Study on the Acoustic Characteristics of Headphone with ECM Simulation and Reverse Engineering

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***Abstract*—In this study, DENON monitor headphones were the investigated target. Through equivalent circuit model, complete and accurate acoustic properties were obtained, with extension of this model to include the influence of front and rear chambers and assembled components, allowing for comprehensive headphone system simulation. Results of simulation and actual measurements were very close. In addition, reverse engineering technology, 3D printing, was used to reproduce the chambers and other components of the headphone system, except to the microspeaker. Fabricated headphone acoustic properties were highly similar to those of the factory produced headphones. This indicates the suitability and feasibility of earphone system development through reverse engineering. Loss was noted at low frequency. This was due to the ventilation materials of the front frame connecting the rear and front chambers. Overall, equivalent circuit simulation of headphone system with 3D printer technology can lead to results that resemble the acoustic properties of headphones sold on the market. The results of this study can be applied to parameter analysis and verification, as well as system development.**

Keywords*—reverse engineering; equivalent circuit model

I. INTRODUCTION

Loudspeakers are devices in which electrical energy is converted into mechanical energy to produce sound. They are used in many types of equipment. In terms of simulation, J. Borwick carried out loudspeaker simulation using analog circuits and divided into three parts [1]: electrical, mechanical and acoustical. Finally, SPL and impedance curve were calculated. In recent years, equivalent circuit method has been used as a foundation. In 2004, Jønsson, Schuhmacher and Nielsen applied equivalent circuit method to carry out simulation on IEC 60711 coupler in Artificial ear [2]. In 2006, ITU-T REC P.57 classification of headphones included five types, based on size and method of wearing [3]. Moreover, testing and measurement methods and equipment were defined. In 2016, Chen designed and fabricated circumaural headphone chambers and used equivalent circuit method to carry out simulation and analyses [4]. This study is based on this method.

II. MEASUREMENT AND SIMULATION

A. Measurement

SoundCheck system and Brüel & Kjær Free-field Microphone Type 4191 were used, with testing conducted in an international-class anechoic chamber to obtain microspeaker sound pressure level (SPL), total harmonics distortion (THD), and impedance curve. Headphone acoustical properties were obtained using SoundCheck system with Head and Torso Simulator (HATS). The results, shown in FIGURE I and FIGURE II, were used in subsequent simulations.

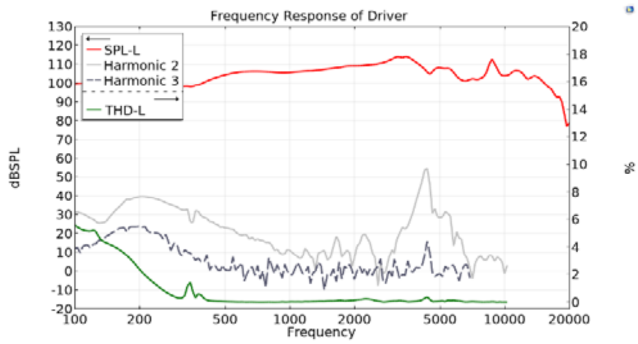

FIGURE I. FREQUENCY RESPONSE OF HEADPHONE

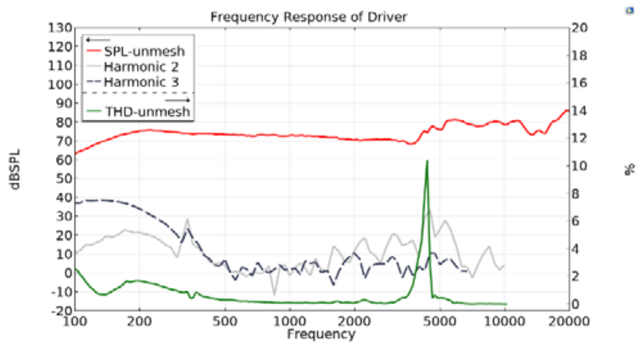

FIGURE II. FREQUENCY RESPONSE OF SPEAKER

1) *T-S Parameters:* To obtain microspeaker acoustic properties for simulation, KLIPPEL LPM system with vacuum measurement kit was used. By measuring diaphragm displacement and electric signal, by using inverse operator method, T-S parameters of microspeaker in a vacuum environment were obtained. The results are shown in FIGURE III.

Electrical Parameters		
Re	33.42	Ohm
Le	0.1115	mH
L2	0.016	mH
R2	1.12	Ohm
fs	259.5	Hz

Mechanical Parameters		
Mms	0.056	g
Rms	0.007	kg/s
Cms	6.652	mm/N
Bl	1.645	N/A
Loss factors		
Qms	13.197	-
Qes	1.1385	-
Qts	1.048	-

FIGURE III. T-S PARAMETERS (VACUUM)

2) *Geometry of Chamber:* Owing to the complexity of the geometry, Vernier caliper was used to manually measure the geometric dimensions of chamber and other components, as well as chamber volume. The results served as references for subsequent simulations of headphone chambers, shown in FIGURE IV and FIGURE V.

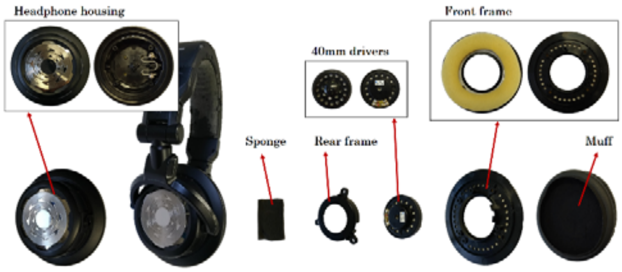

FIGURE IV. PARTS OF HEADPHONE

NAME	SIZE	NAME	SIZE	NAME	SIZE
Front frame hole(1) diameter	1.875×10^{-3} m	Vent hole(1) diameter	1.25x10-3 m	Effect diaphragm area	6.157×10^{-4} m^2
Front frame hole(1) depth	1×10^{-3} m	Vent hole(1) depth	2.5x10-3 m	Front chamber volume	1.1717×10^{-6} m^3
Front frame hole(1) quantity	24	Vent hole(1) quantity	12	Front chamber volume	2.4981×10^{-6} m^3
Front frame hole(2) diameter	1×10^{-3} m	Vent hole(2) diameter	1.25x10-3 m		
Front frame hole(2) depth	1×10^{-3} m	Vent hole(2) depth	6x10-3 m		
Front frame hole(2) quantity	4	Vent hole(2) quantity	1		

FIGURE V. PARAMETERS OF HEADPHONE

B. *Equivalent Circuit*

1) *Microspeaker*

For simulation of the acoustic properties of headphone microspeaker, equivalent circuit method and MATLAB numerical analysis software were used. Based on the core theory of equivalent circuit, if acoustic wavelengths of the various components that make up the microspeaker exceed the diaphragm dimensions, each component is equivalent to a single point operating model.

With circuit system comprised of passive circuit components, various energy conversion factors and far-field sound pressure theory, we investigated far-field acoustic radiation of mini-loudspeaker.

The headphone microspeaker equivalent circuit is shown in FIGURE VI and the simulation results are shown in FIGURE VII. The first resonance frequency point and the first conversion point at intermediate frequency obtained on simulations are extremely close to measured values. This implies that the equivalent circuit model developed in this study complies with actual. Therefore, the results of this study were extended to subsequent simulations of headphone chambers and other headphone structures.

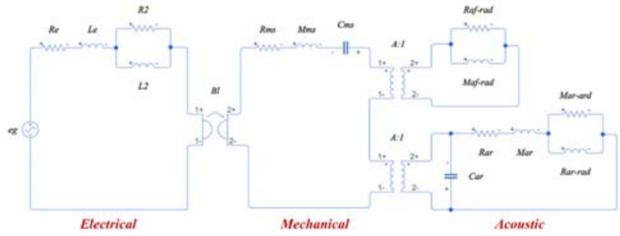

FIGURE VI. EQUIVALENT CIRCUIT MODEL OF SPEAKER

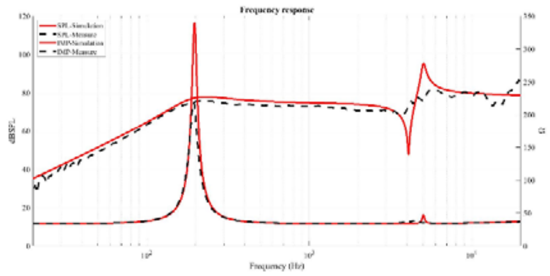

FIGURE VII. SIMULATION RESULTS OF SPEAKER

2) *Headphone*

Equivalent circuit of headphones is shown in FIGURE VIII. For this part, we investigated the air flow at the front and back of the driver. In the front, air flowed past the front frame and entered the cushion, chamber and IEC-711 coupler. At this point, it was necessary to consider a less than tight fit for the headphones and to carry out relevant air leakage simulation.

From the back, air passed driver rear chamber, vented-holes and ventilation materials in that order and entered fixed small back cavity and then large back cavity. Finally, from small vented-holes, it connected to the atmosphere. Results of MATLAB simulations are shown in FIGURE IX. Due to the complexity of headphone internal structure, it was not possible to obtain accurate and complete dimensions and properties. Therefore, there are discrepancies between simulated and measurement. The reasons for these discrepancies include differences in foam rubber and ventilation materials and amount of leakage during wearing, as well as structural complexity.

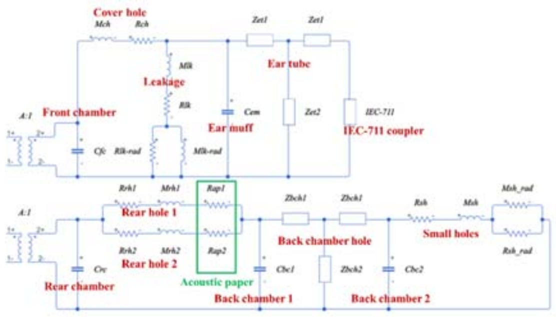

FIGURE VIII. EQUIVALENT CIRCUIT MODEL OF HEADPHONE ACOUSTIC DOMAIN

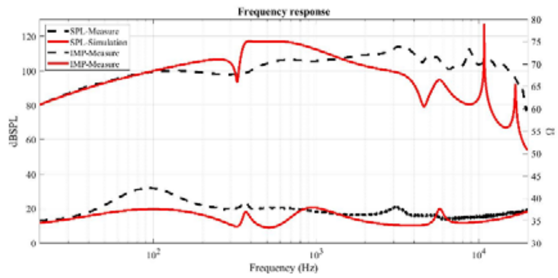

FIGURE IX. SIMULATION RESULTS OF HEADPHONE

III. REVERSE ENGINEERING

Vernier caliper was applied to obtain measurements. Creo software was used for parameterization and to build models of the driver and overall headphones, which were fabricated using 3D printer technology. Following confirmation of volume and tolerance, the headphones were assembled and acoustic properties were measured. Moreover, results of simulation were compared with those of the original headphones.

A. *Modeling*

Once simulation were confirmed to be close to measurements, software was used to build CAD model, as shown in FIGURE X.

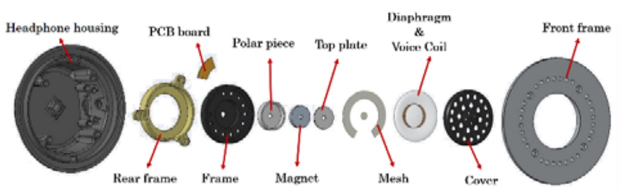

FIGURE X. CAD OF HEADPHONE

B. *3D Printing*

After building CAD model, Cura slicing software was used to convert to G-Code. Then, the objects were fabricated with 3D printer. During the printing process, there were issues with materials and tolerances. Appropriate and reasonable fine tuning and modification of the model were carried out. After fine tuning and modifying several times and verifying the volume and geometry, the front frame, rear frame and headphone housing were build up in that order. Finally, the left and right earphones were assemble, as shown in FIGURE XI. Then, the next step was carried out.

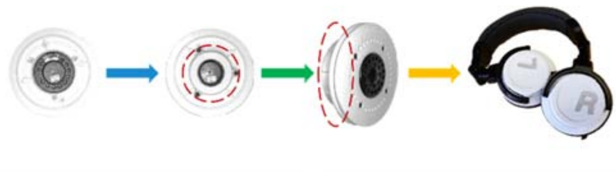

FIGURE XI. HEADPHONE ASSEMBLY PROCESSES

C. *Measurement*

Following fabrication, electroacoustic equipment was used to implement headphone acoustic property measurements, which were compared with those of the original headphones. The results are shown in FIGUREXII. The low-frequency acoustic properties of the fabricated headphones were inferior to those of the original headphones. This may be due to leakage when wearing. Acoustic property parameters were much closer at high frequency. Overall, although we were unable to obtain detailed and accurate geometric dimensions for the chambers and other components, SPL and THD tended to be close to the acoustic properties of the original headphones. Moreover, the high and low values on the curve accurately reflected the front-end ventilation material properties.

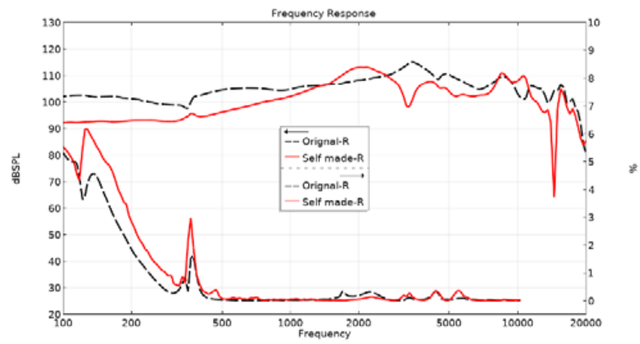

FIGURE XII. COMPARE THE FREQUENCY RESPONSE BETWEEN ORIGINAL HEADPHONE AND PRINTED HEADPHONE

Leakage at low frequency was most likely due to the ventilation materials of the front frame of purchased headphones, as shown in FIGURE XIII. To verify this, we used breathable tape of similar properties to substitute for the original ventilation materials. The results are shown in FIGURE XIV. The trends were very similar using breathable tape.

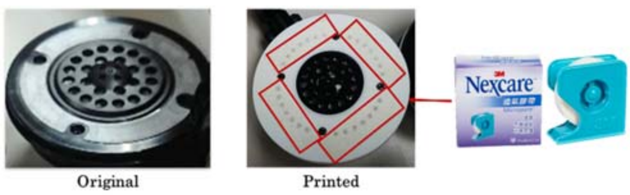

FIGURE XIII. MESH ON FRONT FRAME

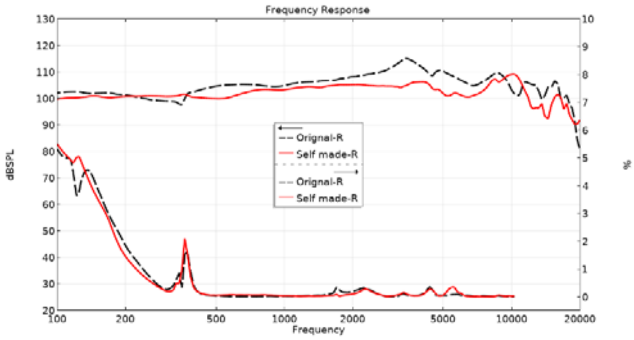

FIGURE XIV. COMPARE THE FREQUENCY RESPONSE BETWEEN ORIGINAL HEADPHONE AND PRINTED HEADPHONE

IV. CONCLUSION

We used monitor headphones in this study. From equivalent circuit model, we obtained the acoustic properties of headphone internal microspeaker woofer and headphone system. The simulated results were close to actual measured results, confirming the validity of predicted monitor headphone woofer and system acoustic properties obtained on simulation. In addition, in this study, we fabricated headphones similar to the purchased monitor headphones including chambers and other components with 3D printer. From testing and comparison, acoustic properties were similar, confirming the feasibility of producing headphones using 3D printing technology. In terms of inaccuracies at low frequency, following confirmation and verification, the main reason was leakage from front frame ventilation materials.

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