LOUDSPEAKER VOICE COIL IN VARIOUS MAGNETIC ENVIRONMENTS : A PRACTICAL APPROACH FOR STUDENTS

Antonin Novak **Pierrick Lotton**
Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR 6613,
Institut d'Acoustique - Graduate School (IA-GS), CNRS,
Le Mans Université, France

ABSTRACT

After teaching transducer measurements to master's students for several years, we noticed that the voice coil inductance and the associated physical phenomena inside the loudspeaker motor are frequently considered the most challenging concepts for students to grasp. Consequently, we developed a 3-hour practical lab session to address this topic, where students are guided to measure the voice coil in various configurations. The voice coil impedance is measured in various conditions, including air, in the disassembled speaker motor (without magnet), inside conductive but non-magnetic materials, with another coil shorted in its proximity, and inside the assembled motor. The objective of the lab is to gain a clear understanding of the influence of each phenomenon related to permeability, currents, and other related factors. The purpose of this document is twofold: first, to serve as a support material for students; and second, to share our university laboratory experience with other institutions.

Keywords: *loudspeker motor, voice coil, practical lab*

1. INTRODUCTION

A voice coil is a component of a loudspeaker that converts electrical energy into mechanical energy, causing the speaker cone to vibrate and produce sound waves [1]. It is typically made of a coil of wire wrapped around a cylindrical former, and when an electrical current is applied to the coil, it interacts with a magnetic field to produce a force that moves the speaker cone back and forth, producing sound.

Despite its importance and simple structure, the complex physical phenomena that influence the voice coil's behavior make it a challenging topic for students to comprehend fully. To address this challenge, we developed a 3-hour practical lab session that explores the various factors that affect voice coil performance, including permeability [2], eddy currents [2–4], and other related phenomena [5]. The main objective of the practical work is to study and understand inductance and eddy currents.

During the experiment, students use two disassembled loudspeakers, along with several metallic parts and a speaker coil. The measurements are conducted under various conditions, including in air, on a copper core, on an iron core, with and without shorting rings, and with and without magnets.

2. MEASUREMENT SETUP

2.1 Measurement equipment

The measurement setup used in this practical work (Fig. 1) is designed to measure the impedance of a loudspeaker voice coil as a function of frequency. This type of setup is relatively simple to construct and can be done with a data acquisition card and commonly available laboratory equipment.

During the practical work, we use a National Instruments USB 4431 data acquisition device, which has one output and four inputs (only two inputs are required). A Python script is used to communicate with the data acquisition device and to generate a swept-sine signal with a starting frequency of 10 Hz and an ending frequency of 22 kHz. The excitation signal is amplified by a standard class AB audio amplifier. Students measure the voltage across the voice coil and the voltage across a $1\ \Omega$ resistor, which gives us the voice coil current . The sample rate is set to 48 kHz, which allows us to accurately capture the data across the desired frequency range.

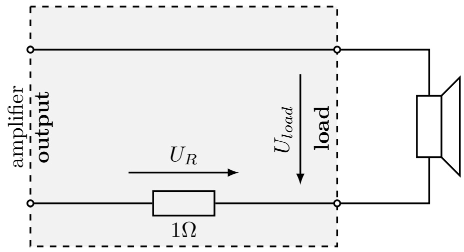
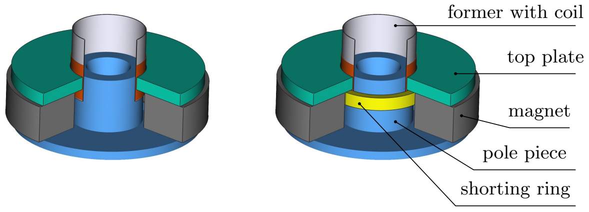


Figure 1. A setup for impedance measurement.



(a) Faital 5FE100 (b) Faital 5FE120

Figure 2. (a) Faital 5FE100 driver motor without shorting ring and (b) Faital 5FE120 driver motor with a shorting ring.

2.2 Additional equipment

In this practical work, students measure the impedance of the voice coil under many conditions to show the influence of different physical phenomena separately. They use a whole loudspeaker motor, a disassembled loudspeaker motor of the same loudspeaker type, some copper pieces, and another coil.

For this practical work, we used the Faital 5FE100 motor, although any electrodynamic loudspeaker could be used in theory. We chose this particular motor because there is a similar version available (Faital 5FE120) that includes a shorting ring (shown in Fig. 2), which allows the effect of the presence of a shorting ring to be included in the practical work. To obtain the motor, we removed the mechanical parts of an existing loudspeaker by cutting out the surround and spider and carefully soldered out the voice coil to make it available for use in the practical work. To get another motor disassembled we used a bench wise, nonferite pieces and a hammer. We completely removed the magnet and replaced it with a piece of the same dimensions. Alternatively, disassembled loudspeaker motor parts can be purchased from a supplier.

Additionally, we used a piece of copper rod with a diameter slightly smaller than that of the voice coil to fit inside, as well as two pieces of copper hollow rod - one with a diameter slightly smaller than that of the voice coil and the other with a diameter slightly higher than that of the voice coil (Fig. 3). The height of the rods is slightly higher than the one of the voice coil. Finally, we used another voice coil with shorted terminals and a slightly lower diameter to fit inside the measured voice coil.

To secure the voice coil inside the motor, two thin plastic sheets are inserted into the gap. These sheets have a height that allows for easy insertion and removal. The voice coil is then wrapped around the plastic sheets and slid down into the motor. Once inside the motor, the voice coil is well fixed, preventing any movement during the measurements. However, it remains easy to remove by pulling the plastic sheets.

3. EXPERIMENTS

3.1 Voice coil behavior

In the first experiment, students conduct two measurements: the first is performed with a voice coil blocked inside the motor, and the second is performed with the voice coil placed outside of any conductive or magnetic material, i.e. in air. When in motor, the voice coil is centered in the air gap and its position corresponds to the voice coil rest position in a complete (assembled) loudspeaker.

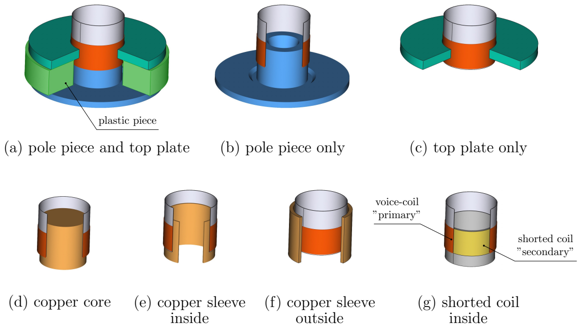
Fig. 4 shows the results of the apparent resistance,

$$R_e(\omega) = \Re\{Z_e(\omega)\}, \tag{1}$$

and the apparent inductance

$$L_e(\omega) = \frac{\Im\{Z_e(\omega)\}}{\omega}, \tag{2}$$

as function of frequency f (note that $\omega = 2\pi f$ is the angular frequency). On the one hand, when a coil is placed in air (blue curve), the only magnetic field that affects it is the one produced by the current in the coil itself. In this case, the impedance of the coil is determined solely by the inductance of the coil and resistive losses that occur in the coil. In such a case both the inductance and resistance are independent of frequency. On the other hand, the blocked impedance of the voice coil inside the motor (orange curve) exhibits a significant change with frequency. The resistance increases with frequency, while the inductance decreases with frequency.



(a) pole piece and top plate (b) pole piece only (c) top plate only

(d) copper core (e) copper sleeve inside (f) copper sleeve outside (g) shorted coil inside

Figure 3. Experimental configurations.

3.2 Influence of materials

To investigate the physical phenomena underlying the previous results, students conduct experiments replacing loudspeaker motor components with different materials or adding/removing pieces.

First, to determine which part of a loudspeaker motor has the greatest influence on the frequency dependency of blocked impedance, students use a disassembled motor, replacing the permanent magnet with a plastic piece of the same dimensions (Fig.3(a)). This isolates the magnetic field effects created by the magnet from the pole piece and top plate. Results (green curve in Fig.4) show that the blocked impedance's frequency dependence resembles the previous measurement on the assembled motor, indicating the pole piece and top plate's significant role.

Next, students measure the effect of the pole piece and the top plate separately using setups depicted in Fig. 3(b) and Fig. 3(c). Both results (Fig. 5) exhibit a similar trend of increasing resistance and decreasing inductance with frequency, but differ significantly in amplitude. To further investigate this effect, students perform a measurement with a copper core (Fig. 3(d)). The results of this measurement are represented by the red curve in Fig. 5.

To understand the observed effects, we explain two electromagnetic phenomena to students: inductance and permeability, and eddy currents. We focus first on the low frequency domain, where inductance and permeability effects dominate.

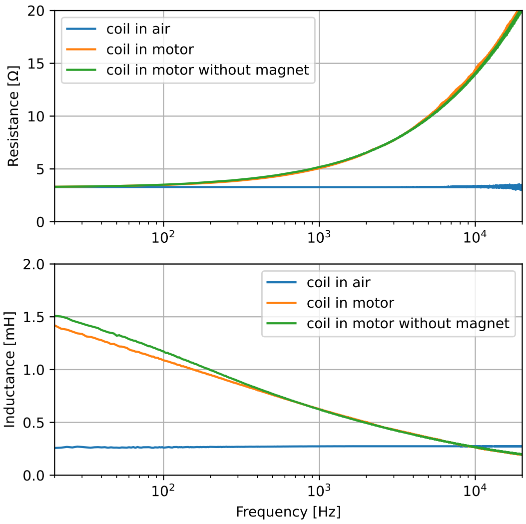


Figure 4. Measured resistance and inductance of a blocked voice coil: (blue) in air, (orange) in a loudspeaker motor, (green) in a loudspeaker motor with a magnet replaced by a plastic piece.

Inductance

The behavior of an inductor carrying current is analogous to that of a mass m in motion, as they both store energy. When a mass moves, it gains kinetic energy that is proportional to its velocity v squared, expressed as $\frac{1}{2}mv^2$. Similarly, a coil carrying current i stores energy in its magnetic field. This energy is proportional to the square of the current and can be calculated as $\frac{1}{2}Li^2$, where L is the inductance of the coil.

We can use an example of a carousel spinning around a central axis to illustrate the analogy between an inductor carrying current and a mass in motion. Just as the mass of the carousel determines how much kinetic energy it stores as it spins, the inductance of the coil determines how much energy it can store in its magnetic field as current flows through it. Just as it takes more energy to stop a carousel with a high mass because it has more kinetic energy stored in its motion, it also takes more energy to change the current through an inductor with a high inductance because it has more magnetic energy stored in its field.

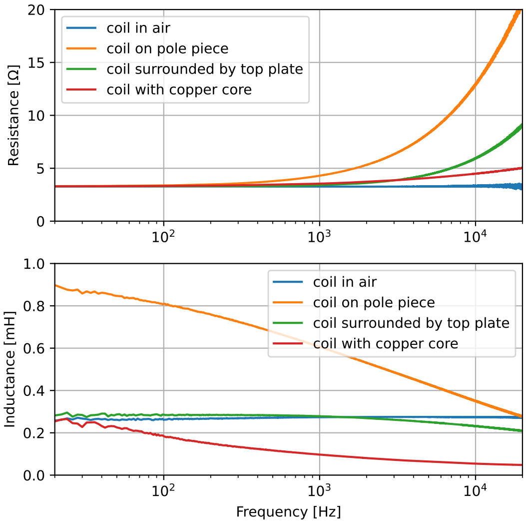


Figure 5. Measured resistance and inductance of a blocked voice coil: (blue) in air, (orange) on a pole-piece only, (green) surrounded by a top plate only, (red) with a copper core.

Permeability
Adding a ferromagnetic material with high permeability to the coil increases the inductance of the coil, and makes it more difficult to change the current flowing through it, just like adding mass to the carousel makes it more difficult to change its velocity. Indeed, a ferromagnetic material consists of small magnetic domains that can align themselves with the magnetic field of the coil. The alignment of the domains increases the magnetic field strength and the amount of energy stored in the coil's magnetic field.

Consequently, the voice coil of a loudspeaker has a higher inductance when placed in its motor, due to the high permeability of the iron pole piece. However, when a voice coil is surrounded by a ferromagnetic material, e.g. a top plate, but its core is air only (Fig. 3(c)), the inductance of the voice coil can still be affected by the ferromagnetic material, but to a much lesser degree than if the material was part of the core. This is because the magnetic flux path of the voice coil is longer and more spread outside the voice coil than inside the voice coil where it is concentrated.

As copper has a very low magnetic permeability, which is similar to that of air, using it as a voice coil core will not significantly affect the inductance of the voice coil at low frequencies as can bee seen in the results of the measurement represented by the red curve in Fig. 5.

At higher frequencies, the presence of eddy currents becomes more prominent as they are influenced by the rate of change. The voice coil, at these frequencies, may experience eddy currents in any conductive material nearby, the pole piece, the top plate, as well as in the copper core. The strength of eddy currents depends on many factors, but mainly the geometry and conductivity of the material.

Eddy currents
Eddy currents are electric currents, i.e. the flow of free electrons in a material, that circulate within a conductor when it is exposed to a changing magnetic field. The magnetic field is a conservative field, which means that it tends to resist any changes in itself. When a magnetic field changes, it induces electric currents, such as eddy currents, that generate their own magnetic fields in opposition to the original field. This phenomenon is known as Lenz's Law, which states that the direction of an induced current is such that it opposes the change that produced it. Consequently, the eddy currents can cause a reduction in the coil inductance as the total magnetic energy is reduced. This effect can be particularly noticeable at higher frequencies, where the changes of magnetic field are faster.

In the last experiment of this part students conduct measurements using two copper sleeves of different diameters. The first configuration is with a copper sleeve of slightly smaller diameter than the voice coil, placed inside the coil (Fig. 3(e)), while the second configuration is with a slightly larger diameter copper sleeve, placed outside the voice coil (Fig. 3(f)). The results are plotted in Fig. 6 and compared with the previous measurement with the whole copper core. Students should note that the placement of the copper sleeve (inside or outside the coil) has very little influence on this behavior, and that the skin effect also plays an important role in eddy currents. Although the shape of each curve differs slightly, the tendency, i.e., the drop of inductance with increasing frequency and the increase of resistance with increasing frequency, is kept unchanged.

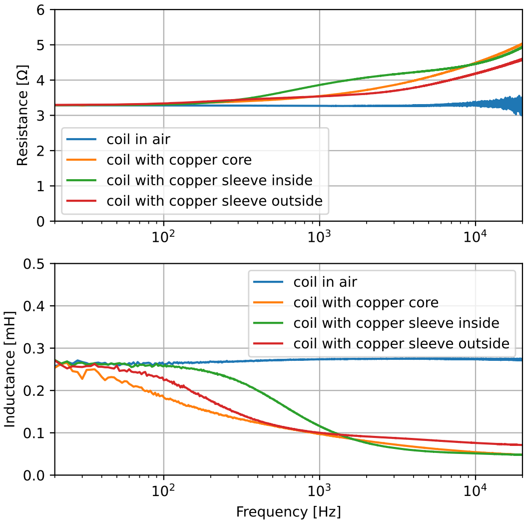


Figure 6. Measured resistance and inductance of a blocked voice coil: (blue) in air, (orange) with a copper core, (green) with a copper sleeve inside, (red) with a copper sleeve outside.

3.3 Like a shorted transformer

The experiments conducted thus far have helped students understand why inductance decreases with frequency. However, the reason behind the increase in resistance with frequency may still be unclear. To provide clarity on this point, the students are asked to perform an experiment where they use another coil which is shorted and placed inside the voice coil (Fig. 3(g)) and compare the results with the experiment with copper sleeve inside the voice coil.

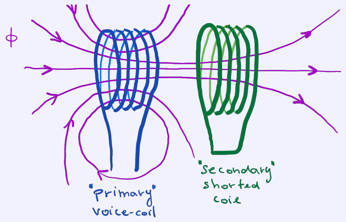
The observation of similar results in inductance and resistance behavior in the coil with a copper sleeve and the shorted secondary coil (Fig. 7) can again be attributed to the effect of eddy currents. The shorted secondary coil also experiences the changing magnetic field, and currents are induced in the same way as the eddy currents in the copper sleeve. The advantage of using the shorted secondary coil is that we can describe the frequency-dependent impedance with equations.

Shorted secondary coil

The effect of the shorted secondary coil on the voice coil's impedance, can be derived from the two following equations. The first is describing the primary coil (voice coil), the second the secondary shorted coil as

$$\begin{aligned} U(\omega) &= R_e I(\omega) + j\omega L_e I(\omega) - M j\omega I_s(\omega), \\ 0 &= R_s I_s(\omega) + j\omega L_s I_s(\omega) - M j\omega I(\omega), \end{aligned}$$

where R_e, L_e are associated to the voice coil resistance and inductance, R_s and L_s represent the resistance and inductance of the secondary coil, and M is the mutual inductance between both coils [6]. The following drawing represents schematically the primary and the secondary coil and the principle of the mutual inductance M.



The impedance $Z_e(\omega)$ seen by the voice coil can be then expressed from the two previous equations as

$$Z_e(\omega) = \frac{U(\omega)}{I(\omega)} = R_e + j\omega L_e + \frac{\omega^2 M^2}{R_s + j\omega L_s},$$

from which the resistance and inductance can be expressed from its real and imaginary part as

$$\Re\{Z_e(\omega)\} = R_e + \frac{\omega^2 M^2 R_s}{{R_s}^2 + \omega^2 {L_s}^2},$$

$$\frac{\Im\{Z_e(\omega)\}}{\omega} = L_e - \frac{\omega^2 M^2 L_s}{{R_s}^2 + \omega^2 {L_s}^2}.$$

Note, that the resistance, i.e. the real part of the impedance is increasing with frequency and inductance is decreasing with frequency.

3.4 Position dependence

Previous experiments have demonstrated that voice coil impedance exhibits significant frequency dependence due to eddy currents generated in conductive materials located

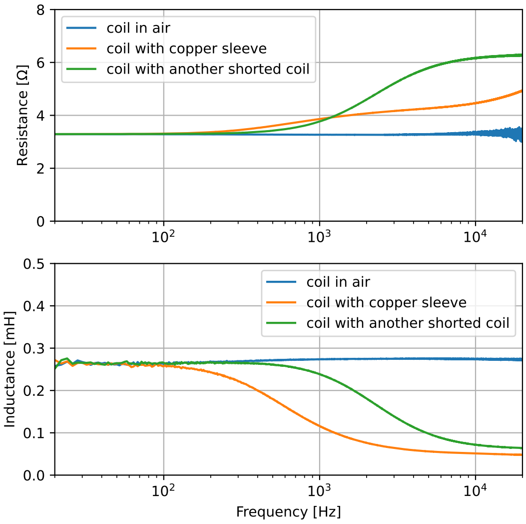


Figure 7. Measured resistance and inductance of a blocked voice coil: (blue) in air, (orange) with a copper sleeve inside, (green) with another shorted coil inside the voice coil.

in close proximity to the voice coil. As the voice coil moves during actual operation, its surrounding environment changes, with the coil becoming more surrounded by pole pieces when it moves deeper into the motor, and vice versa. This suggests that the voice coil's impedance may vary during the loudspeaker's real-world operation as the position of the voice coil changes [7,8]. To investigate the influence of voice coil position on its impedance, the following experiment is proposed to students.

The voice coil is placed in various positions in an assembled motor as shown in Fig. 8, and for each position, the impedance is measured while the coil is blocked. The same procedure is repeated for the loudspeaker motor with a shorting ring, as depicted in Fig. 2(b). The results are presented in Fig. 9, where the arrow indicates the position from the voice coil being outside the motor to it being completely immersed inside the motor. The results obtained with a normal motor (i.e., a motor without a shorting ring) (Fig. 9(a)) show that both the resistance and inductance are highly dependent on the voice coil position. However, when the motor is equipped with a shorting ring (Fig. 9(b)), the dependence on position is greatly reduced, particularly in the useful frequency range for this midrange loudspeaker, which is approximately 100 Hz to 3 kHz.

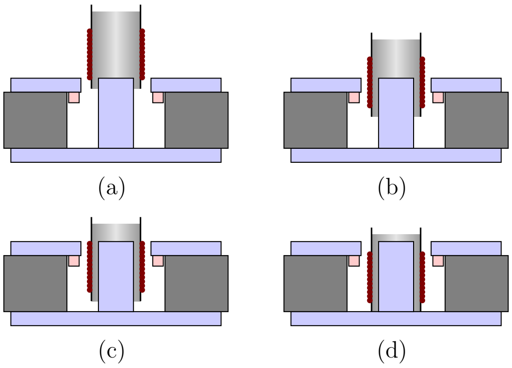
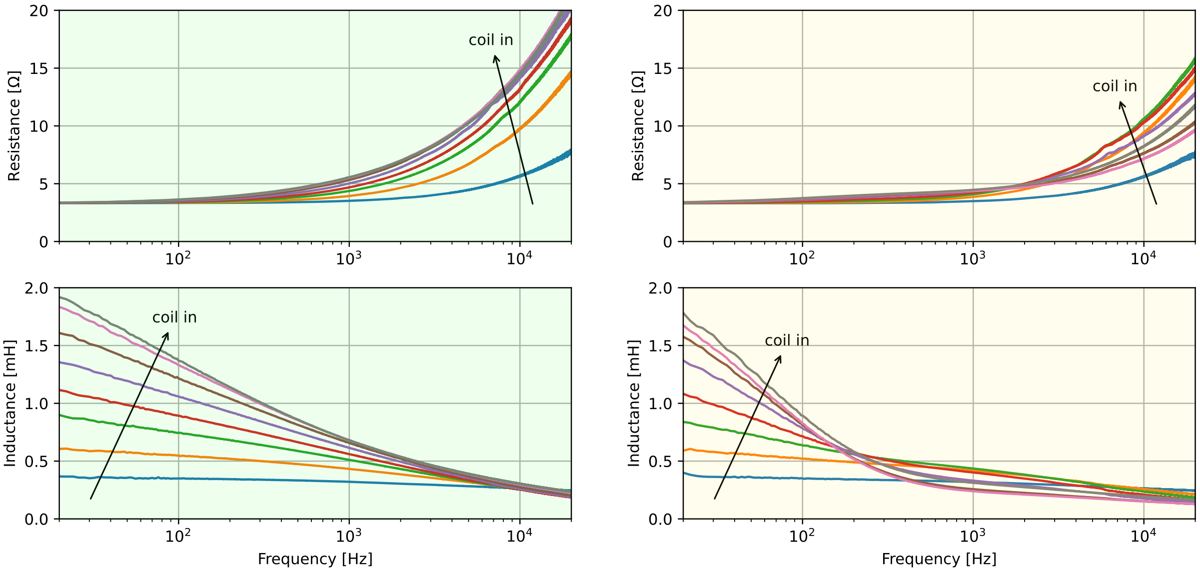


Figure 8. Examples of voice coil placement in position dependence experiment. The shorting rings (pink color) are only present on the Faital 5FE120 motor.

The shorting ring, typically made of aluminum or another conductive nonferrous material, is located in close proximity to the voice coil, thereby generating eddy currents in it instead of in pole pieces. Since the conductivity of a shorting ring is higher than that of pole pieces, its resistance is lower, resulting in a reduction in the total resistance experienced by the voice-coil. This effect becomes stronger when the voice coil is fully immersed in the motor near the shorting ring, thus reducing the dependence of impedance on position.

3.5 Current distortion

The final experiment investigates current distortion. For this test, the voice coil is blocked inside the motor and a sinusoidal voltage signal with a frequency of 300 Hz is applied to it. When an electrical current flows through the voice coil of a loudspeaker, it generates its own magnetic field. This magnetic field interacts with the static magnetic field generated by the speaker's magnets, resulting in a phenomenon called flux modulation [9,10]. Essentially, the magnetic flux created by the motor is modulated by the magnetic flux of the voice coil, resulting in nonlinear effects. Nonlinearities in the magnetic circuit can introduce distortions in the current waveform, leading to the presence of higher harmonics. Fig. 10 shows the power spectra of the current for both the speaker with and without a shorting ring.



(a) normal motor

(b) motor with shorting ring

Figure 9. Measured resistance and inductance of a blocked voice coil for different voice coil positions.

The speaker without a shorting ring (Fig. 10(a)) exhibits stronger current distortion than the speaker with a shorting ring (Fig. 10(b)). The reduction of distortion in the speaker with shorting ring can be attributed to eddy currents that are induced in the conductive material surrounding the voice coil, such as the shorting ring. These eddy currents are created in a way that they attempt to counteract changes in the magnetic field. This results in the creation of a magnetic field that opposes the magnetic field generated by the voice coil. This decreases the flux modulation and helps to reduce distortions in the current [11].

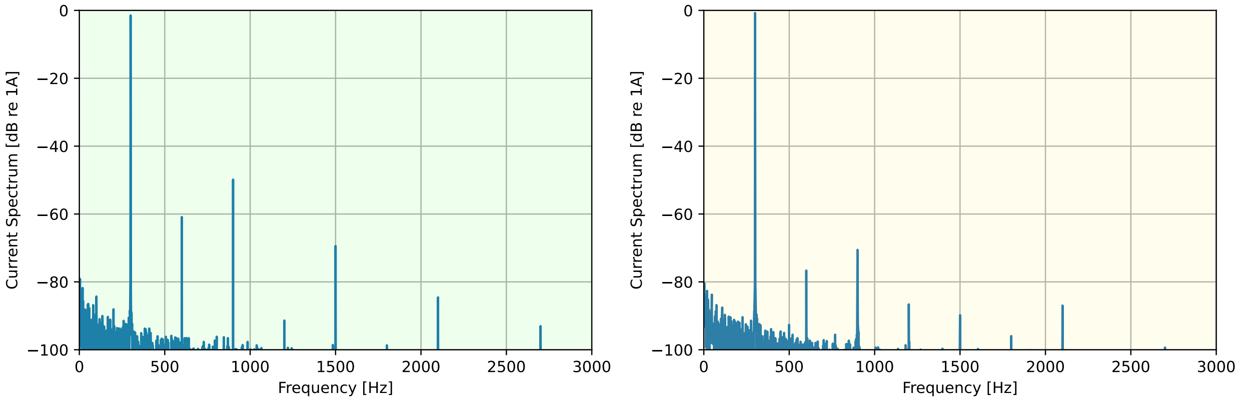
4. DISCUSSION & CONCLUSION

The practical work presented in this paper provides students with a hands-on approach to understanding the complex physical phenomena that affect the behavior of voice coils in loudspeakers. As discussed above, while voice coils are a seemingly simple device, the factors that influence their performance are anything but simple. The practical exercises proposed in this work help to bridge the gap between theory and application by allowing students to measure the blocked impedance of a coil and observe the effects of different materials and conditions on its behavior.

One key concept that students will explore in this work is the inductance of a voice coil. While this may seem like a minor factor, it can significantly impact the loudspeaker's performance, particularly at higher frequencies. By understanding the role of inductance, students will gain insights into how they can optimize the design of a loudspeaker for optimal performance.

Another important concept that students explore is the use of eddy currents in loudspeakers. While eddy currents may seem like an unwanted side-effect, they can be incredibly useful in reducing distortion related to position dependence and current dependence, leading to increased sensitivity and improved sound quality. The correct placement of these components is crucial when designing loudspeakers [11].

In conclusion, the practical work presented in this paper provides an effective and engaging way for students to learn about the physical phenomena of inductance and eddy currents in loudspeaker voice coils. Through hands-on experimentation and measurement, students can



(a) normal motor

(b) motor with shorting ring

Figure 10. Current spectra for 300 Hz excitation signal of a blocked voice-coil.

gain a deeper understanding of the role of coil inductance and eddy currents in loudspeaker design and performance. Additionally, the use of different conditions during the measurements allows students to explore and observe the impact of these phenomena on the speaker's impedance and sensitivity. This practical work has been successfully running for four years, and we have received consistently positive feedback from students who found it both informative and enjoyable.

5. REFERENCES

[1] M. R. Gander, "Moving-coil loudspeaker topology as an indicator of linear excursion capability," *J. Audio Eng. Soc*, vol. 29, pp. 10–26, 1981.

[2] F. M. Murray, "The voice coil & eddy currents," in *Audio Engineering Society Convention 97*, Audio Engineering Society, 1994.

[3] J. Vanderkooy, "A model of loudspeaker driver impedance incorporating eddy currents in the pole structure," *J. Audio Eng. Soc.*, vol. 37, p. 119–128, 1989.

[4] K. Thorborg and A. D. Unruh, "Electrical equivalent circuit model for dynamic moving-coil transducers incorporating a semi-inductor," *J. Audio Eng. Soc.*, vol. 56, pp. 696–709, 2008.

[5] D. R. Birt, "Nonlinearities in moving-coil loudspeakers with overhung voice coils," *J. Audio Eng. Soc*, vol. 39, pp. 219–231, 1991.

[6] I. Anazawa, "Impact of the coupling factor on lossy voice coil impedance," in *Audio Engineering Society Convention 146*, Audio Engineering Society, 2019.

[7] M. Dodd, W. Klippel, and J. Oclee-Brown, "Voice coil impedance as a function of frequency and displacement," in *Audio Engineering Society Convention 117*, Audio Engineering Society, 2004.

[8] W. Klippel, "Tutorial: Loudspeaker nonlinearities—causes, parameters, symptoms," *J. Audio Eng. Soc.*, vol. 54, pp. 907–939, 2006.

[9] I. A. Aldoshina, A. Voishvillo, and V. Mazin, "Modeling of flux modulation distortion in moving-coil loudspeakers by the finite-element method," in *Audio Engineering Society Convention 98*, Audio Engineering Society, 1995.

[10] M. Halvorsen, C. Tinggaard, and F. T. Agerkvist, "Flux modulation in the electrodynamic loudspeaker," in *Audio Engineering Society Convention 138*, Audio Engineering Society, 2015.

[11] L. Bortot, "Optimization of demodulation rings in professional loudspeakers," 2013.