Design and Equivalent Circuit Method Based Simulation of 3-D Printed Supra-Aural Headphones for Accelerated Product Development

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Abstract

This work reports the design of supra-aural headphones based on the commercially successful supra-aural headphone available in the market. Using the fundamental outline of the supra-aural headphone, all the headphone components have been designed along with the micro-speaker cavity to house the corresponding micro-speaker in the headphone. The sound can be radiated from the front and rear side of the vibrating diaphragm of the micro-speaker. Four headphones have been fabricated in various ways by which the sound radiated from the rear side of the micro-speaker contributes to the sound produced by the headphone. Specifically, in the first headphone, there is no sound from the micro-speaker to the rear side of the headphone since the headphone housing is closed. Thus, the sound remains in the rear cavity of the headphone only. In the second headphone, the sound radiated to the rear side of the micro-speaker diaphragm is diverted to the front side of the diaphragm in the front chamber and collectively radiated to the front side of the headphone along with the sound radiated by the front side of the micro-speaker. In the third headphone, the sound radiated by the micro-speaker diaphragm to the rear side is allowed to move to the front side of the headphone independently without interference with the sound radiated by the front side of the micro-speaker. However, in the fourth headphone, the sound radiated by the rear side of the micro-speaker is radiated to the rear side of the headphone due to the holes provided in the headphone casing to the rear side. The 3-D printer entitled "BQ-Witbox" was made by BQ, a Spanish company. The BQ-Witbox is a fused deposition modeling-based 3-D printer that uses a 1.75 mm polylactic acid filament. Simultaneously, all four headphones and micro-speaker have been modeled by equivalent circuit method and subsequently simulated. Furthermore, the Thiele/Small parameters (commonly abbreviated T/S parameters) have been measured for use in the equivalent circuit. The measurement for the frequency response of the micro-speaker has been carried out using standard measurement protocol in an anechoic chamber. Analogously, the frequency response of all the headphones has been measured using an artificial head that is called "Head and Torso Simulator" and commonly mentioned and abbreviated as "HATS" in an anechoic chamber. The measurement and simulation of the micro-speaker have shown excellent agreement. Furthermore, the measured and simulated frequency responses of all four headphones have depicted acceptable agreement. This work concludes the effectiveness of 3-D printing in accelerated product development and the use of resourceful equivalent circuit methods for simulation.

Keywords:3-D printing, Anechoic chamber, Equivalent circuit method, Frequency response, Headphones

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Introduction

Today, headphones might symbolize the most authoritative inflection point in music history. However, study/research article on headphones is seldom available in academic journals/conference proceedings owing to their commercial value, industrial importance, competitive environment, and market potential1. As per the records, the first patent was proposed for an electrodynamic transducer in 1878. Since 1880, telephone operators have initiated the use of individual earpieces. However, personal listening with headphones has been started in 1890. Subsequently, electrophones came into the market and have been familiarized for the local opera house for music performances by 1895[2]. One can identify Nathaniel Baldwin's "Radio Head-Set" (1910) as the first headphone. This early device has two ear cups with loudspeakers and a headband connecting them that can be rested against human pinna. After the invention and marking of loudspeakers in 1924 by Eugen Beyer, Beyerdynamic in 1937 introduced dynamic headphone that can unarguably be adjudged as the World's first "Dynamic headphone". In 1958, the credit for invention and successful market penetration of first-ever stereo headphone goes to Mr. John C. Koss, an American jazz musician, who later on founded Koss Corporation (Milwaukee, USA). With efforts of Koss Corporation, a new era has stated in music and sound production. Since then, Koss Corporation has marketed more than 100 headphones. On the same track, another giant, Sony Corporation invented Walkman in 1979 and successfully marketed it. In the quest for better and uninterrupted sound, by 1989 the noise cancelling headphones were conceived, initially, those were evolved for in-cabin pilots during flights operation and for noise free interaction during flight navigation. Since 2001 onwards, Apple's approach to intuitive user interface has transformed music listening by replacement of foamy headphones with more petite and space-age-looking earbuds. Bluetooth Technology (2008) has initiated another key development in the arena of headphones by making them wireless[3]. As per report[4], the worldwide headphones/earphones market has been estimated to be about 25.1 billion USD in year 2019. With the continuously growing demand, headphones/earphones market is predicted to propagate at an astonishing values of compound annual growth rate (CAGR) about 20.3% in the span of next eight years (2020-2027). Some of the primary factors responsible for motivating market growth could be increasing customer preference for enhanced audio experience and growing music industry that has been combined with mobile telephony expertise and global household internet infiltration across different continents.

Our group[5-7] also did substantial work on the miniature-loudspeakers (micro-speakers) by using the equivalent circuit method (ECM) to get a simulated frequency response and compare it with a measured response. Our group[8-9] has also reported an ECM modeling, simulation, and measurement of insert and earbud earphones. In this research, four headphones have been designed based on the general outline of the commercially successful supra-aural headphone available in the market. In this research, four headphones have been designed based on the general outline of the commercially successful supra-aural headphone available in the market. The design difference between headphones is the interaction of sound radiated by the micro-speaker to the front and rear side of the headphone. Using the 3-D printer BQ-Witbox (BQ, a Spanish company), all headphones have been fabricated and measured for frequency responses. Subsequently, equivalent circuit method-based models have been created to simulate frequency responses.

Headphones/Earphones

Headphones/Earphones Types

As per (ITU-T-Rec.P.51, 2005)[10], headphones/earphones can be classified into five main categories viz. (1) Circum-aural earphones (Open (Fig. 1 (a)) and closed (Fig. 1 (b)) which encloses the pinna completely and rests on the surface of the head by totally encapsulating human pinna, (2) Supra-aural earphones (Open (Fig. 1 (c)) and closed ((Fig. 1 (d)) are having at least 45 mm an external diameter (maximum dimension) such that during usages, it rest upon the human pinna and slightly pushes pinna, (3) Supra-concha earphones (Open (Fig. 1 (e)) are having an external diameter (maximum dimension) greater than 25 mm, but less than 45 mm. Thus, it is anticipated to touch the ridges of the concha cavity, (4) Intra-concha earphones (Open (Fig. 1 (f)) and closed (Fig. 1 (g)) are having and external diameter (maximum dimension) of less than 25 mm so that they can be easily placed within the concha cavity of the human ear, however, it is not expected that earphones should enter the ear canal, and (5) Insert earphones (Open (Fig. 1 (h)) and closed (Fig. 1 (i)) are having and external diameter (maximum dimension) much less than 25 mm so that earphone can partially or completely enter the ear canal. Apart from there are two significant points in reference to the human outer ear viz. (1) Ear reference point (ERP), which is located at the entrance to the listener's ear and is a virtual point for geometric reference used for calculating telephonometric loudness ratings and specification of acoustic input impedance and frequency sensitivity response and (2) Ear canal entrance point (EEP) which is also a virtual point that is a point situated at the centre of the ear canal opening, the ear canal starts from EEP. Both points are shown in Figs. 1 (a-i).

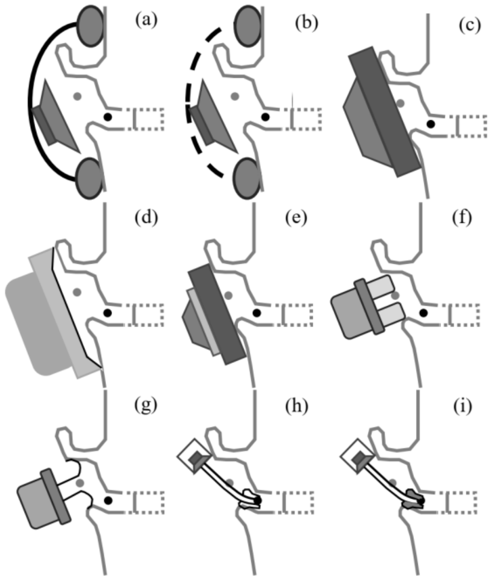


Fig. 1 — Main types of headphones/earphone (a) Circum-aural earphones (Open), (b) Circum-aural earphones (closed), (c) Supra-aural earphones (Open), (d) Supra-aural earphones (closed), (e) Supra-concha earphones (Open), (f) Intra-concha earphones (Open), (g) Intra-concha earphones (closed), (h) Insert earphones (Open), and (i) Insert earphones (closed)

Headphones/Earphones Components

The headphone consists of the following components viz. 1 - Headphone front cover, 2 - Diaphragm, 3 - Earmuffs cloth support frame, 4 - Earmuffs cloth, 5 - Vent, 6 - Front chamber, 7 - Rear chamber. 8 - Magnet, 9 - Polar piece, 10 - Rear (back) cavity, and 11 - Housing. In this work, four types of headphones (H1-H4) have been conceptualized, as shown in Figs. 2 (a-d). Precisely, the first headphone (Fig. 2 (a)) avoids the sound from the micro-speaker to the rear side of the headphone due to the completely closed headphone casing. Hence, the sound remains only in the rear cavity of the headphone and can't escape. The second headphone (Fig. 2 (b)) allows the diversion of the sound radiated to the rear side of the micro-speaker diaphragm to the front side of the diaphragm in the front chamber, thus, collectively radiating sound to the front side of the headphone with the sound radiated by the front side of the micro-speaker. The third headphone (Fig. 2 (c)) also allows the passage of the sound radiated by the micro-speaker diaphragm from the rear side of diaphragm to the front side of the headphone independently without interference with the sound radiated by the front side of the micro-speaker diaphragm. The fourth headphone (Fig. 2 (d)) allows the sound radiation from the rear side of the micro-speaker to the rear side of the headphone due to the holes provided in the headphone casing. For better understanding, the sound propagated from the front side of the micro-speaker diaphragm is shown by gray solid arrows and the sound that is radiated from the rear side of the micro-speaker diaphragm is specified by gray dotted arrows.

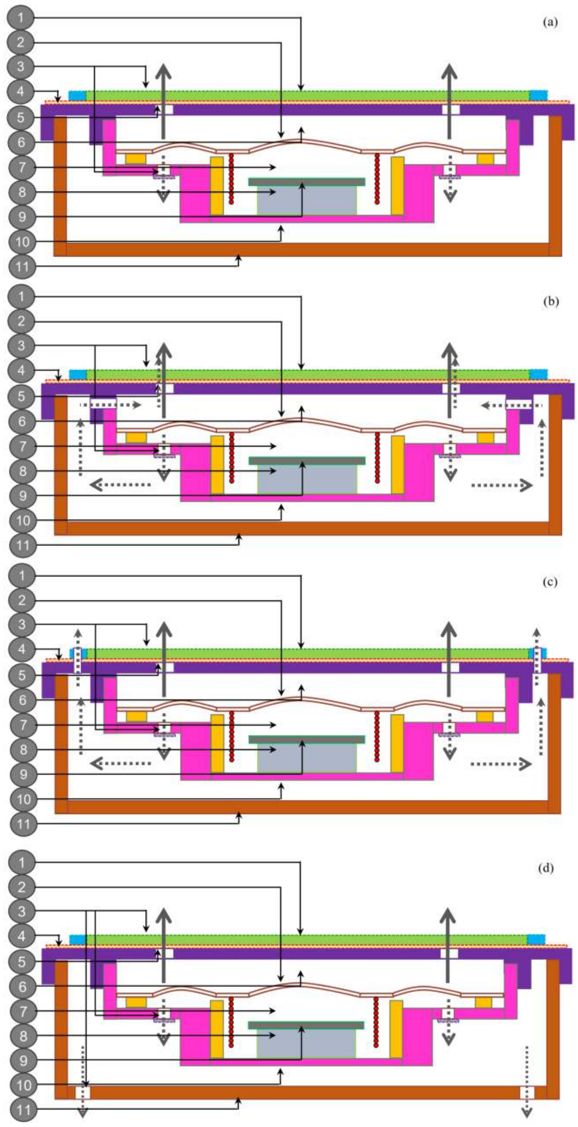


Fig. 2 — Schematic of (a) First headphone (H1), (b) Second headphone (H2), (c) Third headphone (H3), and (d) Fourth headphone (H4)

Headphones/Earphones Design and Fabrication

All headphones have been designed and drafted by using computer-aided design (CAD) software entitled "Creo Parametric" as per the schematics depicted in Figs. 2 (a-d). One can see the difference between the front cover and the headphone housing of H1-H4. The detailed CAD drawings are shown in Figs. 3 (a-d)

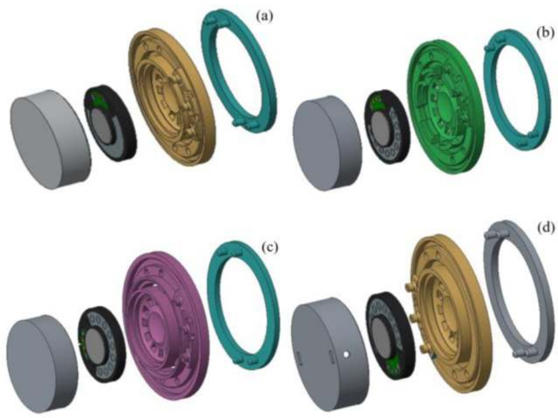


Fig. 3 — Schematic of (a) First headphone (H1), (b) Second headphone (H2), (c) Third headphone (H3), and (d) Fourth headphone (H4)

After confirming the CAD drawings with intended designs, the models have been sliced into a tomographic scan across several 2D planes and subsequently converted into G-code, which has been imported into a 3D printer to print the model. UltimakerCura has created the G-code. The G-code instructs the 3-D printer when to print, where to print, where to move, how much material to use, etc., and the 3D printer follows these instructions and builds the model in layer-by-layer mode. The G-code also includes 3D printing parameter settings, including material diameter, spray gun temperature, printing speed, printing density, and printing position.

Table 1 gives all the main parts of headphones which have been 3-D printed using a BQ-Witbox 3-D printer supplied by BQ[11], a Spanish company. The material used for printing is Poly-Lactic Acid (PLA) polymer, a biodegradable polymer. The filament of PLA has a diameter of 1.75 mm. The PLA polymer is one of the most common materials for 3D printers because it is odorless, easy to curl, insoluble in water, and will not be decomposed by UV. It is an excellent material for display products. The PLA plastic is made from a mixture of biomass materials such as corn starch and sugar cane derivatives. It complies with food grade and biodegradable standards and is suitable for all 3D printers. The assembled headphones are given in Table 2.

Table1—All main parts of headphones

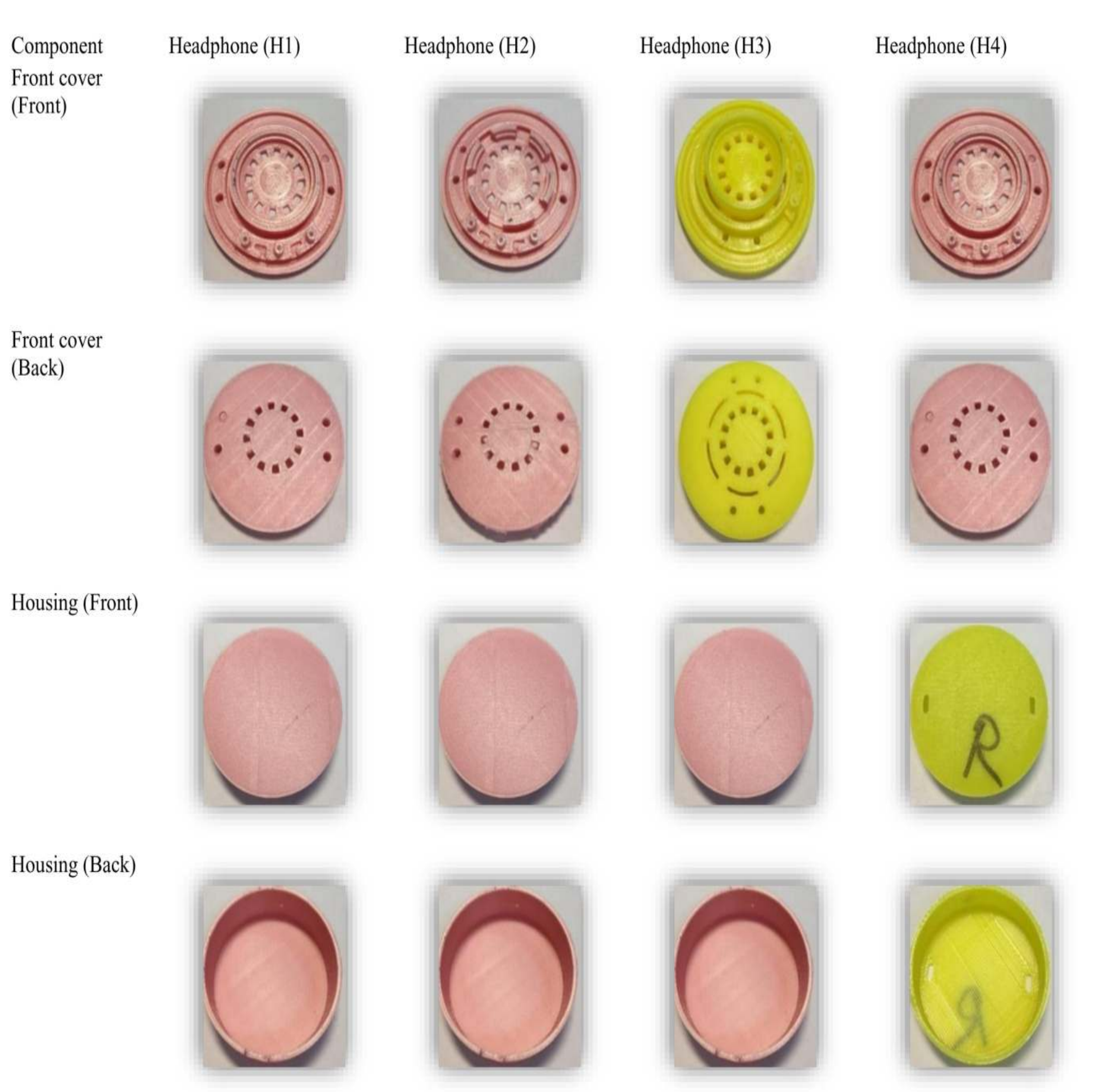
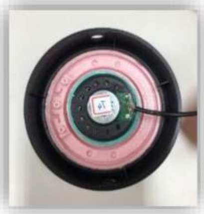


Table 2—All assembled headphones

Component	Headphone (H1)	Headphone (H2)	Headphone (H3)	Headphone (H4)
Headphone cub with microspeaker				
Headphone cup with microspeaker and housing				
Complete headphone				

Headphones/Earphones Simulation

Before the simulation of headphones, micro-speaker need to be discussed. Micro-speaker is mainly composed of a magnetic system, a vibration system, and a support system. The magnetic loop system comprises a magnet, an upper pole piece, and a lower pole piece, whose primary purpose is to create fixed magnetic field that is uniform which empower the voice coil to operate in the gap via reciprocating motion. The vibration system includes a voice coil and a diaphragm, which are responsible for receiving electric signals to drive the diaphragm, which in turn pushes the adjacent air particles to generate sound waves in the medium. The support system supports the entire micro-speaker by the housing and maintains overall stability under working conditions. A typical micro-speaker is shown in Fig. 4. Micro-speaker consists of the following components 1 - Diaphragm, 2 - Polar piece, 3 - Voice coil, 4 - Vent, and 5 - Magnet. The micro-speaker used in this work is DSH742-005, whose specifications are given in Table 3.

Table 3—Specifications of SH742-005

Parameter	Value	Remark
Impedance	32 ohm ±20%	At 1 kHz
Sensitivity	110 ±3dB	At 1 kHz with V(input) 5mW(400mV/B&K 4185)
THD	100 Hz - 200 Hz<25%	
	400 Hz - 10k Hz<15%	
Fundamental frequency (F_0)	80 Hz ±20 Hz	
Rated input	5 mW	
Max input	20 mW	

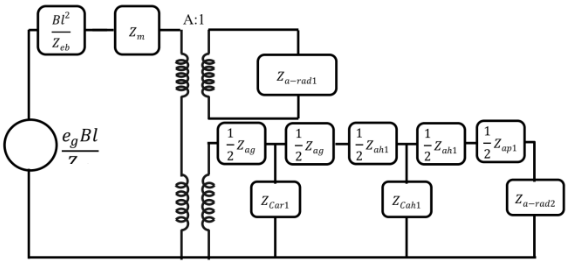


Fig. 4 — Schematic of a micro-speaker

As per the micro-speaker measurement standard industrial practices, during measurement the micro-speaker should is positioned on an infinite barrier so that only the sound waves radiated in the forward direction of the diaphragm are directly emitted outward (towards measurement microphone) and received by microphone at a distance of 10 cm from the center of the diaphragm. The equivalent circuit method model is presented in Fig. 5, and its simplified version is given in Fig. 6. All parameters and mathematical formulation of this micro-speaker are provided in our earlier work[12]. The prior knowledge of ECM[13] is essential for formulating equivalent circuits.

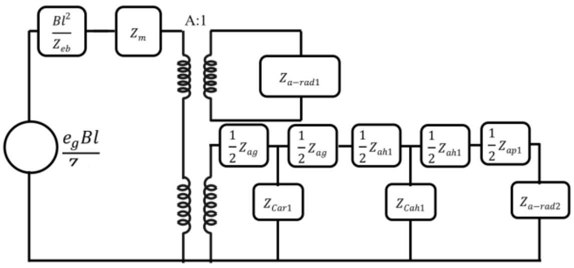


Fig. 5 — Equivalent circuit model of a micro-speaker

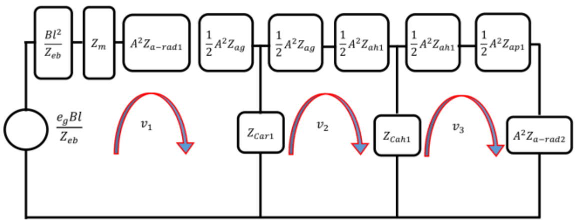


Fig. 6 — Simplified equivalent circuit of a micro-speaker

Similar to the micro-speaker, all headphones have been characterized by corresponding equivalent circuit models. These models are based on the headphone measurement schematics as per general industrial procedures. The measurement procedure includes headphone followed by earmuff. Thus, it should be positioned on HATS's silicone pinna such that the set-up mimics similarity with human sound hearing. Typical HATS have an artificial ear and IEC711 coupler. All parameters and mathematical formulation of headphones H2-H4 are reproduced from our earlier work[14]. However, the equivalent circuits of all headphones are given in Figs. 7 (a-d).

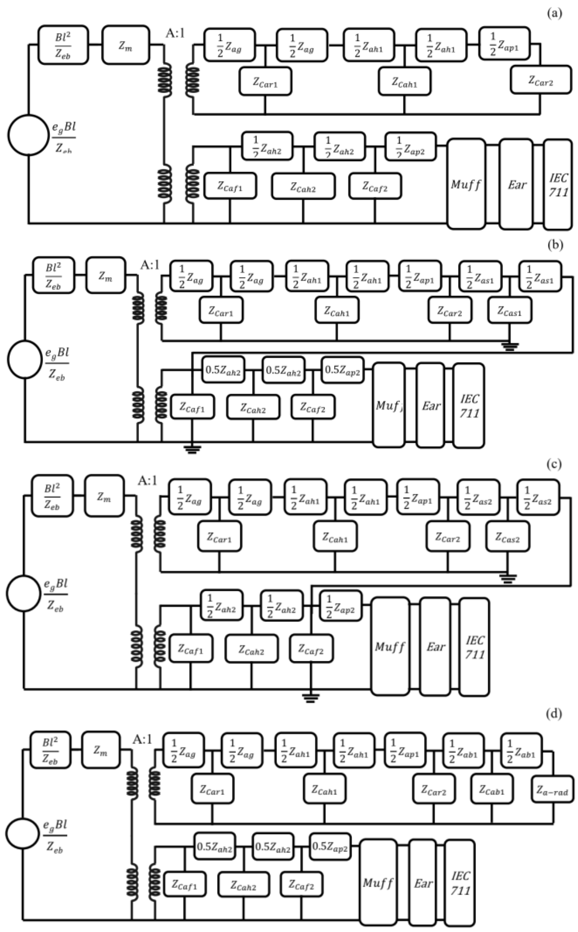


Fig. 7 —Equivalent circuit of headphones (a) H1, (b) H2, (c) H3, and (d) H4

Frequency Response Measurements

The T/S parameter of the micro-speaker (DSH742-005) has been acquired by using laser scanning vibrometry (laser displacement sensor) by the KLIPPEL system which has been established by KLIPPEL, Germany. Further, for the measurement of frequency responses of micro-speaker and headphones, SoundCheck software has been employed.

The SoundCheck has been developed by Listen Inc., USA. An anechoic chamber is used for the measurement of frequency responses of the micro-speaker and headphones in accordance with the schematics shown in Fig. 8. The left side schematic is for the micro-speaker measurement (micro-speaker is placing on an infinite baffle with a microphone (B&K 4191) locate on axis at 10 cm from the diaphragm center in an anechoic chamber), on contrary the right side figure depicts headphone measurement schematic wherein an artificial ear, IEC60711, and Head and Torso Simulator in an anechoic chamber are used. In both measurements external to the anechoic chamber, a power amplifier is also required

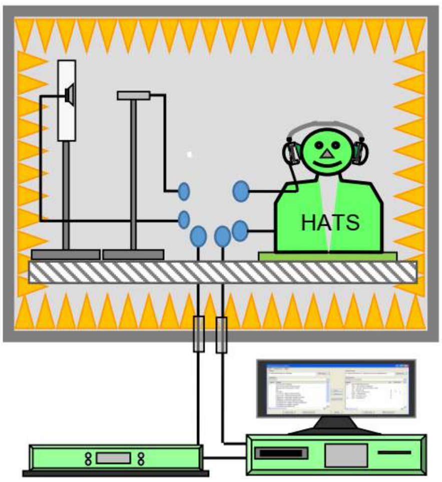


Fig. 8 — The frequency response measurement schematic of micro-speaker (left in an anechoic chamber) and headphone (right in an anechoic chamber)

Results and Discussion

Micro-speaker

The T/S parameter of DSH742-005 has been obtained and are given in Table 4. The frequency response curves of the micro-speaker are shown in Fig. 9. One can see the better agreement of the simulation and measurement curve before the second resonance. Initially, the response rises continuously till the fundamental frequency. Further, response becomes flat/straight with constant dBSPL till the next resonance. Certain variations are seen in measurement and simulation responses which are acceptable. Additionally, an apparent deviation in responses at the peak and valley during 4 ~ 5 kHz could be due to the mode splitting of the diaphragm which normally evident at high frequencies. After 5 kHz, the measured and simulated responses are in agreement with each other. Based on the observations, it is concluded that the ECM model of the micro-speaker has accurately estimated the characteristics of the micro-speaker's frequency response.

Table 4—T/S parameter table of DSH742-005

Name	Comment	Value	Unit
R_e	Electrical voice coil resistance at DC	30.81	Ohm
R_2	Electrical resistance due to eddy current losses	2.16	Ohm
L_e	Frequency independent part of voice coil inductance	0.135e-3	H
L_2	Para-inductance of voice coil	0.108e-3	H
M_{ms}	Mechanical mass of voice coil and diaphragm without air load	0.101e-3	kg
R_{ms}	Mechanical resistance of total-driver losses	0.022	N.s/m
C_{ms}	Mechanical compliance of driver suspension	10.282e-3	m/N
Bl	Force factor (Bl product)	2.467	T.m
S_d	Diaphragm area	9.62e-04	m^2

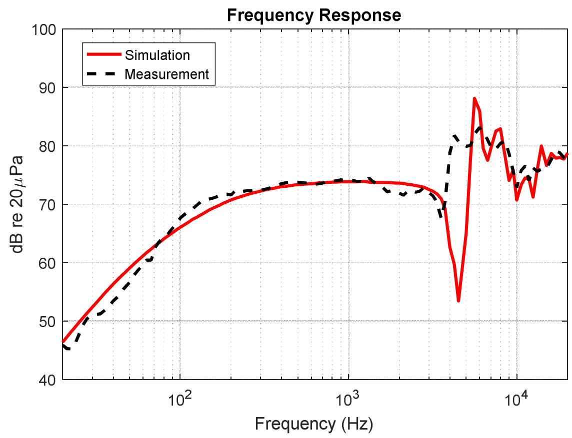


Fig. 9 —Measured and simulated frequency response of micro-speaker

Headphones

The frequency responses by an anechoic chamber measurement of all headphones are given in Figs. 10-13 (H1 to H4, respectively) along with ECM simulated responses. For uniformity, black dashed lines depict measurement curves and gray solid lines (red solid lines in colour) show measurement curves. One can observe acceptable agreement between measured and simulated responses. By comparing Fig. 9 with Figures 10-13, one can see the effect of headphone housing on the frequency response of the micro-speaker.

The effect of design modifications can be easily seen in the responses. For better understanding, responses from the start of the measurement frequency to the first resonance condition can be compared. For H1, responses (measured and simulated) start at around 114 dBSPL and remain flat till the rise and show fundamental frequency at 1050 Hz (measured) and 1500 Hz (simulated). For H2, responses start at around 102 dBSPL (simulated) and remain flat with fundamental resonance at 2200 Hz; however, the measured response begins at about 85 dBSPL and rises with some dips till the fundamental frequency at 2250 Hz. The simulated response of H3 starts at around 115 dBSPL and remains flat with fundamental resonance can be seen at 1200 Hz; however, the measured response begins at about 105 dBSPL and rises with some dips till the fundamental frequency at about 1700 Hz. Surprisingly, the simulated response of H4 starts at about 136 dBSPL and shows concave behavior until the fundamental resonance, which can be roughly estimated at 360 Hz, followed by a big dip. The measured response of H4 starts at 132 dBSPL, shows a slight upward trend, and shows no fundamental frequency peak; however, the fundamental resonance can be approximately assessed to be 450 Hz.

The frequency responses after the first resonance condition always remain spiky with many ups and dips. Simulated and measured responses show varied agreement after the first resonance till 20 kHz. This response behavior is called spurious resonances, which are very common in electroacoustic transducers. Ideally, the frequency response of earphone/headphone/loudspeaker should continue to remain flat (constant dBSPL) during the maximum possible frequency range for better sound production. One possible reason for the slight variations in the simulation and measurements shall be inevitable deviations in the electroacoustic parameters of the micro-speaker used in the headphone, and another shall be the unwanted sound leakage and fit of the headphone components. Based on the simulated and measured responses, it is concluded that the attempt to model the headphones by ECM has judiciously been realized within acceptable accuracy range. However, in certain places limitation of ECM has also been exposed. However, the computational simplicity of ECM prompts its use for modeling electroacoustic transducers.

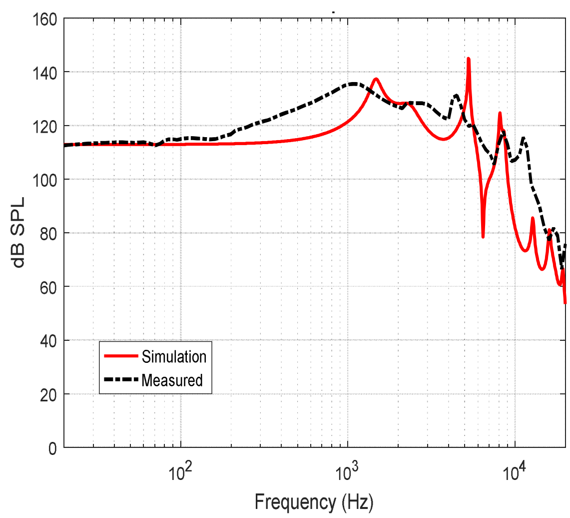


Fig. 10 —Measured and simulated frequency response of headphone H1

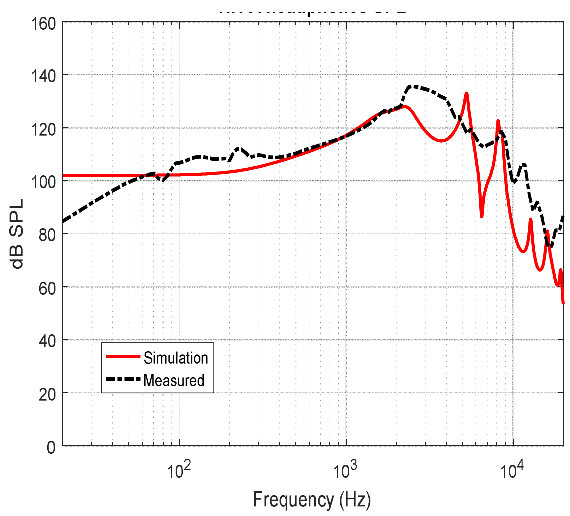


Fig. 11 —Measured and simulated frequency response of headphone H2

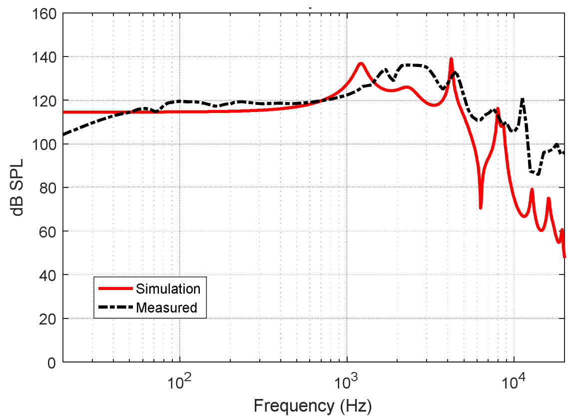


Fig. 12 —Measured and simulated frequency response of headphone H3

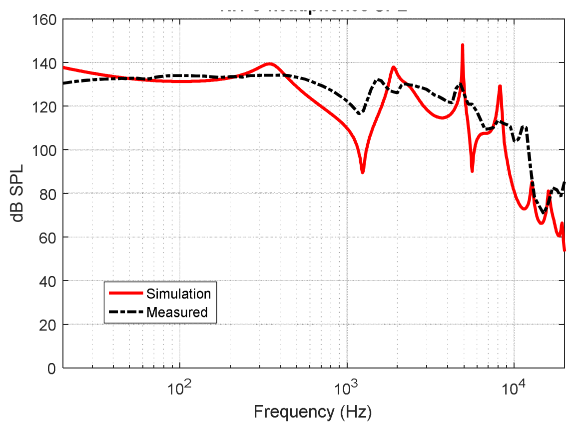


Fig. 13 —Measured and simulated frequency response of headphone H4

Conclusions

Based on this research, it is concluded that 3-D printing can effectively fabricate headphone components during the initial stages of the product design cycle. With advanced 3-D printers, better-quality prototypes are easy to fabricate. The measurement and simulation of the micro-speaker reveal the accuracy of the ECM simulation. Furthermore, measured and ECM simulated frequency responses of headphones can leads to the conclusion that the attempt to model the headphones by ECM has been attained and can be extended for further invesitgations. However, the limitation of ECM has also been exposed at certain places. However, the computational simplicity of ECM prompts its use for modeling electroacoustic transducers. The variation in the frequency responses of headphones design distinctions is also constructively proved. Finally, using ECM, CAD modeling, 3-D printing, and measurement methodologies could accelerate product design and development time and effort.

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