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2pEAa10. How a hearing aid transducer works
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The oldest magnetic earphone, the Balanced Armature Receiver (BAR), is the most widely used receivers in modern hearing-aid instruments, where the efficiency of the power (battery life) and the size of the device, as well as the larger frequency bandwidth, are critical parameters. Since these miniature loudspeakers remain one of the most expensive components of the hearing-aids, a detailed studying of them is a cornerstone of understanding the hearing-aid system, and we believe that the appropriate and rigorous analysis of this transducer is critical. The motivation of this study started from the modeling of a widely-used commercial hearing-aid receiver ED series, manufactured by Knowles Electronics, Inc. Our proposed model includes a semi-inductor and a gyrator along with the two-port network glue which enables us an intuitive design of the electromagnetic transducer. Based on the BAR model, we will investigate and discuss the roles of each physical component in the BAR such as a coil, magnets, an armature, a diaphragm, and the rear volume of the receiver. Ultimately, this work will deliver a fundamental and innate answer for the question, 'How does a hearing-aid transducer work?'

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INTRODUCTION

Previously, we proposed a novel circuit model of Knowles ED7045 receiver (Kim and Allen, 2012). In this study, based on our transducer model, we analyze the hearing-aid transducer by explaining the roll each circuit component in terms of its frequency response. Also we measured electrical input impedance ($Z_{in}$) of the transducer in different voltage levels and demonstrated the nonlinearity of the transducer is possibly in the magnetic field by modeling the $Z_{in}$ response only changing the magnetic value.

To verify the model we performed a sensitivity analysis of each circuit element in the model in Fig. 2, by changing each component value by ±20%. These results are presented in Tables 1-2. Next we described the role of each circuit element in terms of its impact on the frequency response of the input impedance $Z_{in}$. New findings include the importance of driving the Balanced Armature Receiver (BAR) with a current rather than a voltage, to greatly improve the output frequency response out to 12[kHz], and the nonlinear properties of the BAR.

ANALYSIS OF THE MODEL

In the following section we analyze the circuit model shown in Fig. 1. A version of this model was provided in the previous report. The analysis includes a sensitivity analysis as well as an analysis of the nonlinear behavior of the BAR. Referring to Fig. 1, we next discuss each of the three sections of the final model: the electrical, mechanical, and acoustical parts.

![Figure 1: Our transducer design of the Knowles ED27045 balanced armature receiver (BAR). The model consists of 3 physical components: the electrical, mechanical, and acoustic parts.](image)

**Electrical part**

The current in the coil and the core of the E-shaped armature give rise to the coil inductance $L_{em}$, while the penetration of the magnetic field into the core induces an eddy current, depicted by a semi-inductor element $K_1$ (Vanderkooy, 1989; Thorborg and Unruh, 2008). $L_e$ represents the leakage flux, in air gap.

**Mechanical part**

To the immediate right of the gyrator are the mechanical parts of the transducer. We can model the mechanical section as a mechanical series combination of the armature and the diaphragm's stiffness ($C_m$), mass ($L_m$) and damping ($R_m$). Because we use the nonreciprocal gyrator (GYR), rather than a reciprocal transformer, to represent the electrical-mechanical transformation, it is not necessary to use the traditional mobility method (Beranek, 1954). This greatly simplifies our analysis of the mechanical circuit. It is important to note that Maxwell's equations are nonreciprocal. This effect is carefully explained in detail in (Hunt, 1952), which defines the starting point of our analysis. Somewhat surprisingly, it appears that even Beranek (Beranek, 1954), who was personally close to Hunt (Hunt, 1952), failed to explore this connection of the gyrator in loudspeaker analysis. This application of the gyrator, along with the use of a semi-inductor, represent the primary contributions of our model. It appears that Elmer Carlson understood all of these points (Killion,
FIGURE 2: Final model of $Z_{in}$: The left two panels describe the magnitude (upper) and the phase (lower) of $Z_{in}$. The right panel is a “polar plot” of the impedance, defined as the real part (abscissa) vs. imaginary part (ordinate) of the impedance. The large loops of the blue and red curves of the polar plot correspond to the resonances in the magnitude and phase plots (1-3 [kHz] range). For example, the blue curve peaks at 2.2 [kHz] and 3800 ohms, and has a phase of zero degrees. The corresponding point on the right panel is 3800+j0 ohms, representing the maximum real part of the blue loop. The legend for the solid red line in the right panel should read: ‘Model $Z_{in}, U = 0$’.

1992), but his deep understanding of the problem has not “bubbled to the top”. That seems to be at least poorly supported by Knowles (Killion, 1992; Kim and Allen, 2012).

**Acoustical part**

Going from the mechanical part ($F_{out}, V$) to the acoustical part ($P_{in}, U_{in}$), a transformer (TRF) with a “turns-ratio” $A$, representing the effective area of the diaphragm, is required. The capacitor ($C_a$) and a transmission line, account for the rear cavity stiffness and front cavity sound delay, respectively.

Figure 2 provides the final model response. Two experimental conditions are plotted; one is $Z_{in}$ in vacuum (blue), the other is $Z_{in}$ under normal condition (red). Tables 1 and 2 show the sensitivity of each circuit element. Each plot is similar to Fig. 2 in format [i.e., consists of 3 panels: the magnitude, the phase, and real/imaginary parts of $Z_{in}$ (polar plot)].

**Sensitivity Analysis**

Tables 1 and 2 provide a sensitivity analysis of the circuit input impedance $Z_{in}$. Each component value of the final model shown in Fig. 1 is modified by ±20%, and then compared to results of the unmodified response in Fig. 2.

**Nonlinearity of the transducer input impedance**

The nonlinear (NL) properties of the BAR are important because they determine the level of distortion during the presentation of pure tones, while measuring distortion products coming from the cochlea. Thus we must pay careful attention to these NL properties.

For this study we measured $Z_{in}$ as a function of the drive voltage ($E_{in}$ of Fig. 1). To minimize the acoustic load impedance, we take the $Z_{in}$ condition when the volume velocity is zero ($U = 0$, blocked sound port). In this case, we can approximate $Z_{in} = Z_e$, in terms of the electrical impedance defined as one of Hunt’s parameters ($Z_e$=voltage/current when $U = 0$). We found that we can fit the nonlinear $Z_{in}$ data by making the gyrator parameter $T$ a function of voltage. We plotted the real and imaginary parts of the different levels of $Z_e$ in Fig. 3. The model and the measurement data are in good agreement. Based on the above sensitivity analysis, only the gyrator value $T$ affects the response in a manner similar to the observed nonlinear behavior.
FIGURE 3: This shows the effect of changing $T = B_0l$ (indicated as ‘G’ in the legend) on the input impedance. The solid lines represent the measured impedance data, as a function of voltage, while the dashed lines represent the model impedances. One may conclude that the magnetic field ($B_0$) is a function of the voltage. As a result, the nonlinearity of the BAR is independent of the acoustic load. This is a very useful experimental finding.

(response around the resonance). The gyrator value is assumed as $B_0l$. Thus the similarity of the sensitivity analysis for $T$ and the voltage dependent $Z_{in}$ data lead us to the conclusion that $B_0$ is voltage dependent. This demonstrates that the nonlinearity is in the magnetic field of the transducer.

CONCLUSION

In this study, we have discussed the critical elements of a hearing-aid transducer circuit model including a gyrator, and a semi-inductor along with other mechanical and acoustical components. Starting from performing the sensitivity analysis of the receiver, we described the role of each circuit element in terms of its impact on the frequency response of the input impedance $Z_{in}$. The most interesting finding of the proposed study is that the transducer’s nonlinear response, which accounts for distortion products generated by the BAR, is caused by the magnetic field. We was able to infer that the nonlinear effect is not a function of the electrical or acoustic load. For the further study, a demagnetized transducer could be used to explore the nature of the electromagnetic transducer by looking at the electrical impedance is dominated only by the electrical circuit parameters ($R_e, L_e, K_1, L_{em}$).

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REFERENCES


TABLE 1: Impedance sensitivity analysis (Part 1): Tables 1 and 2 are in the same format as Fig. 1. Each subplot corresponds to the impedance as one element is varied by ±20%.

\[
\begin{align*}
R_c: & \text{ DC resistance, mostly affects the low frequency region} \\
L_e: & \text{ Leakage inductance, mostly affects high frequency region} \\
K_1: & \text{ Semi-inductance, mostly affects resonance area and high frequency region} \\
L_{em}: & \text{ Main inductance, mostly affects anti-resonance area and high frequency region} \\
GYR: & \text{ Gyrator value assuming } T = B_0 l \text{ where } B_0 \text{ is magnetic field and } l \text{ is length of the wire. Changing } T \text{ mainly affects the resonant region} \\
C_m: & \text{ Mechanical stiffness. This mostly affects the location of the resonance and anti-resonance. Increasing } C_m \text{ lowers the resonance frequency}
\end{align*}
\]
**TABLE 2:** Impedance sensitivity analysis (i.e., Table 1-Part 2): Tables 1 and 2 are in the same format as Fig. 1. Each subplot corresponds to the impedance as one element is varied by ±20%. The subplot in this table where the transformer (i.e., TRF parameter) was varied, was helpful for understanding the small but significant voltage dependent nonlinearity of the BAR receiver, as discussed in the nonlinear analysis section.

$L_m$: Mechanical mass. Similar to $C_m$, increasing $L_m$, lowers the resonance frequency, but change is more concentrated in the resonance area.

$R_m$: Mechanical damping. This value is related to the resonance and anti-resonance peak-to-peak height.

Transformer: (Starting from this element, only the normal condition will be changed). TRF value is related with the area of the diaphragm. Increasing TFR results in decreasing the resonance frequency.

$C_a$: This quantity represents any back volume in the transducer. Increasing this value results in decreasing the resonance frequency.

Transmission line Characteristic impedance ($Z_c$): Any internal sound delay can be represented by a transmission line; decreasing $Z_c$ results in a smoother resonance in other words, shorter peak-to-peak height.

Transmission line delay: Decreasing delay results in a larger peak-to-peak height.