An Investigation of the Earphone Design with Regression Analysis

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Abstract

The current research work provides an investigation into the connection between the design parameters of an earphone and the sound quality performance in order to generate recommendations for future designs. As the earphone design was highly dependent on the empirical experience of the engineers, along with extensive trial and error, it was found to be difficult for research and development. Therefore, the current study sought a systematic approach to deal with the design. Along with the simplification of the earphone design problem, the sound quality performance outcomes were characterized by six factors, including total harmonic distortion, output power, frequency response, signal-to-noise ratio, speaker impedance, and headroom with seven levels with eight design parameters for the selection of types of divers (dynamic driver/moving coil, balanced armature driver, and planar magnetic driver), magnet (N35, N40, N45, and N50 Grade Neodymium Magnet), voice coils (copper wire, copper-covered aluminium wire, and silver wire), and diaphragm (polyethene terephthalate, polyethene naphtholate, polyetheretherketone, and polyetheretherketone + polyurethane) for the two drivers with zeros for the earphone products with a single driver. After the consolidation of the data from the manufacturer, regression analysis was conducted, while the six equations were formulated, and the models highlighted the importance of the selection of the type of primary driver and the irrelevance of the type of secondary driver. The result not only provides a direct and evidence recommendation for the research and development of earphones, but the research work also proposes an innovative way for knowledge generation from the information as well as existing data.

Keywords
Earphone Design, Regression Model, Knowledge Management, Sound Quality and Computer-aid Design.

1. Introduction
The current study provides an evaluation of the design practice of an earphone so that the recommendations for future designs can be backed by the completed project. For the sake of having a systematic illustration of the contents, the motivation for the study of the design parameters and the linkage with the sound quality outcomes would be highlighted in order to justify the urgency and needs of the study. Earphone design was found to be complicated and highly dependent on the experience of the developers, while it limited the transfer of knowledge and organizational growth (Patel, Cheer, & Fontana, 2020). Therefore, it would be advisable to gain the know-how from the previously conducted projects in order to provide directed suggestions for future development. In the current work, the related research gap would be catered to in order to benefit the design process of earphones. Essentially, the current project can be considered a consolidation of the design knowledge and a typical example of the utilization of the previously collected data for computer-aided design (Klich, 2017). Practically, the major innovation of the research study was the simplification and the design practices and the employment of statistical tools in generating recommendations and knowledge to guide future research and development (Xiao & Chan, 2017).

With respect to the mentioned motivation, the aim of the current research study was defined to reveal the connection between the design parameters of an earphone and the resulting sound performance quality in order to generate the practice implication for future design. Therefore., with the intention of accomplishing the defined aim, the four objectives of the work were formulated.

1. To simplify the design problem of earphone design so that the development can be characterized with parameters

2. To quantify the sound quality outcomes so that a systematic measurement of the preferred performance can be accomplished.
3. To seek the linear models to characterize the connection between the design variables and the sound quality outcomes in order to gain insight from the conducted projects.
4. To give recommendations for the future design so that the supported wise design can be included in the development process

By considering the objectives stated above, the relevant studies are conducted in Section 2. The organization of the paper will be presented as follows. With reference to the research design, the paper consists of the following Methods, Data Collection, Results and Discussion, and Conclusion respectively.

2. Literature Review

The literature review was divided twofold with the associated titles of Design Parameters of an Earphone Product and Sound Quality Performance in order to support the derivation of the research framework in the next section.

2.1 Design Parameters of an Earphone Product

First of all, with respect to the structure of an earphone, it was known that the product consists of three major components, namely, Magnet, Voice Coils, and Diaphragm, while the combination of them can generate new products, while the details of them can be seen in the following table (Table 1).

Table 1. Design Parameters and Assigned Values of an Earphone Product

Major Component	Details
Magnet	The magnet in an earphone driver is used to produce the magnetic field so as to interact with the voice coils. Therefore, the used magnet would affect the quality of the produced sound, while the strong magnet can generate a strong air movement with the same number of turns of the coil. Hence, it can provide better coverage for the frequency range (Denk, Hiipakka, Kollmeier, & Ernst, 2018). Thus, an earphone core with a strong magnet has an enhanced sound quality due to the large driving force.
Voice Coils	The coils have physical contact with the diaphragm, while the coils induce the driving force coming from electromagnetic induction in order to drive the vibration of the surrounding air. Although almost all of the coils are made from copper, various qualitative of copper can be selected in the earphone design (McRackan et al., 2018). Essentially, the sound quality of the earphone is directly related to the conductivity of the used material of the coils as the large current can be generated with the same among of voltage, and hence the large driving force.
Diaphragm	Finally, the diaphragm was found to be an essential component of the earphone core because of its direct contact with the air or the conduction media (Smull, Madsen, & Margolis, 2019). As the sound wave generated by the diaphragm was directly picked by the human ears, the interaction between the movement of the membrane and the perception of humans is essential for the design of the product. Nonetheless, the nonlinear and complicated relationship can be observed, which contributed to the difficulty of the design (Chang, Luo, Lo, & Tai, 2019). Essentially, along with the empirical experience, diversified materials were used for the diaphragm, but the association between them is still a mystery.

Along with the three major components, a diversified design can be adopted for the product design. For instance, different technologies can be applied to the divers so that the air can be vibrated with diversified techniques. Also, in some high-end earphones, multiple drivers (Bi, Sun, Liu, & Cao, 2022) would be included in order to enrich the frequency range of the generated sound, while the drivers can be mixed and applied to some special products (Ramatsoma, Koekemoer, Clark, & Malan, 2021). First, with respect to technology nowadays, there are three types of headphone drivers that can be found in the market, and they are highlighted in the following table (Table 2).

Table 2. Summary of the Types of Drivers Using in the Earphone Core **(Headphonesty, 2017)**

Type of Driver	Details
Dynamic Driver/Moving Coil	The design places the voice coil inside the permanent magnet so that the movement of the coils can be directed to the diaphragm, while the design leaves sufficient room for vibration, so the design has a wide range of frequency responses (Liu et al., 2021).
Balanced Armature Driver	In the design, the coil was wrapped on the armature in order to magnetize it, while the movement of the diaphragm is conducted by the magnetized armature within a permanent magnet. Essentially, the design has superior energy efficiency along with a small size (Xu, Jiang, Zhang, & Hwang, 2019).
Planar Magnetic Driver	Similar to the dynamic driver, the coil is printed on the diaphragm so that the vibration happens within the magnetic field provided by two stators with magnets. The design provides a flattened solution to the earphone to suit the inclusion of multiple drivers (Jiang, Xu, & Hwang, 2018).

Second, apart from the selection of the drivers, adopting multiple drivers enabled the performance benefits of using the small components, while it was considered a common technique in earphone design (Taniguchi, Chiaki, Kurosawa, & Nishikawa, 2017). One of the most significant advantages of applying multiple drivers with the same configuration for the earphone design is achieving the same function with smaller components. As the magnetic field inside the coil has attenuation effects, it is virtually impossible to have a uniform magnetic flux for the induction (Ahmed et al., 2021), while it may consider a source of distortion. Along with multiple components, the unity of the flux can be enhanced while it escalates the quality of sound generated. Nonetheless, putting two drivers into an earphone yields the miniaturization of the drivers, while the driving force may not be preserved (Kurosawa et al., 2019). Then, the designers should strike a careful balance of the issue. At last, apart from adopting the same drivers, the mixed drivers can yield unique performance of the end product, while it was commonly used in the design. Along with the adoption of different drivers, their advantages of them can be captured in the designed earphone, such as a wide frequency range. Nonetheless, similar to the idea of including multiple drivers, the manganic field of each driver was reduced due to the restriction of size, which may affect the overall performance. Additionally, the resultant effect of the adopted diaphragms with diversified materials on the sound quality is unpredictable, and it will escalate the uncertainty of the design (Abhishek et al., 2017).

2.2 Sound Quality Performance

Apart from the development of the representation of the earphone design, the performance outcome would be defined. With reference to the review about the measurement metric of sound quality, it can be seen that sound quality can be measured by six parameters, namely, total harmonic distortion, output power, frequency response, signal-to-noise ratio, speaker impedance, and headroom, though the subjective feedback may involve in the benchmarking (Audio Mention, 2020). Therefore, the section consists of six subsections in order to explain the contents of the evaluative factors. First, the measurement of total harmonic distortion (Alaei, Saghaeian Nejad, Gieras, Lee, & Ahn, 2019) evaluates the amount of distortion of the sound generated from the earphone in comparison with the original signal so as to measure how the sound produced by the earphone core reflects the audio source (Hang et al., 2020). In short, the high quality of sound should be with low total harmonic distortion, while an excellent earphone has a distortion rate of less than 1%, while the moderately performed system has a rate ranging from 1% to 5%. For the low-quality system, the distortion rate can be as high as 10%. Nonetheless, as the human ears are unable to clearly differentiate the distortion, while some of the distortions are reversely precepted, the nonlinear behaviour limits the possibility of adopting a single measurement for the quality of sound. Second, the output power (Sánchez, Moreno, Ferreira, & Crepaldi, 2019) evaluates the loudness of the earphone that can be generated, while it is commonly measured by the root mean square power in order to reflect the inverse square law of attenuation. Although the loudness may not directly relate to the quality, the output power demonstrated the capability of the earphone core in producing the sound with low frequency or bass. Therefore, it was considered a criterion. Third, in audio equipment, the frequency response (Liu, You, Tan, Zhang, & Liu, 2018) was considered the most direct way to determine the capability of a system, while the measurement evaluated the possible support gains for the range of frequency. Therefore, a full range system for humans should be capable of responding to the frequency range from 20 Hz to 20k Hz. Nonetheless, due to the physical limitation, earphones can provide responses to the range of 310 Hz to 12k Hz commonly, while the high-quality system can attain a wide frequency range. Fourth, the signal-to-noise ratio (Kandukuri, Yu, Yao, & Yuan, 2017) considered the proportional influence of the noise on the sound. In essence, the human ears perceive the loudness with a log scale, while decibel is used to measure the signal to the noise level. For a good earphone, the typical range of the ratio is 90 to 100 decibels. Fifth, similar to the output power, the impedance (Curbelo et al., 2019) of the device constrains the current flow through the system, while it is related to the maximum power drawn from the source. Additionally, the low impedance is also reflected by the low loss of power, while the low impedance device is of high quality. Finally, headroom (Budros & Fendrick, 2018) refers to the ability of the sound system to generate a short burst, while it is a subjective perception of the audience in experiencing the thrilling feeling of the sound, especially in the explosions of action movies.

3. Methods
3.1 Development of Research Framework
First of all, with reference to the research constructs captured in the literature review and the assumption of the earphone design with at most two drivers, the framework for the research study was constructed, while the associated visualization can be seen in Figure 1. From the depiction, it can be seen that the design of the product was simplified by the selection of the eight options, namely, the type of driver 1, the magnet of driver 1, the voice coils of driver 1, and the diaphragm of driver 1, type of driver 2, the magnet of driver 2, the voice coils of driver 2, and the diaphragm of driver 2, while the sound quality was characterized by the six variables, including, total harmonic distortion, output power, frequency response, signal to noise ratio, speaker impedance, and headroom. Thus, the research study targets to seek the regression equation of the outcomes with the eight design parameters as the inputs. Thus, after the consolidation of the results, the implication of the design can be generated to guide the development of future projects.

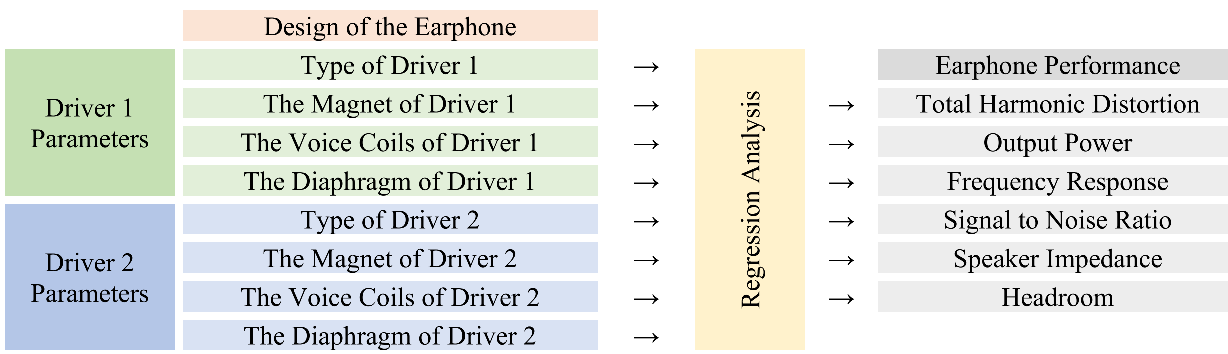

Figure 1. Visualization of the Research Framework for the Study Related to the Earphone Design and Performance

3.2 Steps for the Research Implementation
Then, with reference to the derivation of the research framework, the steps for the implementation of the research study would be developed, while the associated procedure can be classified into five steps.

1. The organizational consent should be ground from the organization in order to access the design data and the associated performance of the design.
2. After the collection of the data, the data cleaning process was conducted in order to ready the data for the analytic process.
3. Subsequent to the consolidation of the data, the data would be input into a computer in order to perform the analytic process.
4. With the gathered findings, the analysis of the results and the generated linear models would be closely inspected in order to gain design implications.
5. After the consolidation of the implication, the recommendations and suggestions for future design will be generated.

3.3 Adopted Analytic Methods
Then, with respect to the designed steps for the execution of the study, it can be seen that the analytic tools to be applied were the cores of the investigation. Hence, prior planning of the statistical tools was essential. Along with the defined objectives, it can be seen that descriptive analysis (Rodríguez-Pintó et al., 2016), which provides a general trend of the collected data; correlation analysis (Vlasova & Barasheva, 2018), which inspects the association of the factors; and regression analysis (Norton, Dowd, & Maciejewski, 2019), which derived the linear models of the sound

quality factors with the design parameters, should be adopted in the study. As they were the core part of the study, the equations of correlation and regression analysis were shown in the following.

$$\text{Correlation Coefficient} = \frac{n(\sum xy) - (\sum x)(\sum x)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

$$\text{Regression Model: } \mathrm{Y} = \mathrm{a} + \mathrm{bX}$$

$$a = \frac{\sum y\,(\sum x^2) - (\sum x)(\sum x\,y)}{n\sum x^2 - \ (\sum x)^2}, \qquad b = \frac{n(\sum xy) - (\sum x)(\sum x)}{n\sum x^2 - \ (\sum x)^2}$$

4. Data Collection

Further to the derivation of the methods for the implementation of the research investigation, the details of the data collection will be explained in order to justify the research study. On the one hand, for the sake of simplifying the design problem, the eight parameters were constrained with finite options of the variable selection in order to enable the research inspection, while the assigned values and the possible options can be seen in the following table (Table 3). For instance, although virtually infinite selections of the type of driver can be selected in practice due to technological development, the research study simplified the research problem by limiting the driver type option with dynamic driver/moving coil, balanced armature driver, and planar magnetic driver only.

Table 3. Summary of the Option of the Eight Earphone Design Parameters

Design Parmenter	**Design Option**	**Assigned Value**
Type of Driver 1	Dynamic Driver/Moving Coil	1
	Balanced Armature Driver	2
	Planar Magnetic Driver	3
The Magnet of Driver 1	N35 Grade Neodymium Magnet	1
	N40 Grade Neodymium Magnet	2
	N45 Grade Neodymium Magnet	3
	N50 Grade Neodymium Magnet	4
The Voice Coils of Driver 1	Copper Wire	1
	Copper Covered Aluminium Wire (CCAW)	2
	Silver Wire	3
The Diaphragm of Driver 1	Polyethylene Terephthalate (PET)	1
	Polyethene Naphtholate (PEN)	2
	Polyetheretherketone (PEEK)	3
	PEEK + Polyurethane (PU)	4
Type of Driver 2	No Driver 2 Involved in the Design	0
	Dynamic Driver/Moving Coil	1
	Balanced Armature Driver	2
	Planar Magnetic Driver	3
The Magnet of Driver 2	No Driver 2 Involved in the Design	0
	N35 Grade Neodymium Magnet	1
	N40 Grade Neodymium Magnet	2
	N45 Grade Neodymium Magnet	3
	N50 Grade Neodymium Magnet	4
The Voice Coils of Driver 2	No Driver 2 Involved in the Design	0
	Silver Wire	1
	Copper Wire	2
	Copper Covered Aluminium Wire (CCAW)	3
The Diaphragm of Driver 2	No Driver 2 Involved in the Design	0
	Polyethylene Terephthalate (PET)	1
	Polyethene Naphtholate (PEN)	2
	Polyetheretherketone (PEEK)	3
	PEEK + Polyurethane (PU)	4

On the other hand, despite the fact that the sound quality levels can be with infinite steps, the research study mapped the performance indicators with finite steps in order to simplify the research problem, while the definition of the levels for the six indicators and the corresponding assigned values were shown in the following table (Table 4). From the table, the correspondence of the performance ranges and their meaning of them can be observed. Additionally, apart from the simplification of the measurement, the related mapping also unified the scales of all performance factors while it was facilitating the computation and statistical analysis.

Table 4. Sound Quality Indicators and Assigned Values of an Earphone Product

Earphone Performance	**Performance Range**	**Remark**	**Assigned Value**
Total Harmonic Distortion	Serious Level of Harmonic Distortion	Distortion Over 10%	1
	Sensible Level of Harmonic Distortion	Distortion Around 9%	2
	Slightly High Level of Harmonic Distortion	Distortion Around 7%	3
	Moderate Level of Harmonic Distortion	Distortion Around 5%	4
	Slightly Low Level of Harmonic Distortion	Distortion Around 3%	5
	Insensible Level of Harmonic Distortion	Distortion Around 1%	6
	Zero Level of Harmonic Distortion	Distortion Below 1%	7
Output Power	Extremely Low Level of Output Power	Output Power below 80 Milliwatts	1
	Low Level of Output Power	Output Power Around 100 Milliwatts	2
	Below-average Level of Output Power	Output Power Around 120 Milliwatts	3
	Moderate Level of Output Power	Output Power Around 150 Milliwatts	4
	Above-average Level of Output Power	Output Power Around 180 Milliwatts	5
	Strong Output Power	Output Power Around 200 Milliwatts	6
	Extremely Strong Output Power	Output Over 250 Milliwatts	7
Frequency Response	Limited Range of Frequency Response	Less than 610 HZ to 10k HZ	1
	Narrow Range of Frequency Response	Around 610 HZ to 10k HZ	2
	Below-average Range of Frequency Response	Less than 310 Hz to 12k Hz	3
	Moderate Range of Frequency Response	Around 310 Hz to 12k Hz	4
	Above-average Range of Frequency Response	Over 310 Hz to 12k Hz	5
	Wide Range of Frequency Response	Around 20 Hz to 20k Hz	6
	Full Range of Frequency Response	Over 20 Hz to 20k Hz	7
Signal to Noise Ratio	Extremely Low Signal to Noise Ratio	Below 60 dB	1
	Low Signal to Noise Ratio	Around 60 dB	2
	Below-average Signal Noise Ratio	Around 80 dB	3
	Moderate Signal to Noise Ratio	Around 100 dB	4
	Above-average Signal to Noise Ratio	Around120 dB	5
	Large Signal to Noise Ratio	Around 160 dB	6
	Extremely Large Signal to Noise Ratio	Over 200 dB	7
Speaker Impedance	Extremely High Speaker Impedance	Over 40 ohms	1
	High Speaker Impedance	Around 32 ohms	2
	Above-average Speaker Impedance	Around 24 ohms	3
	Moderate Speaker Impedance	Around 22 ohms	4
	Below -average Speaker Impedance	Around 18 ohms	5
	Small Speaker Impedance	Around 12 ohms	6
	Extremely Small Speaker Impedance	Below 12 ohms	7
Headroom	No Effect on Headroom	Evaluation by Human Testers	1
	Low Headroom		2
	Below-average Headroom		3
	Moderate Headroom		4
	Above-average Headroom		5
	Significant Headroom		6
	Extremely Large Headroom		7

Therefore, along with the assignment of the values for the design parameters and the sound quality outcomes, the regression analysis can be conducted in order to generate the implication for future design.

5. Results and Discussion

Subsequently, with reference to the explanation for the data representation, the analytic results for the consolidated data can be generated while they are presented in the section. After gathering the design records from the hosting company, 388 designs and the associated sound performance were retrieved, while they would be used for the data analysis process. In alignment with the planned methods for the data analysis, the section was divided into three subsections with the titles Results of Descriptive Analysis, Results of Correlation Analysis, and Results of Regression Analysis, correspondingly.

5.1 Results of Descriptive Analysis

First of all, the descriptive analysis would be applied to give an overview of the adopted data. On the one side, the distribution of the included design records was calculated, while the associated results can be observed in the following table (Table 5).

Table 5. Distribution of the Design Parameters of the Sampled Earphones

Design Parmenter	Design Option	N	%
Type of Driver 1	1. Dynamic Driver/Moving Coil	196	50.52%
	2. Balanced Armature Driver	90	23.20%
	3. Planar Magnetic Driver	102	26.29%
	Total	388	100.00%
The Magnet of Driver 1	1. N35 Grade Neodymium Magnet	119	30.67%
	2. N40 Grade Neodymium Magnet	114	29.38%
	3. N45 Grade Neodymium Magnet	85	21.91%
	4. N50 Grade Neodymium Magnet	70	18.04%
	Total	388	100.00%
The Voice Coils of Driver 1	1. Copper Wire	161	41.49%
	2. Copper Covered Aluminum Wire (CCAW)	106	27.32%
	3. Silver Wire	121	31.19%
	Total	388	100.00%
The Diaphragm of Driver 1	1. Polyethylene Terephthalate (PET)	141	36.34%
	2. Polyethene Naphtholate (PEN)	98	25.26%
	3. Polyetheretherketone (PEEK)	77	19.85%
	4. PEEK + Polyurethane (PU)	72	18.56%
	Total	388	100.00%
Type of Driver 2	0. No Driver 2 Involved in the Design	86	22.16%
	1. Dynamic Driver/Moving Coil	83	21.39%
	2. Balanced Armature Driver	100	25.77%
	3. Planar Magnetic Driver	119	30.67%
	Total	388	100.00%
The Magnet of Driver 2	0. No Driver 2 Involved in the Design	86	22.16%
	1. N35 Grade Neodymium Magnet	80	20.62%
	2. N40 Grade Neodymium Magnet	74	19.07%
	3. N45 Grade Neodymium Magnet	78	20.10%
	4. N50 Grade Neodymium Magnet	70	18.04%
	Total	388	100.00%
The Voice Coils of Driver 2	0. No Driver 2 Involved in the Design	86	22.16%
	1. Copper Wire	127	32.73%
	2. Copper Covered Aluminum Wire (CCAW)	71	18.30%
	3. Silver Wire	104	26.80%
	Total	388	100.00%
The Diaphragm of Driver 2	0. No Driver 2 Involved in the Design	86	22.16%
	1. Polyethylene Terephthalate (PET)	83	21.39%
	2. Polyethene Naphtholate (PEN)	75	19.33%
	3. Polyetheretherketone (PEEK)	75	19.33%
	4. PEEK + Polyurethane (PU)	69	17.78%
	Total	388	100.00%

On the other hand, apart from the descriptive illustration of the distribution of the design parameters, the average scores of the six sound quality parameters, which are also obtained from the descriptive analysis, were visualized in the following illustration (Figure 2), while it can be seen that the earphone designs of the hosting company have a promising performance in headroom (Mean Score = 4.0335). On the contrary, the overall output power of the designed products (Mean Score = 3.8660) was found to be dissatisfactory.

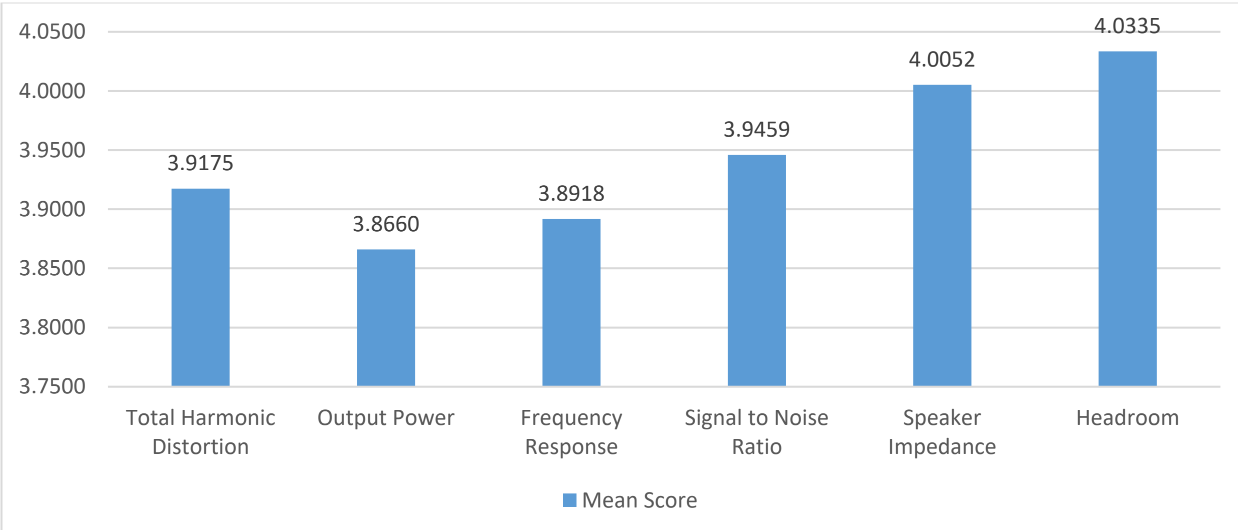

Figure 2. Visualization of the Sound Quality of the Sampled Earphones

5.2 Results of Correlation Analysis

Second, along with the correlation analysis, the correlation between the design parameters and sound quality outcomes was computed, while the associated results can be seen in Table 6. From the table, it can be seen that all design parameters were found to be significantly contributing to the outcomes, while it justified the significance of selected variables in the design process, while the details of the contribution of the parameters would be highlighted with the six sentences. In the first place, with respect to the total harmonic distortion, the influence in descending power of the parameters can be summarized with the following sequence: Type of Driver 1, The Diaphragm of Driver 1, The Diaphragm of Driver 2, The Magnet of Driver 1, The Voice Coils of Driver 2, The Magnet of Driver 2 and The Voice Coils of Driver 1.

In the second place, with respect to the output power, the influence in descending power of the parameters can be summarized with the following sequence: The Voice Coils of Driver 2, The Diaphragm of Driver, The Diaphragm of Driver 1, The Magnet of Driver 2, Type of Driver 2, Type of Driver 1, The Magnet of Driver 1 and The Voice Coils of Driver 1.

In the third place, with respect to the frequency response, the influence in descending power of the parameters can be summarized with the following sequence: The Voice Coils of Driver 2, The Diaphragm of Driver 2 , The Diaphragm of Driver 1 , Type of Driver 2, The Magnet of Driver 2 , Type of Driver 1, The Voice Coils of Driver 1, The Magnet of Driver 1.

Similarly, the relevant information has been shown in Table 6 for the correlation Values Between the Design Parameters and Sound Quality Outcomes.

Table 6. Correlation Values Between the Design Parameters and Sound Quality Outcomes

Correlations							
		Total Harmonic Distortion	Output Power	Frequency Response	Signal to Noise Ratio	Speaker Impedance	Headroom
Type of Driver 1	Pearson Correlation	.520**	.473**	.436**	.466**	.427**	.432**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Magnet of Driver 1	Pearson Correlation	.475**	.457**	.397**	.389**	.419**	.431**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Voice Coils of Driver 1	Pearson Correlation	.384**	.420**	.408**	.391**	.353**	.440**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Diaphragm of Driver 1	Pearson Correlation	.510**	.511**	.458**	.444**	.430**	.512**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
Type of Driver 2	Pearson Correlation	.453**	.487**	.447**	.477**	.442**	.465**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Magnet of Driver 2	Pearson Correlation	.453**	.511**	.445**	.522**	.441**	.492**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Voice Coils of Driver 2	Pearson Correlation	.506**	.545**	.479**	.500**	.493**	.512**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
The Diaphragm of Driver 2	Pearson Correlation	.508**	.542**	.476**	.496**	.460**	.505**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000
	N	388	388	388	388	388	388
**. Correlation is significant at the 0.01 level (2-tailed).							

5.3 Results of Regression Analysis

At last, along with the linear regression approach, the six linear models for each sound quality outcome were developed, while the equations in matrix form were shown in the following. From the equations, it can be observed that the loadings related to the type of driver 2 were zero, while the result suggested the insignificance of the design factor in contributing to the sound quality performance.

6. Conclusion

Although with the review of the research objectives, it can be seen that the work completed the objectives based on the motivation of deducing an innovative approach in gaining knowledge from the previously completed earphone design projects, while the accomplishment of the objectives can be resumed with four statements.

1. The design problem of earphone design was simplified with the selection of eight design parameters for different sound performances so that the development can be characterized by parameters.
2. The sound quality outcomes were quantified so that a systematic measurement of the preferred performance could be accomplished.

3. The linear models were formulated with regression analysis in order to characterize the connection between the design variables and the sound quality outcomes in order to gain insight from the conducted projects.
4. The recommendations were given based on the gained knowledge in order to support the wise design.

To conclude, with reference to the formulated set of equations, three observable conclusive remarks can be drawn. On the one hand, from the loadings corresponding to the type of driver 1, it can be seen that the selection of the type of the primary driver has a significant impact on the total harmonic distortion, output power, frequency response, signal to noise ratio, and speaker impedance, while the result suggested the planar magnetic driver as a supported solution for the earphone product. Second, from the last row of the equation, the result suggested the headroom was highly contributed by the selection of the voice coils of the secondary driver, while the silver wire was recommended. Lastly, with respect to the equation, the irrelevance of the selection of the secondary driver can be evidenced, while the future design should adopt a cheap solution for driver 2 for the wise allocation of resources. All in all, along with the inspection of the equation, it can be seen that know-how can be generated from the conducted projects, while the related findings helped the company to consolidate the design principles of the product design. Furthermore, three directions for future development can be highlighted.

1. Instead of a linear regression model, the nonlinearity of the formulation can be catered to with the adoption of machine learning techniques (Mullainathan & Spiess, 2017) so that the association between the design parameters and the sound quality factors can be characterized.
2. Apart from the proposed selection of the design parameters, more selections can be included in order to enrich the diversity of the design for enhanced representation of the design problem.
3. Similarly, apart from the design parameters, enrichment can be conducted among the sound performance indicators in order to widen the spectrum of the sound quality selection.

References

Abhishek, S. N., Balakirithikaa, R. B., Madhan, C., Vasudevan, S. K., El-Alfy, E.-S. M., and Thampi, S. M. An Innovative and Intelligent Earphone with Auto Pause Facility. *Journal of Intelligent and Fuzzy Systems,* vol. 32, no. 4, pp. 3221-3228, 2017.

Ahmed, R., Ahmed, R., Mehmood, M. U., Mannan, A., Lee, J. Y., Lim, S. H., and Chun, W. Design and Performance Analysis of Powering a Wireless Earphone By a Thermoelectric Generator. *IEEE Access*, vol. 9, pp. 54457-54465, 2021.

Alaei, A., Saghaeian Nejad, S. M., Gieras, J. F., Lee, D.-H., and Ahn, J.-W. Reduction of High-Frequency Injection Losses, Acoustic Noise and Total Harmonic Distortion in IPMSM Sensorless Drives. *IET Power Electronics,* vol. 12, no. 12, pp. 3197-3207, 2019.

Audio Mention. *How Do You Measure Audio Quality? - Audio Mention*. Retrieved Jan 26, 2022, from https://audiomention.com/how-to-measure-audio-quality/, 2020.

Bi, H., Sun, Y., Liu, J., and Cao, L. Smarter: Rhythm-based Tap Authentication Using Earphone in Information-centric Wireless Sensor Network. *IEEE Internet of Things Journal,* vol. 9, no. 2, pp. 885-896, 2022

Budros, M., and Fendrick, A. M. Levers to Reduce Use of Unnecessary Services: Creating Needed Headroom to Enhance Spending on Evidence-based Care. *The American Journal of Managed Care,* vol. 24, no. 8, pp. 353-355, 2018.

Chang, H.-Y., Luo, C.-H., Lo, T.-S., and Tai, C.-C. Compensated Active Noise Cancellation Earphone for Audiometric Screening Tests in Noisy Environments. *International Journal of Audiology,* vol. 58, no. 11, pp. 747-753, 2019.

Curbelo, J., Rodriguez-Cortes, P., Aguilera, M., Gil-Martinez, P., Martín, D., and Suarez Fernandez, C. Comparison Between Inferior Vena Cava Ultrasound, Lung Ultrasound, Bioelectric Impedance Analysis, and Natriuretic Peptides in Chronic Heart Failure. *Current Medical Research and Opinion,* vol. 35, no. 4, pp. 705-713, 2019.

Denk, F., Hiipakka, M., Kollmeier, B., and Ernst, S. A. An Individualised Acoustically Transparent Earpiece for Hearing Devices. *International Journal of Audiology,* vol. 57, no. sup3, pp. 5-25, 2018.

Hang, L., Subramaniam, U., Bayrak, G., Moayedi, H., Ghaderi, D., and Minaz, M. R. Influence of a Proposed Switching Method on Reliability and Total Harmonic Distortion of the Quasi Z-source Inverters. *IEEE Access,* vol. 8, pp. 33088-33100, 2020.

Headphones. *6 Types of Headphone Drivers That You Should Know - Headphones*. Retrieved Jan 26, 2022, from https://www.headphonesty.com/2017/04/5-types-headphone-drivers-know/#Diaphragm, 2017

Jiang, Y.-W., Xu, D.-P., and Hwang, S.-M. Electromagnetic-mechanical Analysis of a Balanced Armature Receiver By Considering the Nonlinear Parameters As a Function of Displacement and Current. *IEEE Transactions on Magnetics,* vol. 54, no. 11, pp. 1, 2018

Kandukuri, J., Yu, S., Yao, T., and Yuan, B. Modulation of Ultrasound-switchable Fluorescence for Improving Signal-to-noise Ratio. *Journal of Biomedical Optics,* vol. 22, no. 7, pp. 076021-076021, 2017.

Klich, R. Amplifying Sensory Spaces: The In- and Out-puts of Headphone Theatre. *Contemporary Theatre Review,* vol. 27, no. 3, pp. 366-378, 2017.

Kurosawa, M., Taniguchi, K., Momose, H., Sakaguchi, M., Kamijo, M., and Nishikawa, A. (2019). Simultaneous Measurement of Ear Canal Movement, Electromyography of the Masseter Muscle and Occlusal Force for Earphone-type Occlusal Force Estimation Device Development. *Sensors (Basel, Switzerland),* vol. 19, no. 15, pp. 3441, 2019.

Liu, F., Xie, S., Zhang, M., Tang, C., Xie, B., He, X., . . . Long, K. Downhole Microseismic Monitoring Using FOSS and Its Field Test Comparison with Moving-coil Geophone. *IEEE Transactions on Geoscience and Remote Sensing*, pp. 1-14, 2021.

Liu, Y., You, S., Tan, J., Zhang, Y., and Liu, Y. Frequency Response Assessment and Enhancement of the U.S. Power Grids Toward Extra-high Photovoltaic Generation Penetrations-an Industry Perspective. *IEEE Transactions on Power Systems,* vol. 33, no. 3, pp. 3438-3449, 2018.

McCracken, T. R., Fabie, J. E., Burton, J. A., Munawar, S., Holcomb, M. A., and Dubno, J. R. Earphone and Aided Word Recognition Differences in Cochlear Implant Candidates. *Otology and Neurotology,* vol. 39, no. 7, pp. 6-15, 2018.

Mullainathan, S., and Spiess, J.. Machine Learning: An Applied Econometric Approach. *The Journal of Economic Perspectives,* vol. 31, no. 2, pp. 87-106, 2017.

Norton, E. C., Dowd, B. E., and Maciejewski, M. L. Marginal Effects—Quantifying the Effect of Changes in Risk Factors in Logistic Regression Models. *Jama: The Journal of the American Medical Association,* vol. 321, no. 13, pp. 1304-1305, 2019.

Patel, V., Cheer, J., and Fontana, S. Design and Implementation of an Active Noise Control Headphone with Directional Hear-through Capability. *IEEE Transactions on Consumer Electronics,* vol. 66, no. 1, pp. 32-40, 2020.

Ramatsoma, H., Koekemoer, D., Clark, J. L., and Malan, K. One-ear tip Solution for Pure-tone Audiometry and Acoustic Immittance Measurements: Using Insert Earphone with an Immittance Probe Ear Tip. *International Journal of Audiology*, pp. 1, 2021.

Rodríguez-Pintó, Moitinho, I., Santacreu, M., Shoenfeld, I., Erkan, Y., Espinosa, D., . . . Ricard. Catastrophic antiphospholipid syndrome (CAPS): Descriptive analysis of 500 patients from the International CAPS Registry. *Autoimmunity Reviews,* vol. 15, no. 12, pp. 1120–1124, 2016.

Sánchez, A. R., Moreno, R. L., Ferreira, L. H., and Crepaldi, P. C. Biasing Technique to Improve Total Harmonic Distortion in an Ultra-low-power Operational Transconductance Amplifier. *IET Circuits, Devices and Systems,* vol. 13, no. 6, pp. 920-927, 2019.

Smull, C. C., Madsen, B., and Margolis, R. H. Evaluation of Two Circumaural Earphones for Audiometry. *Ear and Hearing,* vol. 40, no. 1, pp. 177-183, 2019.

Taniguchi, K., Chiaki, H., Kurosawa, M., and Nishikawa, A. A Novel Earphone Type Sensor for Measuring Mealtime: Consideration of the Method to Distinguish Between Running and Meals. *Sensors (Basel, Switzerland),* vol. 17, no. 2, pp. 252, 2017.

Vlasova, E. L., and Barasheva, E. V. Financial Control and Financial Monitoring Within the System of Government Financial Administration: Correlations and Interrelationships. *Journal of Advanced Research in Law and Economics,* vol. 9, no. 4, pp. 1494-1502, 2018.

Xiao, F., and Chan, P. K. A Performance-aware Low-quiescent Headphone Amplifier in 65-nm CMOS. *IEEE Journal of Solid-state Circuits,* vol. 52, no. 2, pp. 505-516, 2017.

Xu, D.-P., Jiang, Y.-W., Zhang, H.-L., and Hwang, S.-M. Fast Electromagnetic Analysis of a 3-d Magnetic Circuit in a Balanced Armature Receiver. *IEEE Transactions on Magnetics,* vol. 55, no. 2, pp. 1, 2019

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