A human ear as an organ can detect 1 dB change in the SPL. It cannot quantify sound in terms of the sound intensity and/or a sound pressure but can quantify it in terms of loudness. Thus, the quantitative analysis further reveals that a 10 dB change in SPL correspond to 10, 3.16, and 2 times changes in sound intensity, sound pressure, and perceived loudness. Based on the above hypothesis, it has been concluded that the variation in SPL is going to affect the perceived loudness of the sound. Additionally, on the other hand, based on an equal energy principle, a daily safe exposure time limit for a human changes/reduces by half for every

3 dB change/increase in the SPL, respectively. In particular, 80 dB sound exposure for 8 hours (say safe limit) is equivalent to 83 dB for 4 hours and 86 dB for 2 hours. It reduces further to 95 dB for 15 minutes. It is essential to recognize that the daily sound exposure limit of a human being is additive and commutative. Quantitatively, it implies that if one is exposed to 80 dB for 4 hours in a day, then for the safe exposure on the same day, he may be exposed to 83 dB for 2 hours or 86 dB for 1 hour only. Exposure beyond this limit may cause permanent hearing disorder(s).

Referring to anthropometry of the human ear [9, 10] for successful design, development, and market penetration of ear-related products, its correlation with the outcome of the current study of ten different EEs shall become inevitable. The measurement of SPL and THD of all earphones have been carried out by HATS-B & K Type 4128, which is the universally accepted manikin. The HATS is having a built-in ear and mouth simulators for genuine imitation of the acoustic properties of an average adult human head and torso. For this study, only the right and left pinnae of the silicone material are essential for investigations, since the earphones are in direct contact with the pinna at all positions and orientations during the measurements. The silicone pinnae resembles the human ear strictly in appearance and dimensions and are soft with hardness Shore-OO 35. The silicone rubber is a polydimethylsiloxane or silicone-based elastomer, which is widely used in medical, food, consumer industries, military, and aerospace. Moreover, both pinnae support insertion and sealing of earphones and are placed hanging in the concha. The placing of EEs in the pinna is in fixed relation to the ERP and EEP [1]. As depicted in Figures 2 and 3, all main dimensions of pinna become most significant after putting earphones in the concha cavity. Individually, L_a, L_{ab}, L_{ba}, and L_{ca} decides how effectively the crus tragus, tragus, and anti tragus encapsulates earphone cover during its use. So, for particular uses and a particular earphone, these dimensions establish definite relations with EEP and ERP. However, as reported in the literature [9, 20], the right ear is larger than the left one, so all the above-mentioned dimensions differ slightly. When the earphone is placed in the concha, it may lead to a slight difference in relation to EEP and ERP. As a result of these variations, the SPL and THD responses of the right and left ear shall vary. When counted all six possible combinations of positions and orientations of earphones in the concha cavity, the SPL and THD responses and hence, the perceived loudness (sensation of sound) shall be different. Considering the gender dependence of L_a, L_b, and L_c (male with larger ear dimensions than female), a particular earphone, when used by different gender, may result in variations in the SPL and THD responses, which ultimately leads to deviations in the perceived loudness of sound. It is also a prevalent fact that each human may have unique pinnae (size, shape, thickness anatomy, orientation, etc.), so the perceived sound by a particular earphone has to be strongly subject dependent.

Referring to the customer's habit of earphone use which may include, placement of earphone in concha, the volume of sound produced, type of sound produced, duration of use of earphone, environment in which earphone has been used (noisy or silent), time during which earphone is used, etc., one can find appreciable variations in the SPL and THD responses. The volume of sound produced by an earphone depends on the preference of the user for that sound, so the perceived loudness is as per the likings of the user, which in technical terms is analogous to the SPL response. The type of sound produced has strong dependence on the loudness of the sound (ultimately with the SPL response). Additionally, the user prefers to listen to favorite sound loudly than the other sound. In a silent environment, the user requires less loudness due to almost no interference of external sound from the sound produced by the earphone. However, in a noisy environment, a lot of inferencing sound is enclosed in the surrounding which results in masking of the sound. Hence, earphone user has to increase the loudness. A movement of the user's head can lead to the movement of earphones in the concha. Hence it induces the changes in L_a, L_{ab}, L_{ba}, and L_{ca}, and therefore causes the changed SPL response of the earphones. Referring to the user's health and condition of hearing system, may include, occupational sound exposure, hearing loss (as per audiogram), anatomy of an ear-canal, hairs in an ear-canal, body's natural ear wax in an ear-canal, moisture in an ear-canal, middle-ear and inner-ear anatomical differences, condition of auditory nerve (auditory pathways), condition of the brain stem which is responsible for the sound perception, etc. can affect the perceived loudness (SPL response). Mainly, an occupational sound exposure of user depends on the occupation of the user, duration of the occupational sound exposure, and the SPL to which the user is exposed during the occupational sound. An user's hearing loss affects the volume setting of earphones during use. Specifically, an user with no hearing loss would prefer low loudness than the user with mild hearing loss. However, an user with profound hearing loss needs appreciably high loudness. The anatomy of an ear-canal, hairs in an ear-canal, body's natural ear wax in an ear-canal, and moisture in an ear-canal also affects the perceived loudness of sound. The middle-ear and inner-ear anatomical differences, however small affects the perceived loudness. A condition of an auditory nerve (auditory pathways) and a condition of the brain stem, is responsible for sound perception and also accountable for the perceived loudness of the sound. Hence, all these factors are demands for certain loudness that is specific to the SPL responses. Discussing the technological supremacy of the earphone, includes cost of earphone, connectivity of earphone (wired or wireless), earphone with or without ear-clip, noise isolation (passive noise isolation) ability of earphone, anti-noise cancellation (active noise cancellation) facility of earphone, volume controllability (ear touch navigation) of earphone, etc., can also affect the SPL variations and the perceived loudness. High-cost earphones have better SPL and THD responses than other earphones. The wireless earphones are more stable in the concha cavity due to non interference of wire and the user's movement during earphone use. Earphones with ear-clip are better placed in the concha than the earphone without clip. Earphones with noise isolation and anti-noise cancellation are more superior than the earphone without it. The noise isolation earphone shall provide better stability to the earphone in the concha and also avoid the sound from the external environment to the concha cavity. The earphone with active anti-noise cancellation would provide the digital signal processing based methodology for recording background noise and subsequent inversion of it (creation of anti-noise). Finally, the addition of inverted noise with the input of earphone sound selectively filters out noise. Thus, all these factors also cause SPL and THD response variations.

5 Conclusion

Based on the observation and discussion, it can be concluded that EE can be placed anywhere in the concha of a human ear. As a result of routine practices, three positions and two orientations of earphone has been adjudged as the most significant. The SPL and THD responses for all earphones at position 1 and orientation 1 (which is the most common placement style of EE) can be declared as a benchmark. Based on the responses, it has been concluded that there has been variation in SPL and THD responses due to change in position and orientation. The responses at position 1 and orientation 1 are dominating and reflected in the SPL and THD responses of all earphones at all positions and orientations. It has been concluded that the SPL responses can be divided into three sections. Each section shows an unique trend and exclusive effect on the SPL response. The variation in responses finally affects the amount of sound reaching the eardrum for further processing. The proposition (10 dB changes in SPL correspond to 10, 3.16, and 2 times changes in sound intensity, sound pressure, and perceived loudness) leads to the interpretation that variation in the SPL definitely affects the perceived loudness of sound. Since the daily sound exposure limit for a human being is additive and commutative, variations in the SPL illustrated may have a significant effect on the daily sound exposure limit in hours. Finally, the impact on the perceived loudness (SPL response) has been found specific and user-dependent about the ear dimensions, user habits, and practices.

Acknowledgments

The authors thank the National Science Council, Taiwan for financial support under contract numbers : MOST 106-2218-E-002-004 and MOST 106-2622-8-035-002-TE3. The authors also thank Merry Electronic Corp., Taichung, Taiwan and Listen Inc. for supplying the technical support and SoundCheck software. Additionally, authors would like to express high appreciation to Dr. Kemo Badiane of Nanfang College of Sun Yat-Sen University, Guangzhou, China for proofreading and correcting the French abstract.

References

[1] International Telecommunication Union. ITU-T Recommendation P.57, series P: telephone transmission quality, telephone installations, local line networks, objective measuring apparatus, artificial ears. http://eu.sabotage.org/www/ITU/P/P0057e.pdf (2012).

[2] Bruel & Kjaer. Product data, B&K, head and torso simulator - Type 4128. http://www.bksv.com/ (2017).

[3] S. Jønsson, B. Liu, A. Schuhmacher, and L. Nielsen Simulation of the IEC 60711 occluded ear simulator *In Proc. 116th Audio Engineering Society Convention*, paper 6162, Berlin, Germany, May (2004).

[4] J. J. Wojcik and P. G. Cardinal New advanced methodology for near field measurements for SAR and antenna development *In Proc. IEEE Symposium on EMC*, pages 909-913, Seattle, Washington, Aug. (1999).

[5] K. A. J. Riederer and R. Niska Sophisticated tube headphones for spatial sound reproduction *In Proc. 21st International Conference: Architectural Acoustics and Sound Reinforcement*, paper 000085, St. Petersburg, Russia, June (2002).

[6] D. G. Ćirić and D. Hammershøi Coupling of earphones to human ears and to standard coupler *Appl. Acoust.* 120(4): 2096, (2006).

[7] M. Tikander Modeling the attenuation of a loosely-fit insert headphone for augmented reality audio *In Proc. 30th International Conference: Intelligent Audio Environments*, paper 27, Saariselkä, Finland, March (2007).

[8] X. Zhiwen, S. Juncong, L. Yu, and R. Dan Calibration of headphones and earphone with KEMAR *In Proc. 2nd International Congress on Image and Signal Processing*, 978-1-4244-4131-0/09, Tianjin, China, Oct. (2009).

[9] B. S. Liu Incorporating anthropometry into design of ear-related products *Appl. Ergon.* 39(1): 115, (2008).

[10] N. P. Erber Variables that influence sound pressures generated in the ear canal by an audiometric earphone *J. Acoust. Soc. Am.* 44(2): 555, (1968).

[11] J. Zwislocki, B. Kruger, J. D. Miller, A. F. Niemoeller, E. Shaw, and G. Studebaker Earphones in audiometry *J. Acoust. Soc. Am.* 83(4): 1688, (1988).

[12] A. Kulkarni and H. S. Colburn Variability in the characterization of the headphone transfer-function *J. Acoust. Soc. Am.* 107(2): 1071, (2000).

[13] S. E. Voss, J. J. Rosowski, C. A. Shera, and W. T. Peake Acoustic mechanisms that determine the ear-canal sound pressures generated by earphones *J. Acoust. Soc. Am.* 107(3): 1548, (2000).

[14] M. Ruiz, B. Feuereisen, D. Machon, and M. Recuero Factors contributing to the uncertainty in circumaural earphone calibration for audiometric testing *Appl. Acoust.* 66(9): 1033, (2005).

[15] S. J. Pawar and J. H. Huang Effect of sponge and position on the frequency response and total harmonic distortion of earbud-type earphone *J. Chin. Soc. Mech. Eng.* 33(6): 537, (2012).

[16] C. H. Huang, S. J. Pawar, Z. J. Hong, and J. H. Huang Earbud-type earphone modeling and measurement by head and torso simulator *Appl. Acoust.* 73(5): 461, (2012).

[17] S. Ahmed, S. Fallah, B. Garrido, A. Gross, M. King, T. Morrish, D. Pereira, S. Sharma, E. Zaszewska, K. Pichora-Fuller Use of portable audio devices by university students *Can. Acoust.* 35(1): 35, (2007).

[18] F. A. Russo, E. M. Abdoli-E, L. Zizhen, A. Jelen A field study of preferred listening levels for music played on personal stereo players *Can. Acoust.* 35(3): 82, (2007).

[19] I. Ibrahim, R. Malcolmson, M. Jennings, M. Cheesman Effect of headphone type on listening levels and localization abilities of portable audio device users in quiet and traffic noise *Can. Acoust.* 37(3): 176, (2009).

[20] W. Lee, H. Jung, I. Bok, C. Kim, O. Kwon, T. Choi, and H. You Measurement and application of 3d ear images for earphone design *In Proc. The Human Factors and Ergonomics Society 60th International Annual Meeting*, pages 1052-1056, Washington, DC, USA, Sept. (2016).

[21] W. Klippel Assessing large signal performance of transducers *In Proc. 11th Regional Convention of the Audio Engineering Society (AES)*, Japan, July (2003).

[22] W. Klippel Dynamic measurement and interpretation of the nonlinear parameters of electrodynamic loudspeakers *J. Audio Eng. Soc.* 38(12): 944, (1990).

[23] W. Klippel Diagnosis and remedy of nonlinearities in electrodynamical transducers *In Proc. 109th Audio Engineering Society Convention*, paper 5261, Los Angeles, USA, Sept. (2000).

[24] W. Klippel Loudspeaker nonlinearities-causes, parameters, symptoms *J. Audio Eng. Soc.* 54(10): 907, (2006).

[25] W. Klippel and R. Werner Loudspeaker distortion – measurement and perception part 1: regular distortion defined by design *In Proc. 26th Tonmeistertagung*, Leipzig, Germany, Nov. (2010).

[26] C. Chun, S. J. Pawar, S. Weng, Y. C. Shiah, and J. H. Huang Effect of nonlinear stiffness on the total harmonic distortion and sound pressure level of a circular miniature loudspeaker-experiments and simulations *IEEE Trans. Consum. Electron.* 58(2): 212, (2012).

[27] S. J. Pawar, S. Weng, and J. H. Huang Total harmonic distortion improvement for elliptical miniature loudspeaker based on suspension stiffness nonlinearity *IEEE Trans. Consum. Electron.* 58(2): 221, (2012).

[28 S. J. Pawar, S. Weng, and J. H. Huang Experimental verifications and simulations of magnetic motor of circular miniature loudspeaker for total harmonic distortion improvement *Appl. Mech. Mater.* 87: 136, (2011).

[29] S. Weng, S. J. Pawar, and J. H. Huang Magnetic motor nonlinearity modifications for total harmonic distortion improvement of an elliptical microspeaker *IEEE Trans. Magn.* 48(12): 4811, (2012).

[30] P. Hiselius My ears are alight *Can. Acoust.* 44(1): 25, (2016).

[31] Potential Health Risks of Exposure to Noise from Personal Music Players and Mobile Phones Including a Music Playing Function. Scientific Committee on Emerging and Newly Identified Health Risks SCENIHR, European Commission, Brussels, Belgium (2008). https://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_017.pdf.

[32] Hearing loss due to recreational exposure to loud sounds A review, World Health Organization, (2015). https://www.who.int/pbd/deafness/Hearing_loss_due_to_recreational_exposure_to_loud_sounds.pdf.