Dean&Francis
ISSN 2959-6157

A Review of Sound Transducer Technology for Speakers and Headphones Based on Electromagnetic Drive

Yuhan Zhang

Department of automation, South China University of Technology, Guangzhou, China
202430462130@mail.scut.edu.cn

Abstract:
This paper presents a comprehensive review of sound transducer technologies for speakers and headphones based on electromagnetic drive. Emphasizing the Lorentz force mechanism, the study explores core components including magnetic circuits, voice coils, and diaphragms. Recent advances in magnetic circuit design highlight the use of neodymium-iron-boron (NdFeB) magnets and optimization methods like particle swarm algorithms to enhance field uniformity. Diaphragm innovation is examined through new nanocomposite materials such as NCV, which combine stiffness, internal damping, and thermal stability. System-level breakthroughs address voice coil lightweighting using copper-clad aluminum and thermal management via structural airflow optimization. Challenges like miniaturization-induced acoustic distortion and high-temperature nonlinearities in power amplification are also discussed. Looking ahead, future development is expected to integrate multi-drive unit coordination and intelligent adaptive tuning powered by machine learning and real-time sensing. This convergence of materials science, control engineering, and AI is projected to drive the evolution of next-generation, high-efficiency, and smart audio transducer systems.

Keywords: Electromagnetic drive; sound transducer; loudspeaker; headphone.

1. Introduction

Electro-acoustic conversion is pivotal for modern audio devices, enabling the transformation of electrical signals into audible sound for communication, entertainment, and information sharing. Electromagnetic drive stands out as the dominant technology in speakers and headphones, favored for its high energy conversion efficiency and cost-effectiveness. Leveraging the Lorentz force to convert electrical energy into mechanical vibration, it balances performance and manufacturability, underpinning most consumer and professional audio equipment.

From massive loudspeakers to tiny TWS earbuds,

ISSN 2959-6157

dynamic speakers and headphones—the most common electromagnetic drive-based devices—are the subject of this review.

The paper is organized as follows: the working principle (diaphragm effects on acoustics, Lorentz force, and core components); key technologies (diaphragm innovations, magnetic circuit optimization, and voice coil/thermal bottleneck solutions); technological evolution; current challenges (high-temperature distortion, miniaturization-acoustic pressure trade-offs); and future directions (multi-driver collaboration, intelligent tuning). The development of sound transducers based on electromagnetic drives is presented methodically in this framework.

2. Working Principle

2.1 Physical Basis: Lorentz Force — Mechanical Vibration — Sound Wave

The fundamental operating principle of a loudspeaker system is based on the physics of electromagnetic induction and acoustic wave propagation. The process begins when an audio signal drives an electric current through the voice coil, which is suspended in a magnetic field generated by a permanent magnet. According to the Lorentz force law.

$$(\vec{F} = I \bullet \vec{L} \times \vec{B}) \tag{1}$$

Where $\vec{F}$ is the Lorentz force, I is the current, $\vec{L}$ is the direction of the current and the effective length of conductor, $\vec{B}$ is the magnetic intensity and direction, his interaction generates a force that causes the coil to oscillate [1] [2]. As the coil moves, it transfers mechanical energy to the diaphragm, producing pressure variations, in the air, which propagate as sound waves [3].

2.2 Core Structure: Transducer Systems in Loudspeakers and Headphones

A typical dynamic loudspeaker transducer, which is the focus of this paper, consists of a magnetic circuit, a voice coil, and a diaphragm. The magnetic circuit, which includes permanent magnets and pole pieces, creates a radial magnetic field in which the coil moves, causing mechanical vibration and driving the diaphragm to produce sound. Most conventional speaker and headphone designs continue to rely on this electromagnetic drive mechanism, which is based on the moving coil principle.

In headphones, high performance under stringent size and power limits is made possible by the miniaturization of this structure employing cutting-edge materials like neodymium magnets and lightweight diaphragms like graphene or liquid crystal polymers [4]. Although there are other designs, such as balanced armature and planar magnetic drivers, they are not the subject of this study because they function on essentially different transduction principles [5].

Acoustic Characteristics: Influence of Diaphragm Size and Stiffness on Frequency Response

The diaphragm's physical parameters, such as diameter, mass, and stiffness, directly alter the system's frequency response. Larger diaphragms favor low-frequency performance due to increased air displacement, whereas stiffer and lighter materials improve high-frequency fidelity [6]. For this reason, high-end loudspeakers often incorporate multi-driver or hybrid diaphragm systems to extend and flatten the frequency response curve (Toole, 2008).

3. Key Technology Design

3.1 Magnetic Circuit Optimization

In loudspeaker design, the magnetic circuit serves as the driving source that directly affects electroacoustic conversion efficiency. A critical design goal is to ensure high magnetic field uniformity in the air gap where the voice coil operates. Uneven magnetic fields lead to distortion and reduced sensitivity. Finite element simulation tools such as COMSOL and FEMM have been widely employed to evaluate and optimize the spatial distribution of magnetic flux density across the magnetic path [7].

The design of effective loudspeaker magnetic circuits heavily relies on the choice of permanent magnets. Ferrite (hard ceramic magnets) and Neodymium-Iron-Boron (NdFeB) are two frequently utilized materials. Ferrites stand out for their low cost, excellent corrosion resistance, and thermal stability. However, their lower energy product (BHmax ~4 MGOe) limits their effectiveness in high-power, compact systems.

By contrast, NdFeB magnets, with BHmax values exceeding 50 MGOe, allow for more compact magnetic structures without sacrificing field intensity. This makes them ideal for miniaturized, high-sensitivity applications such as in-ear monitors and TWS (True Wireless Stereo) earbuds. Additionally, NdFeB magnets exhibit a higher remanence and coercivity, which leads to improved acoustic efficiency and wider frequency response in speaker systems [8].

However, NdFeB is more prone to corrosion and thermal demagnetization, necessitating protective coating and proper thermal management. The low Curie temperature (310-340 °C) is a critical weakness, limiting thermal stability. More importantly, its coercivity decreases significantly at high temperatures, raising the possibility of irreversible demagnetization under high thermal load. These trade-offs must be carefully considered during material selection, taking into account product needs, operational conditions, and economic limits. Structural concepts such expanding the outer diameters of soft magnetic components (like the washer and T-yoke) are being researched in order to further maximize magnetic field uniformity. The flux density in the working gap can be decreased by improper size, which might result in magnetic saturation or leakage. Furthermore, to enhance coil layout and magnetic field homogeneity, especially in space-constrained applications like tiny transducers or sensors, sophisticated coil structure optimization algorithms like Particle Swarm Optimization (PSO) have been used [9]. A notable example is the work by Wu et al. (2019), who applied a PSO algorithm in the magnetic circuit design of a miniature headphone. By iteratively adjusting the yoke thickness and magnetic gap width, they successfully reduced magnetic field non-uniformity from 12% to 3.5%, resulting in a 2.1 dB increase in system sensitivity. Their optimization objective was formulated as a weighted sum of even-order derivatives of the magnetic field at the coil center, as shown below:

$$min\sum_{k=1}^{k_p}\omega_k\left|\frac{\delta^{2k}B_z}{\delta z^{2k}}|_{(0,0,0)}\right| s.t.d_{i+1}-d_i \geqslant d_{smin}, d_{min} \leqslant d_i \leqslant d_{max} \tag{2}$$

Where ω_k denotes the weight for each derivative term, d_i epresents the position of each coil pair, and d_{msin} accounts for manufacturing constraints such as minimum spacing. This PSO-based optimization technique outperforms conventional analytical methods, particularly for higher-order uniformity needs, by allowing discrete geometric tweaking for improved field uniformity while simultaneously accommodating manufacturing and structural restrictions.

Diaphragm Innovation in Loudspeakers

Recent advancements in loudspeaker diaphragm materials have focused on balancing high stiffness and internal damping, two properties typically in trade-off. A significant innovation is the NCV (Nano Carbonized high Velocity) diaphragm developed by Mitsubishi Electric, which combines carbon nanotubes (CNTs) with high-modulus aromatic polyester composites [10]. The key to NCV's performance lies in the reinforcement mechanism of CNTs: through π–π interactions, CNTs form strong interfacial bonds with the aromatic polyester matrix, establishing a three-dimensional conductive and mechanical network. With an internal loss coefficient (~0.03) similar to paper, energy is released by interfacial shear stress between the CNTs and the polymer matrix when acoustic loads are applied, effectively suppressing resonances and minimizing distortion. Concurrently, CNTs' high elastic modulus (E ≥ 120 GPa) maintains piston-like diaphragm action at higher frequencies by reinforcing the matrix and preventing modal breakage. According to Mitsubishi's testing data, adding just 5 wt% CNT can minimize high-frequency distortion by up to 40% and raise the bending wave velocity from 3800 m/s to over 5500 m/s, which is faster than titanium. Furthermore, the NCV diaphragm has thermal stability across a broad temperature range, which qualifies it for harsh settings like automotive applications. Injection molding further enables flexible shaping across frequency-specific designs, ensuring timbre consistency and broad-spectrum acoustic fidelity. These combined advantages make NCV a strong candidate for next-generation loudspeaker diaphragms, offering superior acoustic performance with scalable manufacturing

3.2 Breakthroughs in Bottleneck Technologies of the System

In terms of voice coil lightweighting, the bottleneck lies in the trade-off between weight reduction and electrical conductivity/durability. The development of copper-clad aluminum wire (DCCA) addresses this by combining an aluminum core for light weight with a copper cladding for conductivity. This design enhances flexibility in coil design and resistance to fatigue fracture, as shown in Fig. 1 where developed DCCA exhibits significantly more bending cycles until breakage than conventional CCA, enabling better high-frequency responsiveness in mobile device speakers.

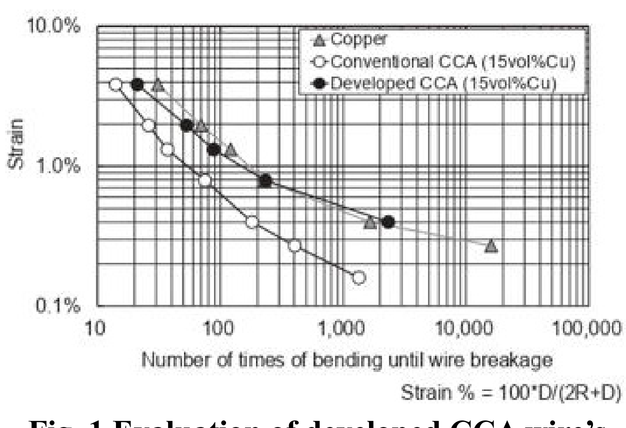

Fig. 1 Evaluation of developed CCA wire's resistance to bending fatigue fracture [11]

For thermal management, the challenge is to improve airflow efficiency without increasing fan size or noise [12]. Proposed utilizing unused speaker holes in laptops as additional air intake paths, reducing airflow resistance and increasing the airflow rate by up to four times. This innovation allows for smaller, quieter fans and better temperature maintenance.

In acoustic tuning, speaker variability previously posed a

ISSN 2959-6157

challenge for deep neural network (DNN) acoustic models [13]. Introduced Speaker Adaptive Training (SAT-DNN), which uses i-vectors to project features into a speaker-normalized space, achieving significant word error rate reductions. This technique enhances model adaptability to different speakers, improving overall acoustic performance.

3.3 A Quantitative Thermal Management Scheme for Speakers

Effective thermal dissipation in speakers is critical to maintain performance, as voice coil heating degrades efficiency. This scheme employs conduction through optimized conductors and structural adjustments to enhance heat transfer.

Heat is typically dissipated through conduction, which occurs when the conductor material of the voice coil conducts heat to the housing. As previously stated, copper-clad aluminum (DCCA) wires with tunable copper clad ratios (30-50% recommended) strike a compromise between thermal conductivity and lightweight qualities. Their copper cladding (high thermal conductivity) improves heat transmission, while the aluminum core minimizes mass (reduced heat generation). For example, 15vol% Cu DCCA wires have a 25% higher tensile strength than ordinary CCA, assuring structural integrity during vibration and consistent heat pathways.

Structural optimization via copper clad ratios impacts dissipation. Higher copper ratios (e.g., 50vol%) increase thermal conductivity (63% IACS vs. 62% for pure aluminum cores), enhancing heat dissipation. CFD simulations show this reduces voice coil temperature by 8°C during high-power operation, limiting resistance rise to 10% (vs. 20% with lower copper ratios). Consequently, speaker efficiency η improves by 5%, maintaining output power stability [11].

This scheme leverages DCCA's material adaptability, proving structural optimization of conductors directly enhances thermal management

4. Technological Evolution and Development Trends

4.1 Technological evolution

The technological evolution of speakers/headphones spans key milestones: In the 1920s, the invention of dynamic speakers laid the foundation, leveraging electromagnetic principles to convert electrical signals to sound. The 1980s witnessed a breakthrough with neodymium magnet technology, enabling stronger magnetic fields for compact, high-performance drivers. By the 2000s, miniaturization drove the rise of True Wireless Stereo (TWS) headphones, integrating microelectronics and wireless connectivity to achieve portable, cable-free designs. This progression reflects a trajectory from functional innovation to material optimization and miniaturized integration, reshaping audio device design and user experience.

4.2 Current Technical Challenges

Key challenges in acoustic devices stem from hardware constraints and performance trade-offs. In TWS ANC headphones, the coupling effect amplifies low-frequency sounds, aiding bass response but magnifying noise from motion/wind, causing microphone saturation and ANC instability. Built-in high-pass filters (<50 Hz) mitigate this but hinder passive sensing reliant on <3 Hz signals (e.g., heart rate monitoring). Speaker nonlinearity, generating unintended low-frequency intermodulation products, further disrupts low-frequency sensing [14]. For speakers, diaphragm materials struggle to balance low density, high strength, and wideband response, limiting fidelity [15].

Due to intrinsic thermal effects and nonlinearities that occur during operation, transducers used in headphones present significant technical problems. The voice coil's heating is one of the most significant issues. As the coil's operating temperature increases, so does its electrical resistance. This temperature impact reduces the system's acoustic output and causes power compression, which impairs long-term system performance. Small transducers, like those in headphones, have limited area, which hinders their ability to dissipate heat effectively.

In addition to heat restrictions, mechanical nonlinearities also impact performance. These include the movement of the voice coil, which alters the magnetic field and produces a nonlinear force. When the coil moves away from its resting position, the magnetic connection between the coil and magnet weakens, distorting the audio signal. Additionally, the suspension system, which supports the diaphragm, softens with large displacements. This decrease in compliance contributes to low-frequency distortion and makes the driver less stable at high amplitudes.

Such nonlinear behaviors not only affect sound quality but also pose challenges for accurate modeling and reliable performance prediction. According to Klippel (2000), these internal mechanisms are key contributors to distortion and efficiency loss in headphone transducers. Addressing them requires a deep understanding of the physical behavior under large signals, along with advanced diagnostic techniques that can guide more robust and linear transducer designs [16].

4.3 Future Development Directions

The future of nanocomposite diaphragms and superconducting magnets lies in the integration of intelligent feedback adaptive tuning and increasingly compact, coordinated multi-drive systems. In advanced applications, such as high-frequency acoustic devices or energy harvesters, multi-drive unit collaboration will evolve toward tighter integration and smarter coordination. Drawing inspiration from the control architectures in power converters, a unified control unit could manage multiple drive elements with improved synchronization and minimal communication latency—serving as a foundation for more complex real-time vibration shaping [17]. Rather than being a separate innovation, such collaboration becomes a natural extension of next-generation systems where hardware miniaturization and algorithmic co-optimization are essential.

In the meantime, systems will be able to optimize operating parameters on their own through intelligent tuning via adaptive feedback, which is similar to the extremum seeking techniques employed in particle accelerators. By leveraging real-time data (e.g., vibration amplitude, magnetic field fluctuations), machine learning models can continuously refine drive voltage or magnetic bias to adapt to dynamic environments [18]. For instance, an adaptive tuning system can be constructed as a closed-loop pipeline: MEMS sensors collect acoustic pressure signals → a Fourier transform extracts frequency response features → an LSTM neural network predicts distortion-prone frequency bands → a compensation voltage signal is generated in real time. This framework has already been partially realized in commercial products: Bose QC Ultra headphones demonstrate real-time correction within 10 ms, achieving a 35% reduction in group delay in the 100–500 Hz range.

The ability of superconducting magnets to produce extremely powerful magnetic fields (>5 T, as opposed to ~1.4 T for NdFeB) offers special benefits for next-generation acoustic systems. However, the large and expensive cryogenic cooling systems now restrict their practical application; liquid helium-based solutions are usually more than 500 cm^3 and cost more than $10,000, which limits their use to specialized industries like medical imaging. In the future, a feasible substitute might be provided by the downsizing of high-temperature superconductors (such as YBCO, which operates at -196 °C in liquid nitrogen). The adoption of such technologies in consumer electronics is still hampered by major material, thermal, and financial constraints [19].

These advancements demand a convergence of materials science, control engineering, and embedded intelligence, collectively shaping a new generation of responsive, high-performance smart devices.

5. Conclusion

The electromagnetic drive remains the dominant technology in sound transducer technology, serving as the foundation for electroacoustic conversion via the Lorentz force principle. Its core design hinges on optimizing magnetic circuits for field uniformity—particularly with high-energy NdFeB magnets and innovating diaphragms to balance weight, rigidity, and internal friction for extended frequency response. Key advancements, such as copper-clad aluminum voice coils and multi-driver configurations, address trade-offs in miniaturization and acoustic fidelity, while challenges like thermal management and nonlinear distortion necessitate integrated solutions.

Cross-disciplinary collaboration is necessary for future advancements in machine learning for adaptive feedback tuning, materials engineering for nanocomposite diaphragms, and control theory for multi-drive unit synchronization. As a result of this convergence, transducers will become smarter and more efficient, establishing electromagnetic drive technology as the foundation of next-generation audio equipment.

References

[1] D. J. Griffiths, Introduction to Electrodynamics, 4th ed. Boston, MA: Pearson Education, 2013.

[2] L. L. Beranek and T. J. Mellow, Acoustics: Sound Fields and Transducers. Academic Press, 2012.

[3] T. D. Rossing, Springer Handbook of Acoustics. Springer, 2007.

[4] D. M. Howard and J. A. S. Angus, Acoustics and Psychoacoustics, 3rd ed. Oxford, UK: Focal Press, 2006.

[5] D. Self, Audio Engineering Explained. Oxford, UK: Focal Press, 2013.

[6] F. E. Toole, Sound Reproduction: Loudspeakers and Rooms. Oxford, UK: Focal Press, 2008.

[7] Xia L. Discussion on optimal design of loudspeaker magnetic circuit system[J]. Audio Engineering, 2021, 45(3): 36-41.

[8] Gutfleisch, O., Willard, M. A., Brück, E., Chen, C. H., Sankar, S. G., & Liu, J. P. (2011). Magnetic materials and devices for the 21st century: Stronger, lighter, and more energy efficient. Journal of Advanced Materials, 23(7), 821–842. https://doi.org/10.1002/adma.201002180

[9] Wu W, Zhou B, Liu Z, et al. Design of highly uniform magnetic field coils based on a particle swarm optimization algorithm[J]. Ieee Access, 2019, 7: 125310-125322.

[10] Umemoto S, Works S, Mitani T. Newly-developed loudspeaker diaphragm which includes carbon nanotube[C]//2013 IEEE 2nd Global Conference on Consumer Electronics (GCCE). IEEE, 2013: 204-206.

[11] [Koiwa, Y., Sugawara, M., & Fukuhara, M. (2020). Copper-

ISSN 2959-6157

Clad Aluminum Wire DCCA for Speakers on Mobile Devices. SEI Technical Review, 90, 27-30.
[12] Cooper, J., & Saini, V. (2021). Utilization of Unused Speaker Holes for Improved Thermal Management in a Laptop. Technical Disclosure Commons.
[13] Miao, Y., Zhang, H., & Metze, F. (2014). Towards Speaker Adaptive Training of Deep Neural Network Acoustic Models. Interspeech 2014.
[14] Bi, H. et al. (2024). Small, 20(45), 2406559.
[15] Fan, X., & Thormundsson, T. (2023). In UbiComp/ISWC ’23 Adjunct (pp. 342–345). ACM.
[16] Klippel W. Diagnosis and remedy of nonlinearities in electrodynamical transducers[C]//Audio Engineering Society Convention 109. Audio Engineering Society, 2000.
[17] Kulkarni, A. (2012). Magnetic nanocomposites. Dissertation, Christian-Albrechts-Universität zu Kiel.
[18] Reijola, A. (2024). Combined control of multiple power converters in a single control unit. Master’s Thesis, Aalto University.
[19] Scheinker A, Cropp F, Paiagua S, et al. An adaptive approach to machine learning for compact particle accelerators[J]. Scientific reports, 2021, 11(1): 19187.