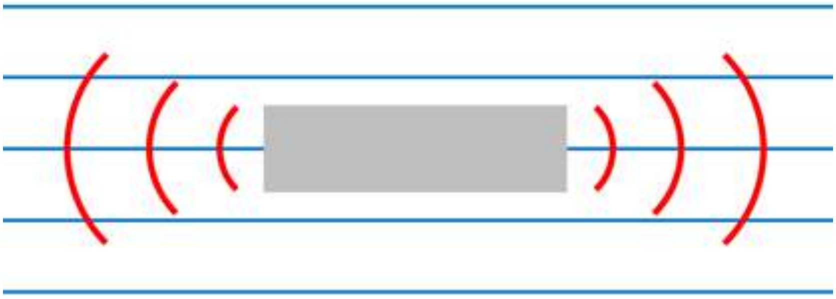
Musical Ferrite

Acoustics of a Ferrite Rod in a Changing Magnetic Field

To what extent can the vibrations of a ferrite rod inserted into a periodically changing magnetic field be described by physical theory?



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Year: 2020

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Word Count: 14'094

Acknowledgement

I would like to express my sincere thanks to my physics teacher for helping me through the process of deciding which topic to choose for this paper and for always being there when I had a question about the physics, the experiments, or anything at all. He taught me most of what I know when it comes to physics and was one of the people who enhanced my interest in the subject.

Furthermore, I would like to thank Mr. Keller who helped me with setting up my experiments and gave me the resources to do my experiments. He was the one who got me into the SYPT in the first place, so I want to express my thanks to him and all SYPT team members for making my entire “career” in the SYPT possible and thus this project.

Throughout this project I contacted very helpful people to whom I am grateful: Professor Johann W. Kolar (head of the Power System Electronic Laboratory of ETH Zürich) for his advice and information about current knowledge and Stefan Schneider (client manager at Megatron AG) for providing me with extra ferrites.

My thanks also go to my friends and family for their advice and support during the process of writing this paper. In particular, I would like to thank my parents for their feedback and proofreading my work.

Abstract

My interest in acoustics dates back to past engagements in musical sound creation. I feel that projects concerning audible sound reveal tangible evidence of the experiment working, because something can be heard besides a visual observation. This paper is about unwanted tones that can, for example, appear in voltage transformers. Vibrations of building parts made out of ferrite cause such noises. Relating to this phenomenon being debated at the Swiss Young Physicists' Tournament 2020, I formulated the research question:

To what extent can the vibrations of a ferrite rod inserted into a periodically changing magnetic field be described by physical theory?

My investigations led to a theoretical explanation of the phenomenon, where two compelling fields (magnetism and acoustics) were combined. I justified the vibrations of the ferrite rod based on my existing and newly acquired knowledge in physics, especially magnetostriction. Not only was I interested in comprehending the phenomenon in theory, I conducted various experiments to actually create the expected sound triggered by the vibrations of the ferrite rods. Measuring the sound waves was an appropriate way to test the phenomenon as the rod's vibrations cause air pressure waves and thus audible sounds. Analyzing my results showed that the predicted frequencies of the sound waves were experimentally confirmed (frequency spectrum was done with Fast Fourier Transform). The relations between the intensity of a ferrite rod's vibrations (or loudness of the sound) and the rod's material (analyzed were ferrite's magnetic permeability and coercive magnetic field strength) or dimensions (analyzed were rod's length and volume) were experimentally tested, but could only be partially explained.

The experiments were performed with 5 ferrite rods and focused on specific material parameters. It would be interesting to do further studies addressing more parameters and also measuring dimensional changes of the rods instead of the produced sounds.

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1 Introduction

Music is always around me: I listen to it, I play it with my saxophone or I experiment with it. For example, I have explored the musical sound that an open bottle creates when blowing over it. What I do not like, though, are certain noises: a ceiling lamp buzzing, a microwave humming or the table in my school's physics laboratory droning when the electricity is switched on. Due to my love of physics I decided to learn about these unwanted audible sounds originating from electric appliances. Furthermore, the acquired knowledge was a great preparation for the SYPT 2020 if competing with problem number 4 (ProIYPT-CH, 2004).

1.1 Phenomenon and Research Question

Phenomenon "Musical Ferrite"

Electric currents in an appliance generate magnetic fields. They have an impact on the parts of the appliance. Certain parts start vibrating and, therefore, creating forces which increase the movement of the particles in the surrounding air. Similar to vibrating vocal cords, this triggers acoustic waves and audible sounds. Such noises can be observed when parts are made out of ferrite[1]. This is the reason for the title "Musical Ferrite" of this paper.

Research Question

This paper focuses on typical building parts in electric appliances: Objects made out of ferrite. Due to the ferrite's properties, the objects vibrate when exposed to a changing magnetic field and thus produce audible sounds. Building parts made out of ferrite come in many different shapes. For consistency reasons, the research in this paper was narrowed down to objects in the shape of a solid rod, meaning a long bar or cuboid. The interesting side of the phenomenon is finding explanations for the vibrations that trigger the audible sounds. Thus, the research question was stated:

To what extent can the vibrations of a ferrite rod inserted into a periodically changing magnetic field be described by physical theory?

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[1] A ferrite is a low-cost material used for parts in electrical appliances. (Also see 2.4 Ferrite Materials.)

1.2 Existing Knowledge

My search for existing academic and experimental knowledge regarding the research question showed that the phenomenon had been investigated for relatively high frequencies (noises with high pitches). However, a general theoretical explanation for all frequency levels has not yet been found (Kolar, et al., 2013) (Bienkowski & Szewczyk, 2018) (Diethelm, 1951). These findings were confirmed in my conversation[2] with Professor J. Kolar[3], one of the authors of one of the referred articles (Kolar, et al., 2013). He is a well-known expert in the field and informed me that the current research, mainly at ETH Zürich, is still aimed toward high frequencies. This is due to the industry particularly being interested in high frequencies as their presence leads to damage in machines.

1.3 Aim

The aim of this paper was to find answers to the research question by investigating the different aspects of the phenomenon shown in Figure 1.

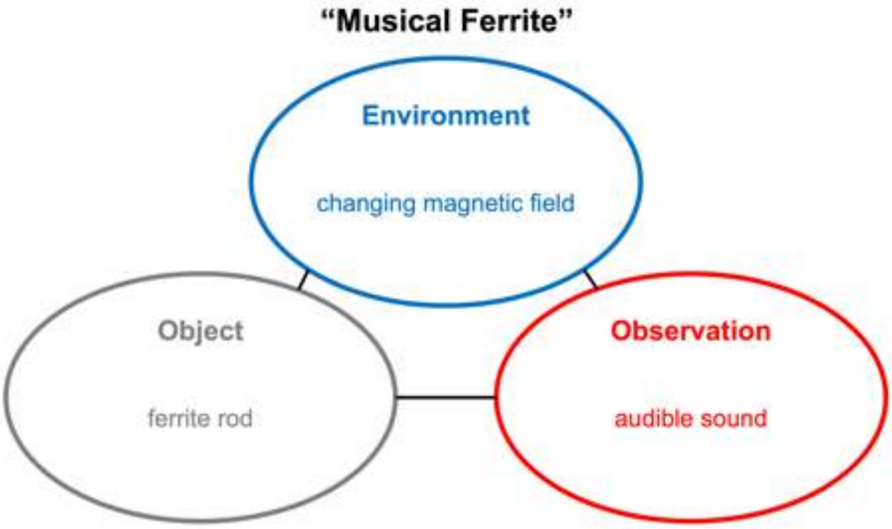

Figure 1: Overview of the Musical Ferrite's Aspects

The aspects where looked at from a theoretical and experimental angle. Debating the phenomenon at the SYPT 2020 was commented on. The paper is structured into:

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[2] Telephone call with Professor J. Kolar on 17th September 2019
[3] Professor Johann W. Kolar is the head of the Power System Electronic Laboratory of ETH Zürich

Part A: Theory

This part gives an overview of the **physical theory** with respect to the creation of the environment and its impact on the ferrite rod. Acoustics will be mentioned because not the vibrations[4], but the sounds created were measured in the experiments.

Part B: Hypotheses and Experiments

The demonstration of the phenomenon is key in this practical part. Several **hypotheses** were formulated and **tested by conducting experiments**. This part also includes the analysis and discussion of the outcomes.

Part C: Swiss Young Physicists' Tournament

An **introduction** to the tournament is given in this part. Furthermore, suggestions regarding the **preparation** for the tournament are formulated.

Summarized Findings pertaining to the Research Question

The work done for this paper resulted in physical theory explaining the "Musical Ferrite" phenomenon and supporting the outcomes of experiments done in the audible[5] frequency range between 50 and 200 Hertz (Hz). The theory:

- explained **why** the ferrite rod exposed to a changing magnetic field **vibrates,**
- **predicted** the loudest sound (**frequency** with the highest amplitude) produced and led to **theoretical ideas** addressing the appearance of other frequencies,
- supported experiments' qualitative results: **dependency** of amplitudes on **system, dimensions** and **material** of rod (quantitative predictions remain complex)

The experiments demonstrated the real-life problem of dealing with unwanted noises in electric appliances based on simple shaped ferrite rods. This paper did not address mitigating or getting rid of the sounds or dealing with different temperatures. This would certainly be an interesting field of further studies.

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[4] The resources and technical appliances to measure the very small vibrations where not available.
[5] Audible range is 20 Hz to 20 kHz (NASA, 1995). The measured frequency range of 50 to 200 Hz was due to using most common electric currents: Europe 50 Hz, USA 60Hz plus 100 Hz.

2 Part A: Theory

The following graphic (Figure 2) gives an overview of the relevant pieces to the phenomenon "Musical Ferrite" from a *theoretical* point of view:

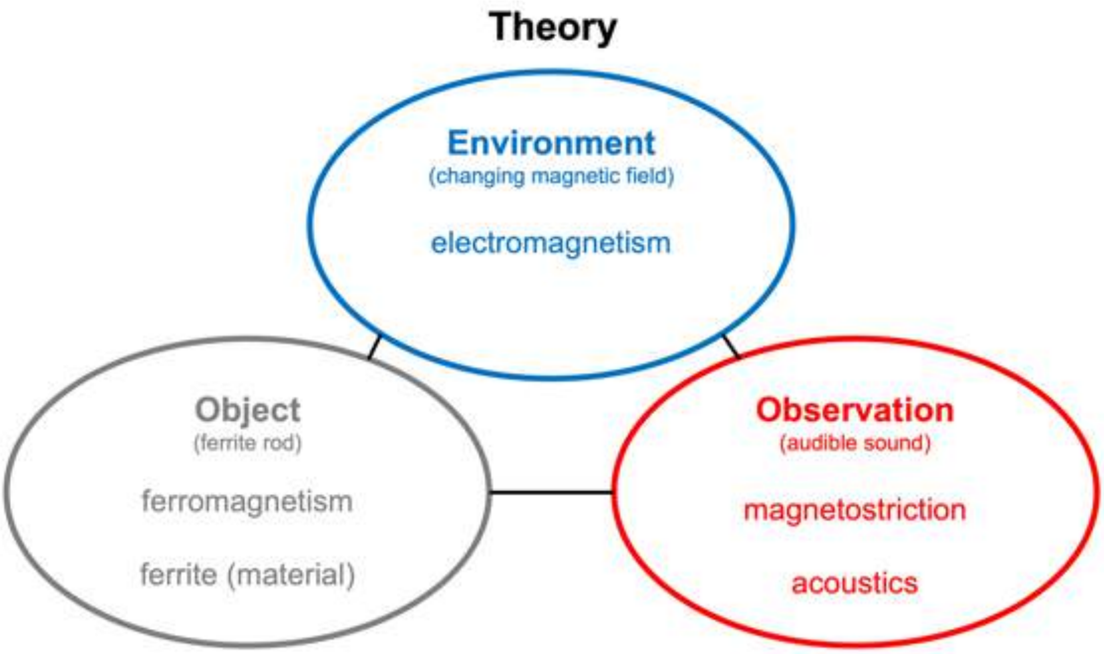

Figure 2: Overview of the Musical Ferrite's Theory

A short description and the order in this paper of the relevant parts is listed here:

2.1 Illustration of the Phenomenon

2.2	Electromagnetism:	creation of the changing magnetic field
2.3	Ferromagnetism:	magnetization of the object
2.4	Ferrite:	material of the object
2.5	Magnetostriction:	deformation and vibration of the object
2.6	Acoustics:	sounds triggered by the object's vibration

2.1 Illustration of the Phenomenon

A magnetic field is generated by a coil of wire (solenoid) fed from a signal generator. If the signal is from a *direct* electric current (DC) as shown in Figure 3, the magnetic field has a certain direction indicated by the arrows on the field lines. Figure 3 shows an object, a ferrite rod, that is inserted into the solenoid. The magnetic field has an impact on the rod's dimensions. A signal from an *alternating* electric current (AC) creates a changing magnetic field and the ferrite rod continually changes dimensions. It starts to vibrate, creates a force acting on the surrounding air particles and thus creates a sound wave, similar to vibrating vocal cords.

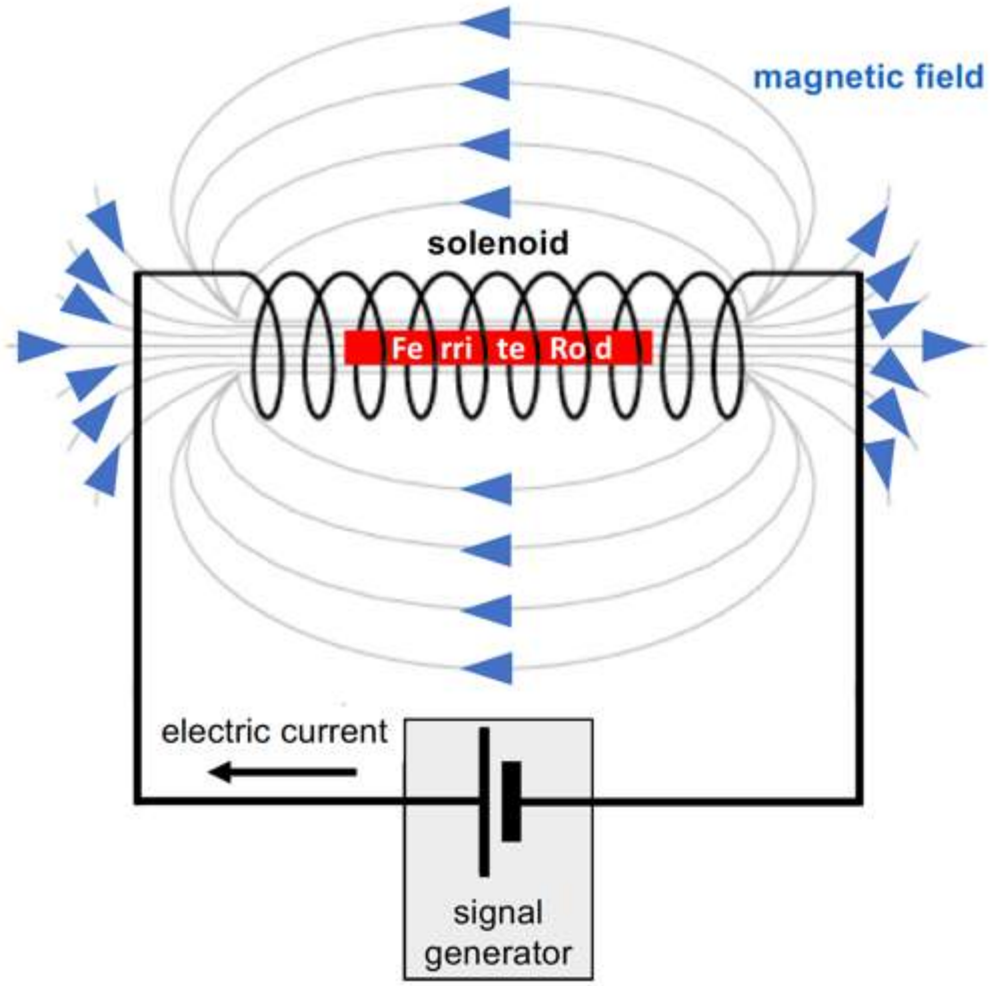

Figure 3: Ferrite Rod in an Induced Magnetic Field (author's graphic)

2.2 Electromagnetism

Electromagnetism is the theory regarding the environment, the *magnetic field*, of the "Musical Ferrite". Explaining how such a magnetic field can be generated and what impact it has on an inserted object is essential to understanding the phenomenon.

2.2.1 Magnetic Dipole Moments and Magnetic Domains

Electrons have two intrinsic properties: spin and charge. From these arises the *electron magnetic dipole moment* (or Bohr moment (Dionne, 2009)). It has direction and magnitude and creates a *magnetic field* around the electron. (MindTouch, 1993) A magnetic dipole can be compared to a bar magnet with a North Pole N and a South Pole S. It possesses a magnetic dipole moment creating the *magnetic field B* as shown in Figure 4. The idea of representing *B* with field lines goes back to the 19th century, when Michael Faraday developed its design. The direction of the *magnetic field B* is indicated by the arrows along the looping lines. It runs from S to N inside the magnet and from N to S outside of it. (Meyer & Schmidt, 2011)

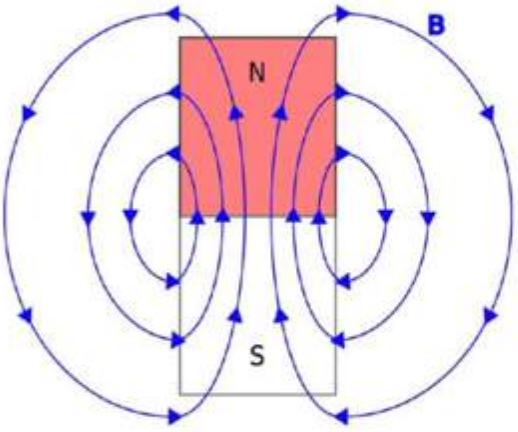

Figure 4: Magnetic Field of a Bar Magnet[6]

In a magnet, all (or almost all) *electron magnetic dipole moments* point into the same direction. Any material that can be magnetized will have several so-called *magnetic domains*. They arise in metals due to the nature of electron flow in them.

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[6] Source: (MindTouch, 1993)

In Figure 5 A and B below, the boundaries of these *magnetic domain* are sketched by straight lines. These so-called Bloch[7] walls are narrow regions where the *electron magnetic dipole moments* keep rotating (Dionne, 2009). Imperfections of the material's crystalline structure can also determine those walls, but within a *magnetic domain*, all *electron magnetic dipole moments* are aligned. Each *magnetic domain* results in a larger *magnetic dipole moment* with its direction denoted by an arrow in Figure 5 A and B.

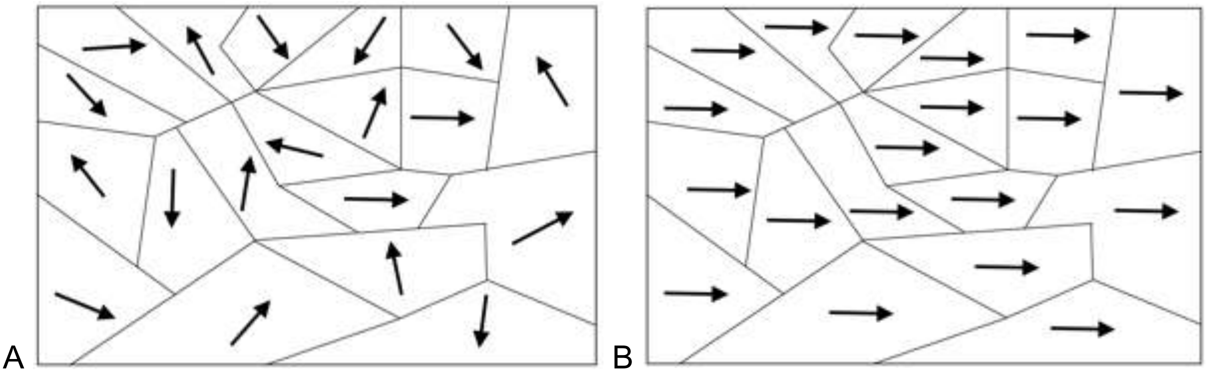

Figure 5: Magnetic Domains and Magnetization (author's graphic)

The process of magnetization of a material is shown in Figure 5 A, where the material's *magnetic domains* are randomly aligned, and in Figure 5 B, showing the aligned *magnetic domains* after magnetization. Collective magnetization is not normally present in any piece of metal with different *magnetic domains*. Certain material can be magnetized, though, when exposed to a magnetic field.

2.2.2 Magnetic Fields

It took until 1855 when James Clark Maxwell formulated his *Maxwell's Equations* to recognize that electricity was not completely independent from magnetism (Trémolet de Lacheisserie, 1993). The fact that the two effects, magnetism and electricity, are unified into one phenomenon (electromagnetism) is central to this paper as the *magnetic field* mentioned in the research question is generated by an electric signal that runs through the solenoid.

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[7] Bloch walls are named after the Swiss-American Physicist and Nobel-Prize-Winner Felix Bloch (ETH Zürich, 1996)

Lorentz Force

A *magnetic field* $\vec{B}$ can be described by a vector field. In electromagnetism, it is denoted as how it affects a moving object (for example an electron) of charge *q* [Coulomb] and velocity $\vec{v}$ [m/s] with the *Lorentz Force* $\vec{F}_L$ [Newton]. The relation is (Britannica, 1995):

Formula 1: Lorentz Force $$\vec{\boldsymbol{F}}_{\boldsymbol{L}} = \boldsymbol{q}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$$

In Formula 1, $\vec{E}$ is the electric field, which may or may not be present, and × stands for the cross product of two vectors. If there is no electric field ($\vec{E} = 0$) present, Formula 1 calculates a *magnetic field* $\vec{B}$ by measuring $\vec{F}_L$ when sending a charge q with velocity $\vec{v}$ through $\vec{B}$. Due to the cross product $\vec{v} \times \vec{B}$ appearing in Formula 1**,** the vector $\vec{F}_L$ is perpendicular to $\vec{v}$ and $\vec{B}$. Measuring the *magnetic field* $\vec{B}$ actually refers to its *magnetic flux density* B (see below: Formula 4, Formula 5 and Formula 6) or *magnetic field strength* H (see below: Formula 7 and Formula 8). (DPK-VSMP, 2016)

Electricity

Electricity is the presence and movement of charge q [Coulomb]. It was long believed to be a positive charge but shown that it is in most cases a negative charge q in the form of electrons. An *electric current* I [Ampere] is present if the negative charges move through conductors, usually metals, because of free electron gas (Wurm, 2012) (Wilfried, 2014). The electric current *I* itself points into the opposite direction than the electron movement due to the former belief that the moving charges were positive. The voltage V [Volt] can be seen as "the pull" that the electrons feel through the conductor and the resistance R [Ohm] as a measure of the "difficulty" with which electrons move through the conductor. The power P [Watts] represents how much "work" is done by the electric current *I* per unit of time. The relations between these quantities are described in Formula 2 and Formula 3.

Formula 2: Electric Current (Voltage) $$\boldsymbol{V} = \boldsymbol{R} \cdot \boldsymbol{I}$$

Formula 3: Electric Current (Power) $$\boldsymbol{P} = \boldsymbol{V} \cdot \boldsymbol{I} = \boldsymbol{R} \cdot \boldsymbol{I}^{2}$$

There are two types of electric currents: direct current (DC, Figure 6 A below), where the electron's movement remains in one direction, and alternating current (AC, Figure 6 B below), where the electron's direction switches back and forth periodically, with a frequency f (number of cycles per second, 1 cycle/sec = 1 Hertz = 1Hz). In an AC the electrons just “pace” back and forth, which can be achieved by switching voltage V up and down (amplitude is the maximum extension) as shown in Figure 6 B below. (Meyer & Schmidt, 2011)

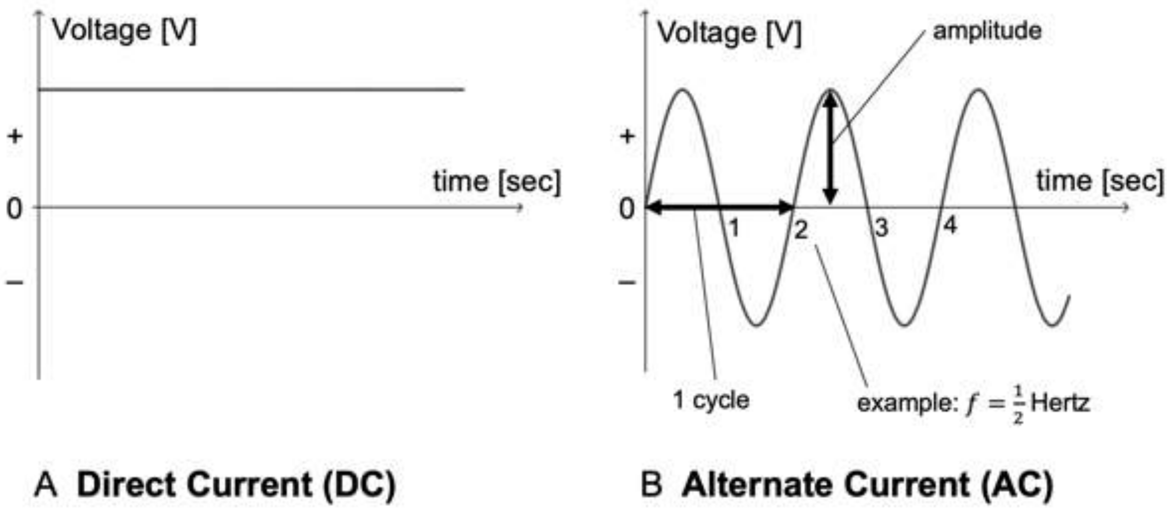

Figure 6: Direct and Alternating Electric Current (author's graphic)

Most conventional electricity is AC, as this allows for less losses over long distances. For example, Continental European standard electricity is AC with frequency f ≈ 50 Hz. In household appliances, the incoming AC is *rectified* (changed) into DC to run them. This is because DC is more energy efficient over small distances. An AC is used for the "Musical Ferrite" such that solenoid creates the desired environment (*changing magnetic field*).

Induced Magnetic Fields

A way to generate a magnetic field $\vec{B}$ is with a straight wire that carries a current I. Using the right-hand-rule as shown in Figure 7, the direction of the *magnetic field* $\vec{B}$ can be determined. (DPK-VSMP, 2016)

Figure 7: Right-hand-rule for Induced Magnetic Fields around a Wire[8]

Applying this right-hand-rule to a solenoid is illustrated in Figure 8 below. A generator will send an electric current *I* through the solenoid which then creates a *magnetic field* $\vec{B}$ around and through it. To derive the direction of $\vec{B}$ of such an *electromagnet* (Meyer & Schmidt, 2011), the right-hand-rule can be applied to each winding of the solenoid in the same way as if it was single straight wire.

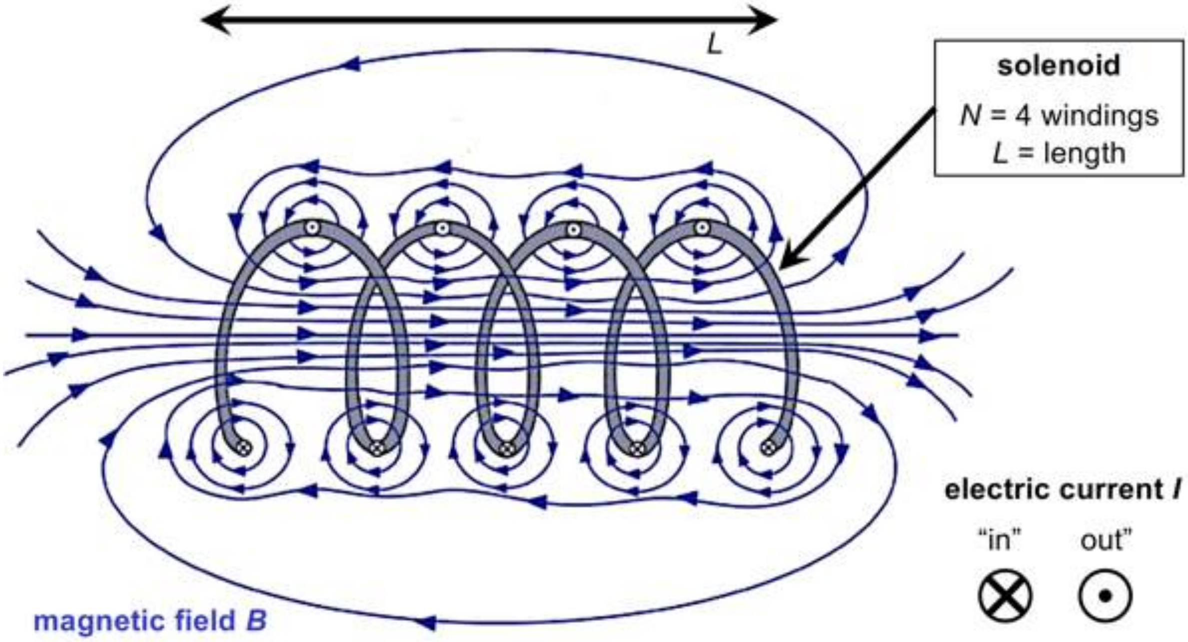

Figure 8: Induced Magnetic Field B in a Solenoid[9]

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[8] Source: (University, Iowa State, 2001)

[9] Source: Britannica ImageQuest, Encyclopædia Britannica, created 25 May 2016 (image edited by author)

A *magnetic field* $\vec{B}$ has a *magnetic flux density* B [tesla[10]] and a *magnetic field strength* H [ampere/meter]. The following variables are relevant to calculate B and H for an *induced magnetic field* in a solenoid:

- L = length of the solenoid [m]
- d = diameter of the solenoid [m]
- N= number of windings of the solenoid
- $n = \frac{N}{L}$ = solenoid's density (windings per unit of length)
- I = electric current that is run through the solenoid [A]
- μ = $\mu_0 \cdot \mu_r$ = magnetic permeability $\left[\frac{\mathrm{V \cdot s}}{\mathrm{A \cdot m}}\right]$
  (μ_0 = vacuum permeability constant[11], μ_r= relative permeability of the substance inside the solenoid compared to vacuum)

If the solenoid is long relative to its diameter (L >> d), then the values of B and H can be calculated with the following formulas (DPK-VSMP, 2014):

Formula 4: Magnetic Flux Density (1) $\boldsymbol{B \approx \mu \cdot \frac{N}{L} \cdot I}$

Formula 5: Magnetic Flux Density (2) $\boldsymbol{B \approx \mu \cdot n \cdot I}$

Formula 6: Magnetic Flux Density (3) $\boldsymbol{B \approx \mu_0 \cdot \mu_r \cdot n \cdot I}$

Formula 7: Magnetic Field Strength (1) $\boldsymbol{H = \frac{B}{\mu}}$

Formula 7 can be rewritten when replacing B using Formula 5:

Formula 8: Magnetic Field Strength (2) $\boldsymbol{H = n \cdot I}$

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[10] Tesla = $\frac{\mathrm{Volt \cdot Seconds}}{\mathrm{Meter}^2}$

[11] $\mu_0 = 4\pi \cdot 10^{-7} \, \frac{\mathrm{V \cdot s}}{\mathrm{A \cdot m}}$

Using Formula 2 to replace $I = \frac{\mathrm{V}}{\mathrm{R}}$ in Formula 8 results in the proportionality $H \sim V$ applicable for a solenoid (given that n, R are material constants) shown Formula 9.

Formula 9: Proportionality of H and V $$H = n \cdot \frac{V}{R} = \frac{n}{R} \cdot V \Rightarrow \boldsymbol{H} \sim \boldsymbol{V}$$

Formula 7 can be rearranged to show the dependency of B from H (Ito, 1996).

Formula 10: Magnetic Flux and Field Strength $$B = \mu \cdot H = \boldsymbol{\mu_0} \cdot \boldsymbol{\mu_r} \cdot \boldsymbol{H}$$

Formula 10 explains why adding a metal core made out of a material with μ_r > 1 increases the magnetic flux density B relative to the electromagnets field strength H (superposition of magnetic fields). The higher μ_r, the more B increases relative to H. (Meyer & Schmidt, 2011)
The situation is more complex, though, as the magnetic field strength H impacts μ_r. Furthermore, μ_r depends on the surrounding temperature and the material's change in temperature if the core gets deformed. (Ito, 1996) These dependencies are relevant for the *magnetic hysteresis loop* explained in 2.3 Ferromagnetism.

2.3 Ferromagnetism

A metal is called *ferromagnetic* if all its *magnetic domains* can be aligned, which means it can be magnetized if exposed to a *magnetic field*. An object made out *ferromagnetic* metal will become a dipole because it develops a North Pole and South Pole on its surface through which the magnetic field lines pass. The prevalent *ferromagnetic* metals are iron, cobalt and nickel (Meyer & Schmidt, 2011).

Depending on the metal and temperature, some *ferromagnetic* metals stay magnetized longer than others (or permanently in the case of a ferromagnet). The resistance to change magnetization (from being magnetized to becoming demagnetization or vice versa or even change direction of magnetization under an external magnetic field) is called *magnetic coercivity*. It is measured by H_c, the *coercive* magnetic field strength needed for full demagnetization of a magnetized material. (Ito, 1996) (Bienkowski & Szewczyk, 2018)

The magnetization process of a material depends on the:

- temperature (external and internal)[12]
- material's relative magnetic permeability μ_r
- material's magnetic coercivity (measured by H_c)

If a material is exposed to an external *changing* magnetic field, it is being magnetized and demagnetized *periodically*, which affects the magnetic flux density $B(H)$. This process is material (and temperature) specific and described by a *magnetic hysteresis loop* $B(H)$ shown in Figure 9. (Ito, 1996) (Bienkowski & Szewczyk, 2018)

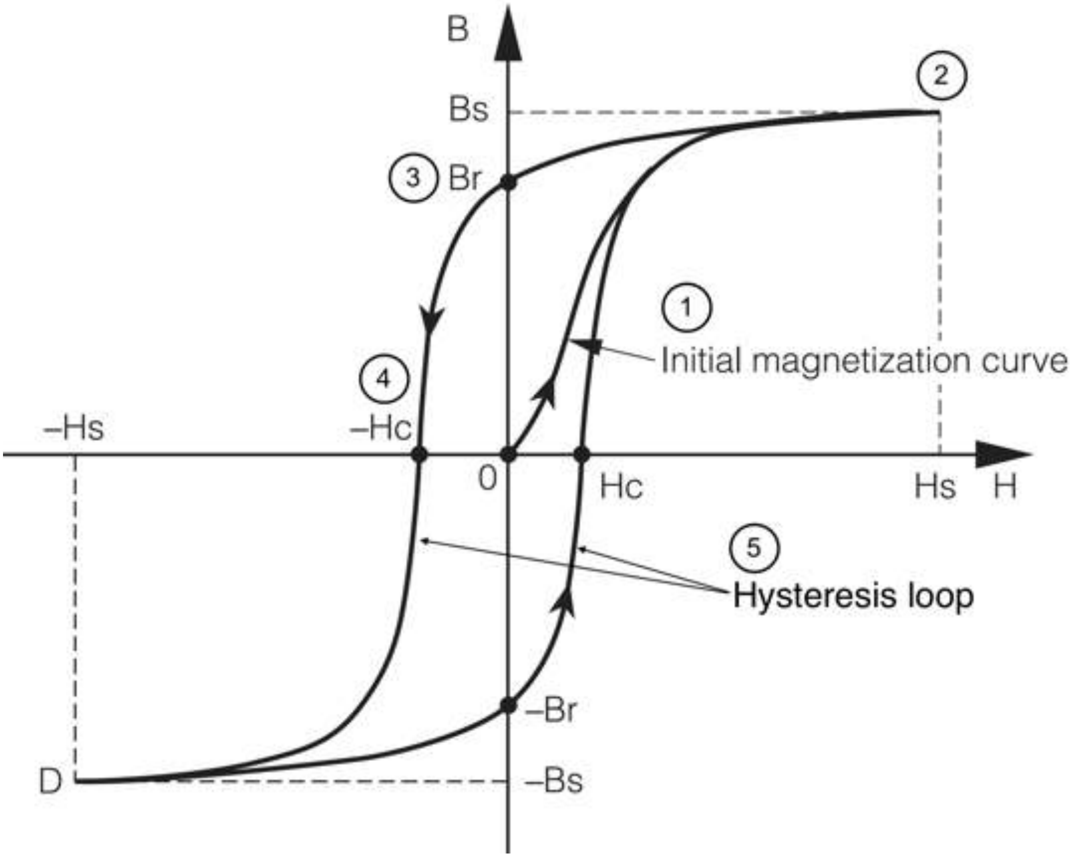

Figure 9: Magnetic Hysteresis Loop (also called B – H Loop)[13]

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[12] Surrounding temperature did not have to be considered because all experiments were conducted at room temperature. The rods heating up as they change dimensions during the experiments was neglected, because the time period of measurements was short.

[13] Source: (Ito, 1996)

The circled numbers in Figure 9 (above) are added by the author and explained here:

1 The *initial magnetization curve* $B(H)$ has, according to Formula 10, a gradient equal to the *magnetic permeability:* $\frac{dB}{dH} = \mu = \mu_0 \cdot \mu_r$, where $\mu_r = \mu_r(H)$ (Ito, 1996). The initial gradient $\mu_i = \frac{dB}{dH}\Big|_{H=0}$ is a material constant. As H increases, magnetization takes place and $B(H)$ increases. The S-shape of the curve shows that the gradient μ first increases and then decreases[14].

2 The *initial magnetization curve* levels off as the material becomes *saturated with flux* and reaches B_S at a field strength H_S, therefore $B(H_S) = B_S$ and $\mu \approx 0$.

3 Removing the magnetic field ($H = 0$) demagnetizes the material to a certain *remaining magnetic flux density* $B_r = B(0)$, where index r refers to remanence.

4 Applying a reversed magnetic field with *coercive* magnetic field strength $-H_c$ is needed to reduce the remanence B_r to zero. (See horizontal axis intercept $B(-H_c) = 0$.) The name hysteresis (or lag) originates from the fact that *demagnetization* still takes place (lags behind) as the magnetic field has already changed direction (sign): $B(H) > 0$ for $H \in]-H_c, 0]$. A reason for this is the inertia of electrons that leads to them being behind the change in magnetic field.

5 The lower half of the graph is symmetric to the upper half. In a ***changing*** *magnetic field*, the material gets magnetized and demagnetized in turns, but with a lag relative to the field strength H. This repeating cycle is labeled as *hysteresis* ***loop*** and indicated by the arrows.

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[14] The change in the gradient or magnetic permeability μ (as H and B increase) can be shown in a graph of the so-called amplitude permeability. This information is included in the ferrite material specifications, but was too detailed to be considered for this paper. It is recommended for further studies. (TDK Product Center, 2014)

2.4 Ferrite Materials

Chemical Formula of Ferrite

The term ferrite describes a family of materials. A ferrite material (ferrite) is a *metal oxide* and its chemical formula is $MO \cdot Fe_2O_3$. The main ingredient is iron oxide (Fe_2O_3). Additionally, it contains metal oxides (MO), where the metal M is, for example, Manganese (Mn), Zinc (Zn), Nickel (Ni), Magnesium (Mg), Cobalt (Co) or Copper (Cu). Manganese-Zinc and Nickel-Zinc ferrites are most common materials in commercial appliances. (Ito, 1996) (Bienkowski & Szewczyk, 2018)

Properties of Ferrite

- *Brittle* due to their lattice structure (susceptible to shear stress as fracturing)
- *Poor or no electronic conductivity* (they can be used as insulators)
- *Ferromagnetic* (they can be magnetized)

Hard Ferrites

Have a *high* magnetic coercivity and thus are:
- "hard" to be demagnetized
- a good material for permanent magnets

Soft Ferrites

Have a *low* magnetic coercivity and thus are:
- easily magnetized and demagnetized
- a suitable material for magnetic cores.

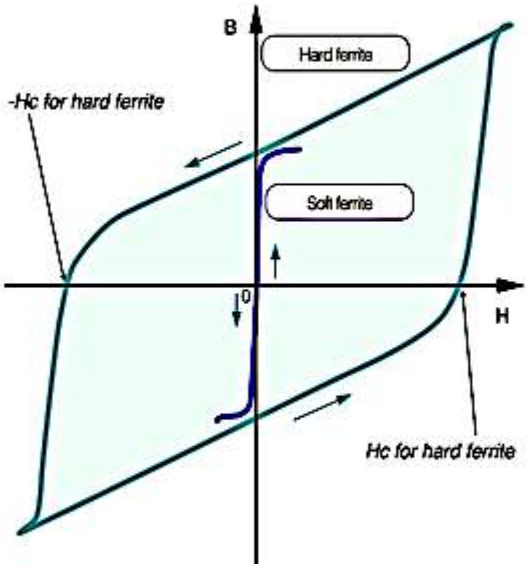

Figure 10: Magnetic Hysteresis Loops for Hard and Soft Ferrites[15]

Figure 10 compares magnetic hysteresis loops for hard and soft ferrites. The horizontal axis-intercepts of the loop for hard ferrites are labeled with $-H_c$and H_c. Those are the coercive magnetic field strength for hard ferrites. Their distance gives

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[15] Source: (Ito, 1996)

the width of the loop. Soft ferrites have a much smaller coercive magnetic field strength than hard ferrites. Therefore, the width of the loop for soft ferrite is much smaller. In this graphic the loop is sketched as a line representing the very narrow loop. (Dionne, 2009) (TDK Product Center, 2014) (Ito, 1996)

The fact that soft ferrites have a narrow magnetic hysteresis loop (Sydow, 1985) and undergo magnetostriction (as explained in 2.5 Magnetostriction below) was the reason why they were utilized for the experiments described in this paper.

Typical Applications of Ferrite

Hard and *soft ferrites* are extremely versatile, cheap to produce and thus widely used. The primary use of *hard ferrites* is as material for small magnets such as refrigerator magnets and paperclip holders. *Soft ferrites* are material for cores of transformers, machines that transform high voltages into low voltages and vice versa. They are useful in conventional electricity production and transportation.

Due to the *low* electric conductivity of ferrite, cores made out of soft ferrite have a high resistance to creating unwanted electric currents, called Eddy currents, in case of a changing magnetic field. Eddy currents create a magnetic field in the opposite direction of the one created by the electromagnet and, therefore, inhibit the efficiency of the core. An electromagnet with a soft ferrite core will have less Eddy currents than, for example, one with an iron core. (TDK Corporation, 1996)

Soft ferrites are also used as insulators on cables, for example in ferrite beads (Figure 11 and Figure 12). Wherever electromagnetic interference (EMI) is a problem, they reduce the influence of other magnetic fields around the wire that is to be protected. (Ferroxcube, 2000) (TDK Corporation, 1996)

Figure 11: Ferrite Bead (Ferroxcube, 2000)

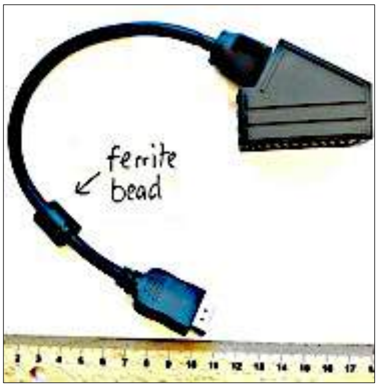

Figure 12: Television Cable with Ferrite Bead (author's photograph)

2.5 Magnetostriction

Physical Explanation and Illustration

When an object made of *ferromagnetic* material enters a *magnetic field*, the object's *magnetic domains* are being aligned. While this magnetization process is taking place, the object undergoes a change in shape or volume or both[16]. This deformation is called *magnetostriction*. It was first discovered by James Joule in 1842 while experimenting with an iron core, but the quantitative explanation is still not fully understood. (Bienkowski & Szewczyk, 2018)

Magnetostriction takes place until all *magnetic domains* in the object are all aligned. At this final stage, the object has reached its so-called *magnetic saturation* (its level depends on the object's material) and any surrounding *magnetic field* does not have any impact anymore. (MindTouch, 1993).

Magnetostriction can be volume-invariant like shown in Figure 13 (below) or shape-invariant where only the volume changes (Sydow, 1985).

The (simplified) illustration of volume-invariant magnetostriction in Figure 13 on the left shows the randomly arranged *magnetic domains* of a *ferromagnetic* object. After being exposed to the *magnetic field* $\vec{B}$ the *magnetic domains* are rearranged and aligned as shown in Figure 13 on the right. (Sketching the Bloch walls as stable lines is a simplification.) The "moving" arrows on the right indicate the change in the object's dimensions and demonstrate the effect of *magnetostriction*. The *ferromagnetic* object became longer in the direction of the *magnetic field* (this is also called *positive magnetostriction*), and thinner in the lower part.

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[16] The object's dimensional changed will affect its temperature, which is not addressed in this paper.

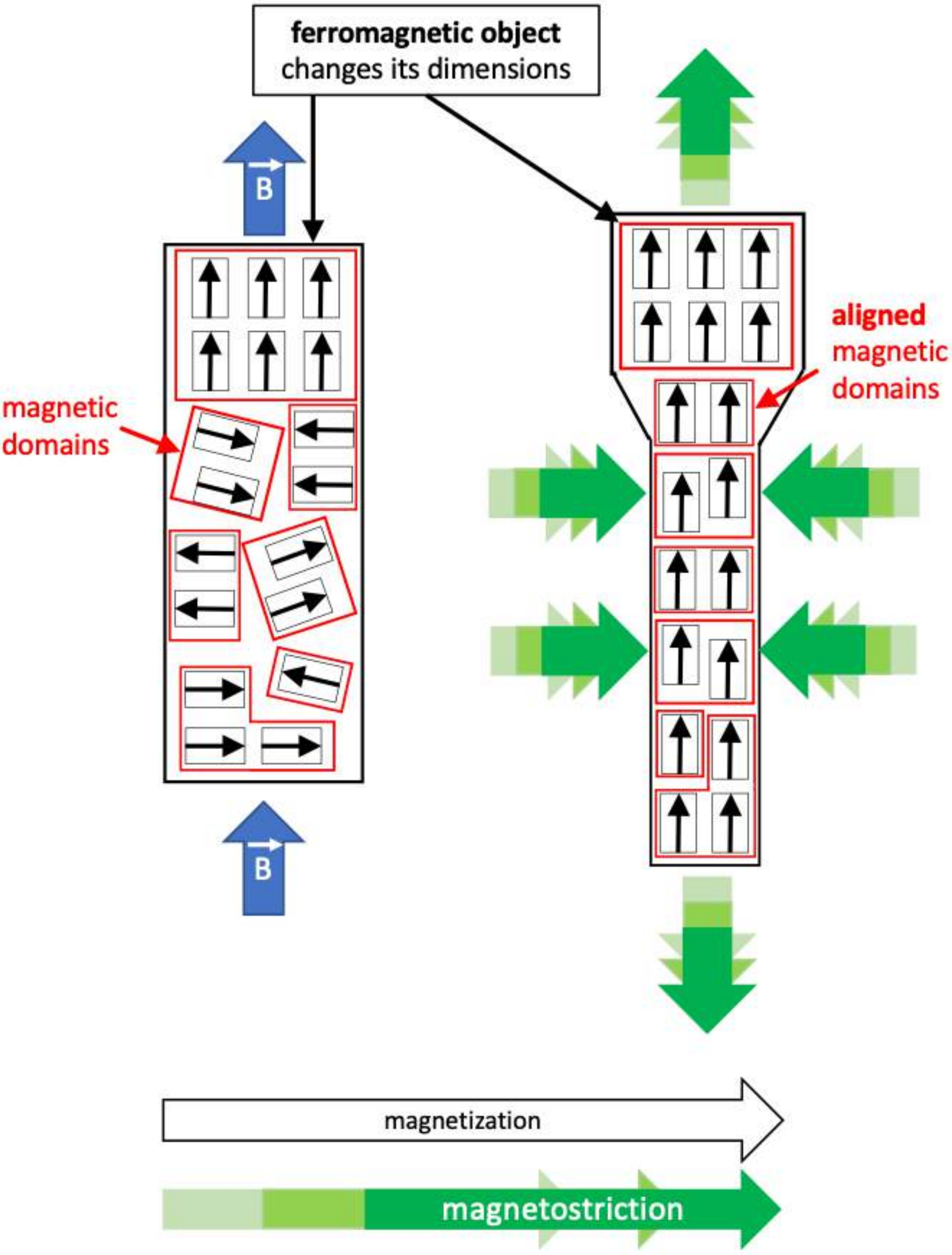

Figure 13: Simplified Illustration of Magnetostriction (author's graphic)

Magnetic Saturation and "Easy-Axis"

Magnetostriction can be compared to the *piezoelectric effect*, where crystals, for example quartz, change shape (and thus can exert a force) when electricity is run through them. Similarly, *magnetostriction* arises from the fact that it takes more energy to magnetize a *ferromagnetic* object in one direction than another. This is called *magnetocrystalline anisotropy* (which can be led back to spin-orbital coupling, so it comes up due to quantum mechanics, but can only be seen on a macro level). This means, that when a *magnetic field* is oriented such that it is not in the optimal direction for the exposed material, the microcrystals (each being a *magnetic domains*) in the metal will rearrange, to keep the free energy in the system at a minimum by creating a structure that allows the least amount of energy possible to magnetize it. **This causes a stress in the material and thus deformation until *magnetic saturation* is achieved.**

If there is an axis in which the applied *magnetic field* does not cause any deformation, it is called the “easy axis”. The larger the object, the lower the chance of such an "easy axis". This is because of the more complex crystalline structure that can lead to different sections with different “easy axes”. Any **ferrite rod** can be considered a large object and will, therefore, most likely have **no “easy axis”**.

The higher the *magnetic coercivity* of the object's material, the wider the magnetic hysteresis loop and the longer the deformation remains. Therefore, hard ferrites stay deformed longer than soft ones.

(MindTouch, 1993)

Mathematical Description of Magnetostriction

The first attempt to describe *magnetostriction* mathematically was made in 1842 when it was discovered. James Joule devised the *magnetostriction coefficient* λ, which is the relative elongation of the object (ratio of change in length after deformation to original length). λ is a quantitative measure of volume-invariant magnetostriction strain, also called "Joule magnetostriction". (Shuai & Biela, 2014)

Same materials have the same *magnetostriction coefficient* λ just like in thermodynamics with respect to the expansion coefficient. (Meyer & Schmidt, 2011)

The definition of the *magnetostriction coefficient* λ is:

Formula 11: Magnetostriction Coefficient $$\boldsymbol{\lambda = \frac{\Delta L}{L}}$$

In Formula 11 the original length of the object is L and ΔL is the change in length after magnetization as illustrated in Figure 14. (Trémolet de Lacheisserie, 1993)

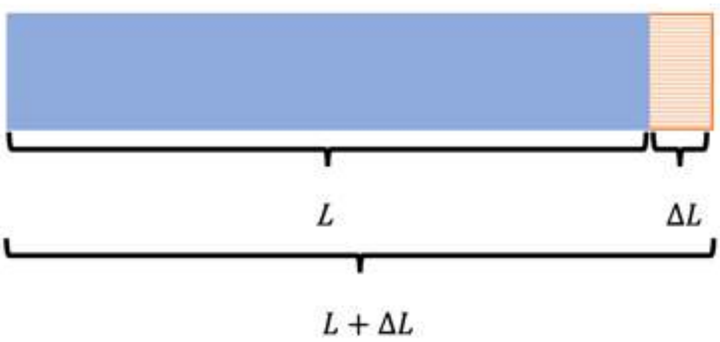

Figure 14: Illustration of Magnetostriction Coefficient $\lambda = \Delta L : L$

A more accurate measure would be the relative change in *volume*. In Physics, a common approach is by approximating the change in volume with a new coefficient $\gamma \approx 3\lambda$. The same idea is used in thermodynamics with the volume expansion coefficient $\gamma \approx 3\alpha$, where α is the longitudinal expansion coefficient. (Meyer & Schmidt, 2011)

The challenge of accurately measuring very small deformations remains in two as well as in three dimensions. If the tools are available to measure the object's dimensional changes (for example with laser technology or strain gauges) then the data could look like that in Figure 15 on the right. (Bienkowski & Szewczyk, 2018)

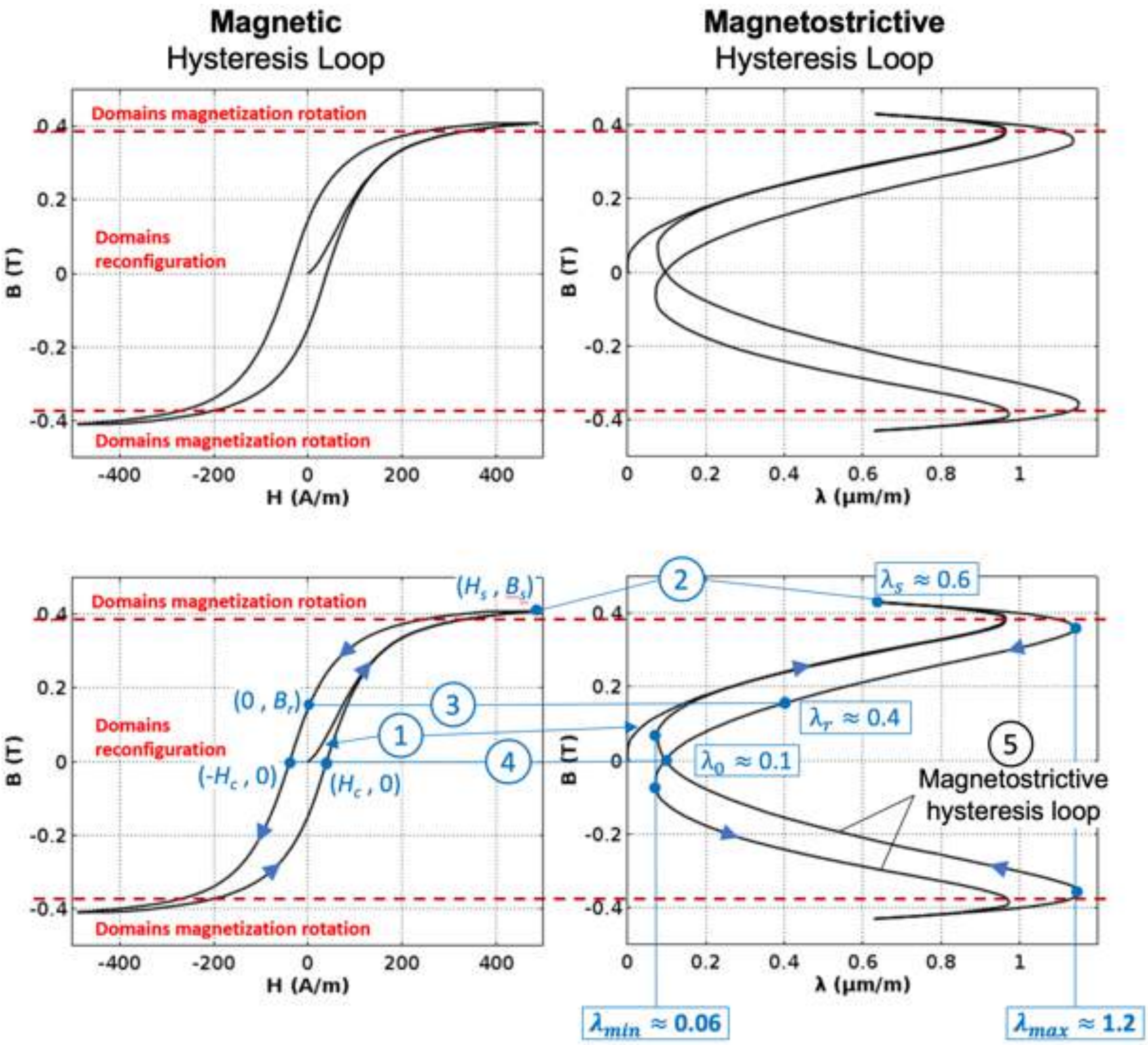

Figure 15: Magnetic and Magnetostrictive Hysteresis Loop for Mn-Zn Ferrites[17]

Figure 15 shows the *magnetic hysteresis loop* (left) and the *magnetostricitve hysteresis loop* (right).

The circled numbers and labels in the lower graphic in Figure 15 are added by the author (and correspond with the ones in Figure 9: Magnetic Hysteresis Loop (also called B – H Loop)) and explained here:

---

[17] Source: (Bienkowski & Szewczyk, 2018)

1 *Initial magnetization* (left) and *initial magnetostrictive* (right) *curves*:
If the H rises from 0 to H_s (horizontal axis on the left), then B increases from 0 to saturation level $B_S \approx 0.4$ (vertical axis). The magnetostricitve strain $\lambda(B)$ (horizontal axis on the right) first rises to $\lambda \approx 0.9$ as B increases.

2 As the material gets close to being *saturated with flux* (close to B_S), the value of drops to $\lambda_s = \lambda(B_s) \approx 0.6$. (Notice that $\lambda_s < \lambda_{max}$[18].)

3 Removing the magnetic field demagnetizes the material: $\lambda(B)$ rises to $\lambda_{max} \approx 1.2$ (domains rotation decreased), then drops to remanence level $\lambda(B_r) \approx 0.4$.

4 Applying a *reversed magnetic field* will remove remanence until and $B(-H_c) = 0$. At that point $\lambda_0 = \lambda(0) \approx 0.1$ and did not reach its minimum $\lambda_{min} \approx 0.06$ yet. It needs a stronger magnetic field to reach that minimum which increases the lag of the magnetostriction effect with respect to H.

5 The process then continuous and forms the other half of the magnetostrictive hysteresis loop when a changing magnetic field is present. Notice that the magnetostrictive strain $\lambda(B)$ cannot be negative. That is why it goes through 2 cycles when B only goes through one. Also, the object will not get a chance to drop to its original length at all (called "lift-off" as $\lambda_0 > 0$). Before this could happen, the magnetization gets stronger and magnetostriction pick up again.

---

[18] A possible qualitative explanation can be found in (Bienkowski & Szewczyk, 2018). It is based on the idea that there are different kinds of magnetostrictive strains (domains magnetization rotation versus domains reconfiguration).

Ferrite Rod in a Changing Magnetic Field

There are three sources for the ferrite rod's vibrations (Kolar, et al., 2013):

- magnetic forces on the solenoid (avoided by appropriate fixation[19])
- magnetic forces on the rod's surface (negligible if only one ferrite rod is used[19])
- magnetostriction

The relevant source is magnetostriction. Only soft ferrites deform quickly enough in a changing magnetic field to create an acoustic wave (Sydow, 1985). Figure 16 gives and overview for $V,\ H,\ B$ and ferrite rod's elongation based on $\lambda(B)$ values from Figure 15. It shows the lag and the longitudinal dimensional changes of the rod.

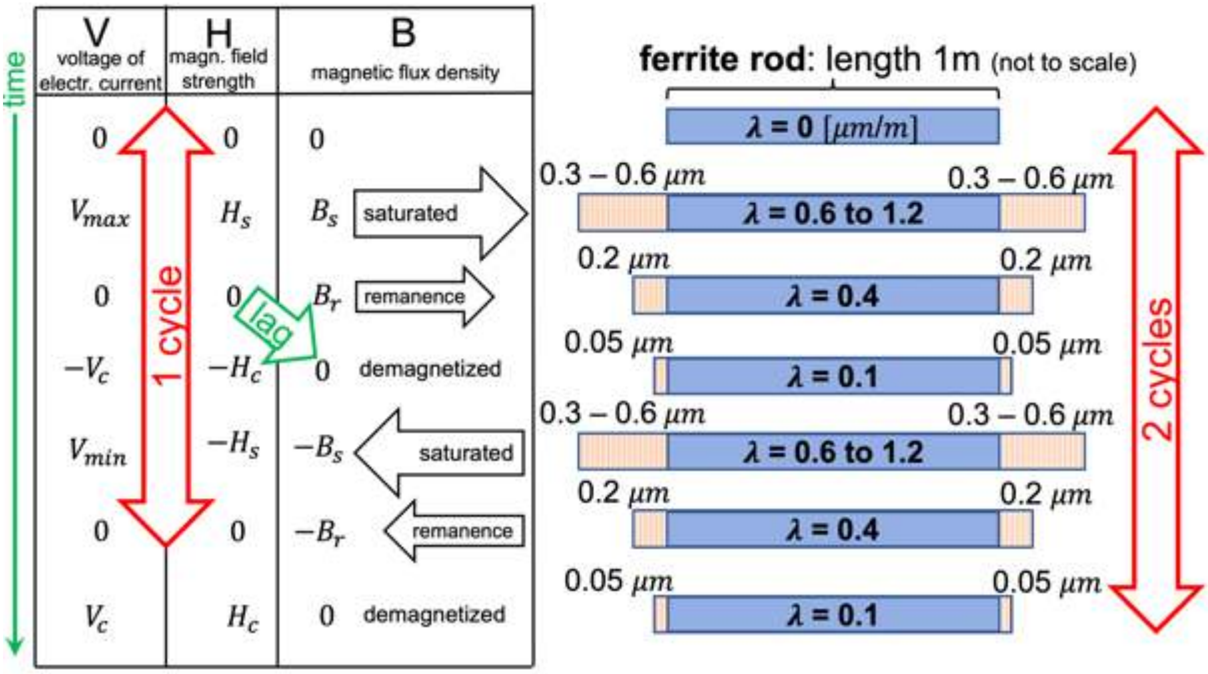

Figure 16: Magnetostriction of a Ferrite Rod in a Changing Magnetic Field

Figure 16 shows the input current's voltage V on the left column. The next column is the field strength H which is proportional to V according to Formula 9. The last column shows the magnetic flux density B shows that lags behind due to remanence.

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[19] Source: (Kolar, et al., 2013) and telephone call with Professor J. Kolar on 17th September 2019

The ferrite rod's dimensional changes are in line with B, however the sign does not matter. That is why the rod undergoes two times the maximal elongation during one cycle of V, H or B. Also, the longer the rod, the larger the absolute change in length is. This implies **that the sound wave created by a longer rod will have a larger amplitude**.

2.6 Acoustics

The research question of this paper is about the vibration of a ferrite rod when inserted into a *periodically changing magnetic field*. The vibration of the object is very small and hard to be visually observed or measured directly. Hence, sound and thus acoustics was an integral part to the discussion of the phenomenon as the way the phenomenon was observed by "listening to it".

Sound Description

Like any other transfer of energy, sounds are transmitted in a wave, namely a pressure wave. This means that a medium must be present for sound waves to be able to travel, as pressure must be generated. The wave is longitudinal, that means the particles in the medium (air in case of the considered phenomenon) vibrate back and forth in the direction of the wave’s progression (Figure 17).

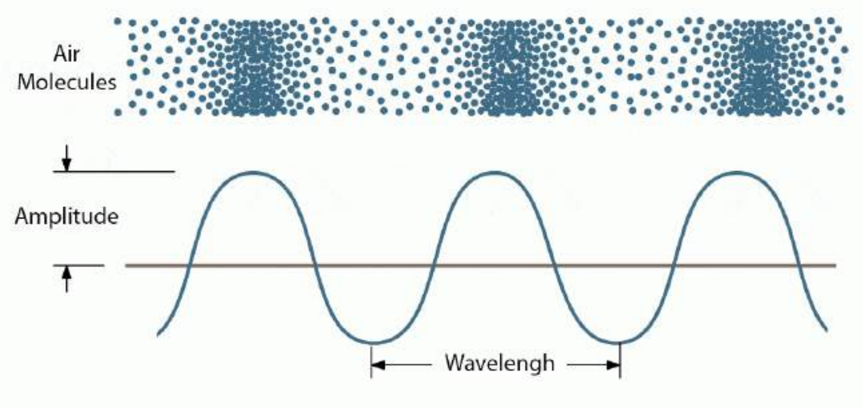

Figure 17: Illustration of Pressure and Sound Wave[20]

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[20] Source: https://www.soundproofingcompany.com/soundproofing_101/what-is-sound

The molecules move back and forth and, thus, make the compressions move along the wave. These compressions reach your ears as vibrations and, thus, are perceived as sound. A pressure wave can be generated by any vibration created, such as a ferrite rod vibrating in a solenoid.

Sound Variables

The following variables of sound waves were important regarding the experiments:

The **speed** [m/s] of sound depends on the medium it is in and the temperature of that medium. The medium and temperature for the conducted experiments described in this paper stay constant. Therefore, it can be assumed that the speed of sound is constant and 343 m/s, which is its normal speed at room temperature in air.

The **frequency** [Hz] of a sound wave is what we humans observe as the pitch of the sound, so how high or low it is. Physically, it is how often the wave passes by a single point per second, so how many compressions go by in an allotted time slot. The frequency is measured in Hertz (Hz), which is s^{-1} (the inverse of seconds). Humans can hear in a range from 20Hz to 20'000Hz. (NASA, 1995)

The **amplitude** of a sound wave corresponds to the audible sound's volume or loudness. A sound wave's amplitude is measured in a logarithmic scale, decibels (dB). It is measured in this way as this is how humans perceive the different intensities of sound. Humans would identify a linear increase in dB as a linear increase in intensity of the sound, even though the compression is much larger.

At this point of this paper, the end of Part A: Theory, the **theoretical description** of the phenomenon mentioned in the research question has been developed. Part B: Hypotheses and Experiments addresses **to what extend** the physical theory can actually be experimentally justified.

3 Part B: Hypotheses and Experiments

The research question states:

> ***To what extent*** *can the vibrations of a ferrite rod inserted into a periodically changing magnetic field be described by physical theory?*

The goal of the experiments was to find an experimental justification for the developed physical theory or model of the "Musical Ferrite" and, in the end, to evaluate *to what extend* the physical theory was appropriate. For this, several hypotheses were stated, where some were supported by the outcome of the experiments and others were not.

The relevant parameters to formulate the hypotheses and outline the experiments for the "Musical Ferrite" are listed in Figure 18:

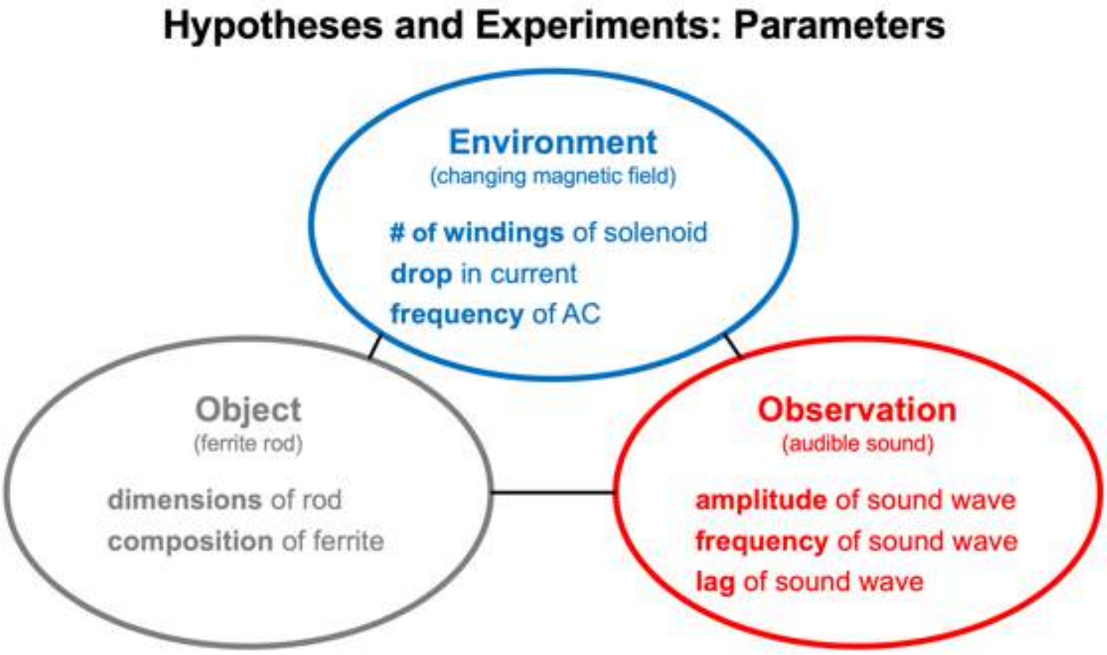

Figure 18: Overview of the Musical Ferrite's Parameters

3.1 Hypotheses

The hypotheses are listed below. Besides the predicted frequency of the produced sound, the hypotheses are qualitative statements. Calculating and predicting numerical outcomes remains difficult as the theory on *magnetostriction* is still not fully explained. This goes back to the fact that spin-orbital coupling in electrons is not fully understood. Many things would have to be known about the crystalline structure of the ferrite material to be able to sufficiently model the ferrite rod's behavior and thus understand how each bar works individually. The hypotheses are based on selected parameters of the ferrite rods and the theory explained earlier. Sufficient experimental results were collected to discuss the effect of the *magnetostriction* on a ferrite rod.
The reasoning for each hypothesis is based on the theoretical findings and further theoretical ideas formulated below each hypothesis.

I. **Number of windings of solenoid:**

$\boldsymbol{higher\ no. of\ windings\ of\ solenoid\ \Rightarrow larger\ amplitude\ of\ sound\ wave}$

Reasoning:

The more windings, the stronger the magnetic field and the faster the rod's dimensional changes. This results in a higher force on the surrounding air particles and thus a higher amplitude of the sound wave created.

II. **Drop in current[21]:**

$\boldsymbol{larger\ drop\ in\ current \Rightarrow larger\ amplitude\ of\ sound\ wave}$

Reasoning:

The AC flowing through the solenoid has an effect on the magnetic field being created. If more current is impeded by the ferrite rod (current drops more, when the ferrite rod is inserted into the solenoid), then more energy will be transferred into the ferrite rod, thus deformation increases and sound is louder. (The drop in the AC cannot be controlled during the experiment, but observed.)

---

[21] Also refers to so called impedance.

III. **Dimensions of the rod:**

Length of rod

$\boldsymbol{longer\ rod \Rightarrow larger\ amplitude\ of\ sound\ wave}$

Reasoning:

Magnetostrictive coefficients λ (Formula 11) are the same for same materials and a relative measure for deformation. Absolute elongation ΔL of a longer rod is larger than for a short one. Therefore, the amplitude of the generated air pressure wave is larger. That means that the sound is louder.

Volume of rod

$\boldsymbol{small\ change\ in\ volume} \Rightarrow little, no\ change\ of\ \boldsymbol{amplitude\ of\ sound\ wave}$

Reasoning:

If a ferrite rod (long bar with L >> d) is just slightly larger (in length, height and width) than another one and thus has a larger volume, it does not produce a much louder sound. A larger amount of energy has to be invested to deform it (which might not be available to the system) reducing the absolute measure ΔL of longitudinal deformation.

IV. **Ferrite material of rod:**

Magnetic permeability $\boldsymbol{\mu_i}$ and magnetic field strength $\boldsymbol{H_c}$

$\boldsymbol{larger\ \mu_i \Rightarrow larger\ amplitude\ of\ sound\ wave}$

$\boldsymbol{lower\ H_c\ \Rightarrow larger\ amplitude\ of\ sound\ wave}$

Reasoning:

This idea arises from the fact that the initial magnetization curve (see Figure 9: Magnetic Hysteresis Loop (also called B – H Loop)) starts off steeper for ferrites with a higher initial magnetic permeability μ_i. At the beginning of magnetization, this has a large effect on the magnetic field inside the solenoid and thus deformation of the ferrite rod will occur faster.

Similarly, if the coercive magnetic field strength H_c is lower, then the loop is narrower and the deformation happens faster. In both cases, the exerted force will be larger and thus the amplitude of the resulting air pressure (and sound wave) will be larger.

V. **Frequencies of AC and sound waves:**

$\boldsymbol{The\ created\ sound\ waves'frequencies\ are\ f_{AC},\ f_{rod}\ (loudest)\ and}$
$\boldsymbol{f = k \cdot f_{AC}; k = 2, 3, 4, \dots (overtones)}$

Example:

f_{AC} ≈ 50 Hz → $f_{rod} = 2 \cdot f_{AC}$ ≈ 100 Hz → musical note ≈ G_2 or $G_2^{\#}$

Reasoning for f_{rod}:

The loudest sound produced refers to the most prevalent pressure wave generated from the rod's dimensional changes. It has double the frequency of the frequency of the AC that induced the magnetic field. This is based on the magnetostrictive hysteresis loop as illustrated in Figure 15: Magnetic and Magnetostrictive Hysteresis Loop for Mn-Zn Ferrites. Figure 16: Magnetostriction of a Ferrite Rod in a Changing Magnetic Field showed the overview of this effect.

Reasoning for f_{AC}:

The rod's ends show different vibration patterns as one side might expand more than the other, depending on the direction of the magnetic field applied.

Reasoning for overtones with $f = k \cdot f_{AC}; k = 2, 3, 4, \dots$:

Overtones do appear in any musical instrument when it triggers a sound by vibrations. (von Helmholtz, 1913)

VI. **Lag of sound waves:**

$\boldsymbol{the\ sound\ waves\ lag\ behind\ the\ AC\ that\ induces\ the\ magnetic\ field}$

Reasoning:

The lag (or phase shift) is due to remanence and the resulting magnetostrictive hysteresis loop as illustrated in Figure 15: Magnetic and Magnetostrictive

Hysteresis Loop for Mn-Zn Ferrites. Figure 16: Magnetostriction of a Ferrite Rod in a Changing Magnetic Field showed the overview of this effect.

Testing the Hypotheses

Various experiments were conducted, but not all hypotheses experimentally tested. The following list gives an overview:

I. **Number of windings of solenoid**:
experiments with 2 different solenoids

II. **Drop in current**:
changes observed during all experiments

III. **Dimensions of rod (length and volume)**:
experiments with 3 differently shaped rods

IV. **Ferrite material of rod**:
experiments with 3 different ferrite materials

V. **Frequencies of AC and sound waves**:
sound waves recorded for all experiments

VI. **Lag of sound waves**:
not tested (reason: special measuring tools not available)

3.2 Conducting the Experiments

3.2.1 Materials, Set Up and Procedure

Materials

- **signal generator** (model: PI-9587B, manufacturer: PASCO scientific)
- **multimeter** (model: M-3650CR, manufacturer: VOLTCRAFT)
- **wires** (manufacturer: MC electronics, length: 60 centimeters)
- **clamps** (manufacturer: LEYBOLD-HERAEUS / TECHNICO Inc.)
- **microphone** (type: iPhone XS microphone, manufacturer: Apple)
- **frequency analysis software** (SpectrumView by Oxford Wave Research)
- 2 **solenoids** (material: copper wire, manufacturer: PHYWE)
  Solenoid 1: length 6.5 centimeters, number of windings **300**
  Solenoid 2: length 6.5 centimeters, number of windings **600**
- 5 **ferrite rods**[22]
  Rod 1 and 2: manufacturer (Ferroxcube, 2000)
  Rod 3 and 4 and 5: manufacturer (TDK Corporation, 1996)
  Rod's specifications see Table 1 below

label	material MnZn[23]	μ_i [(Vs)/(Am)]	H_c [A/m]	length [mm]	width [mm]	height [mm]	volume [m^3]
Rod 1	3C94	2300 +/- 20%	18	100	25	25	6.25E-05
Rod 2	3C94	2300 +/- 20%	18	93	28	30	7.81E-05
Rod 3	N27	2000 +/- 25%	23	93	28	30	7.81E-05
Rod 4	N87	2200 +/- 25%	21	93	28	30	7.81E-05
Rod 5	N87	2200 +/- 25%	21	126	28	20	7.06E-05

Table 1: Specifications of Ferrite Rods Used in the Experiments (at 25° C)

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[22] The rods were purchased at Megatron (Megatron AG, 2016) and Digi-Key (Digi-Key, 1995).

[23] The base material is Mn and Zn. The material codes are: 3C94 from (Ferroxcube, 2000) / N27, N87 from (TDK Corporation, 1996). Ferrite material specifications see Appendix 9.1.

Set Up

The Set Up for the experiments is demonstrated in Figure 19 and Figure 20.

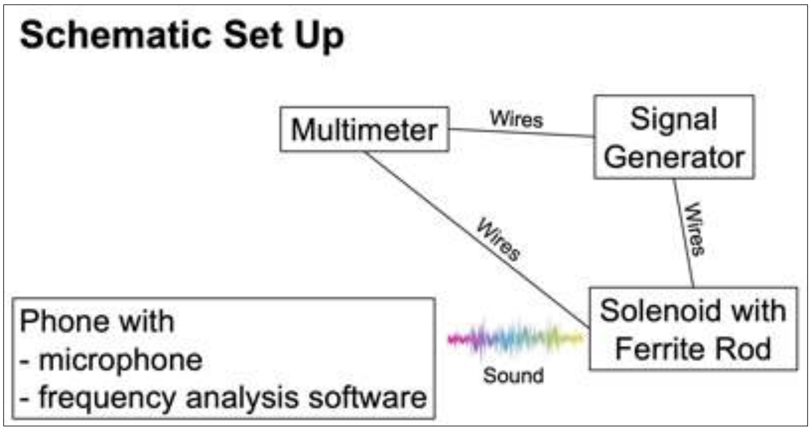


Figure 19: Schematic Set Up of Experiments

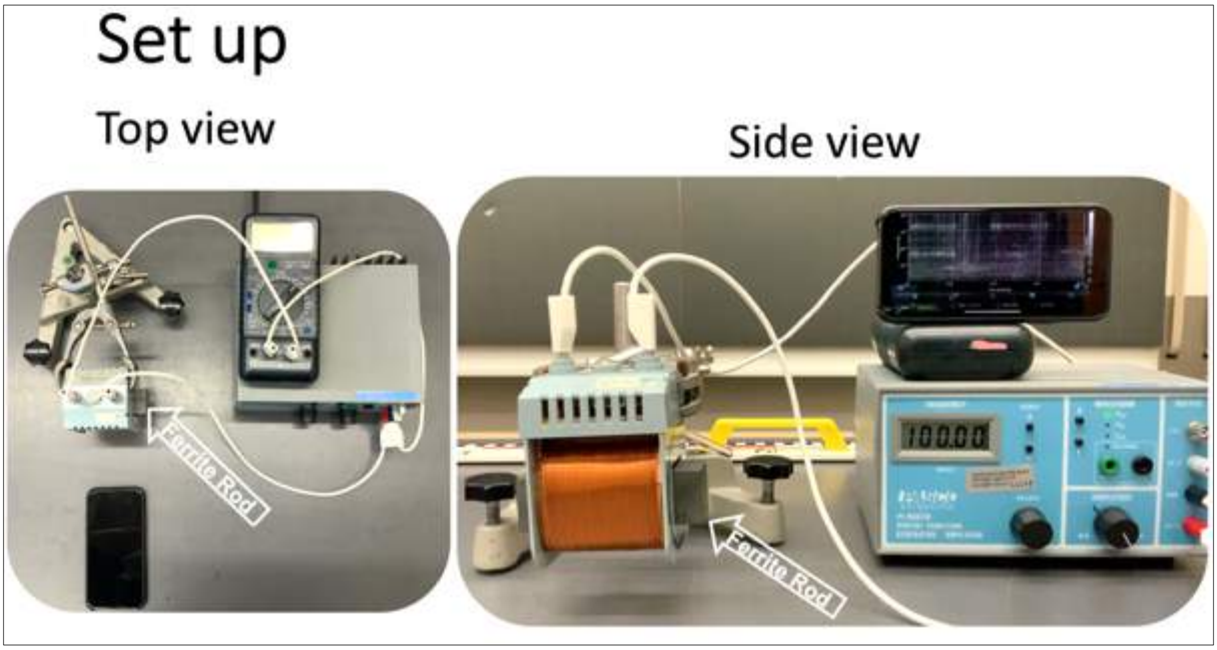
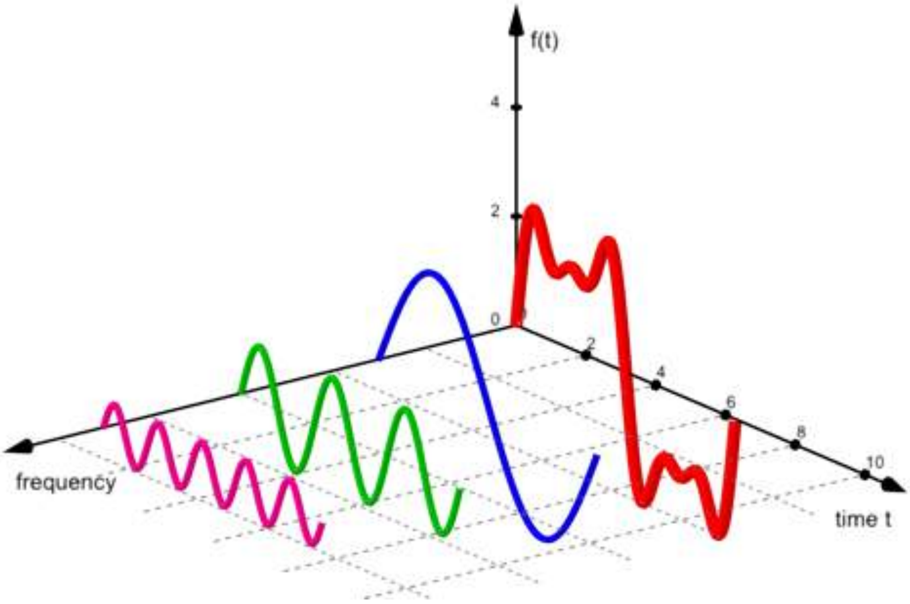


Figure 20: Photograph of Set Up of Experiments

Procedure

Before running the experiment, the signal generator and the solenoid had to be connected with wires and the ferrite rod had to be put into the solenoid. After switching on the signal generator, the produced sound was measured with the microphone that ran into a frequency spectrum analyzer (iPhone software SpectrumView). This was necessary to check the amplitude of each frequency.

The frequency spectrum analyzer runs an internal FFT (Fast[24] Fourier Transform), which takes a sound wave and dismantles it into its unique frequencies with their corresponding amplitudes. This allows extracting the dominant frequencies and thus the different pitches that can be heard. A visualization of how this works can be seen in Figure 21 below. The wave $s_f(t)$ on the far right is being dismantled into its three component waves $2\sin(t)$, $\sin(3t)$, and $\frac{1}{2}\sin(5t)$. In case of an audible sound, the relatively small waves are the different frequencies and the addition of these waves is the sound that is heard.



$$s_f(t) = 2\sin(t) + \sin(3t) + \frac{1}{2}\sin(5t)$$

Figure 21: Illustration of Fourier Transform Waves (author's graphic)

3.2.2 Measurements and Results

There were 240 (= 2 · 5 · 4 · (5+1)) measurements taken: 2 solenoids, 5 rods, 4 different system frequencies f_{AC} (50, 60, 100 and 200 Hz), 5 trials plus drop in AC (same for all trials per rod and f_{AC}). (Details see 9.2 Appendix: Experiments Raw Data.)

---

[24] The Fast Fourier Transform is an algorithm used by computers to perform a Fourier Transform.

Results for frequencies (referring to Hypothesis V)

Examples of the visualized frequency spectrum done in the experiments are shown in Figure 22 and Figure 23 below.

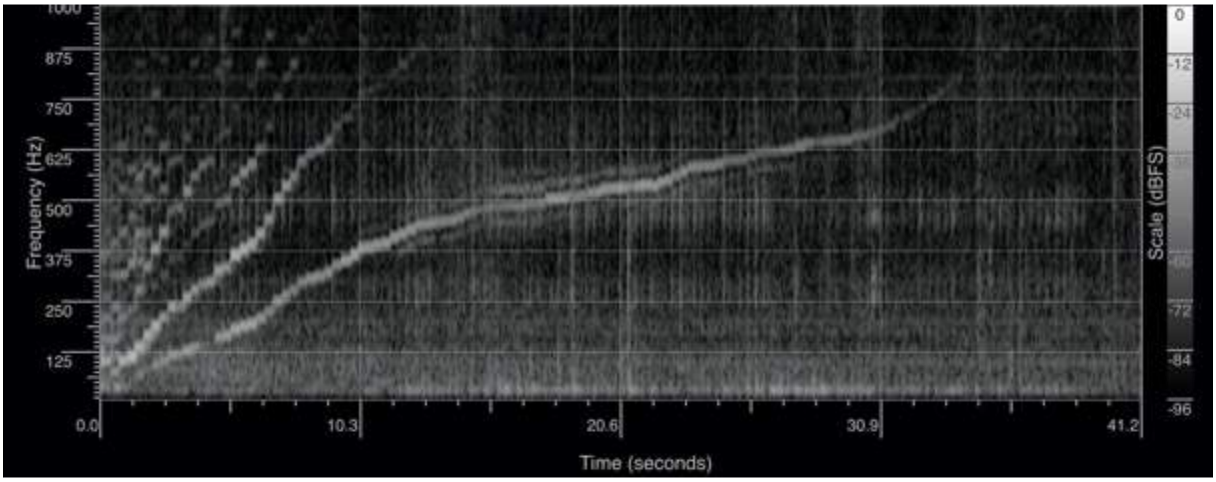


Figure 22: Example 1 of Frequency Spectrum by SpectrumView FFT

In Figure 22 (above) the horizontal axis is time [s], the vertical axis is frequency [Hz] and the brightness of each dot is amplitude (or loudness) with the corresponding scale [dB] on the right (dBFS stands for dB relative to full scale). It shows the result of an experiment with Solenoid 1 and Rod 1, where the frequency of the AC was turned up and thus the white line rise. The lowest line has frequency f_{AC} and the next lowest has frequency $f_{rod} = 2 \cdot f_{AC}$. It is, as expected (see Hypothesis V), the brightest and thus largest amplitude resulting in the loudest sound. The other lines further up are the frequencies $f = k \cdot f_{AC}$ $(k = 2, 3, 4, \ldots)$ of the overtones. They raise and fade away much faster as they are multiples of f_{AC}.

A graph of one of the experiments, where the overtones are clearly portrayed, is displayed in Figure 23 (below). (In the middle there is a gap between the sounds because the intensity (amplitude of the AC) was turned down and back up again.) The input frequency f_{AC} = 100 Hz shows in the lowest line. The one above, again the brightest as expected (see in Hypothesis V), corresponds to $f_{rod} = 2 \cdot f_{AC} =$ 200 Hz. This illustration also shows the overtones with $f =$ 300 Hz or 400 Hz or 500 Hz etc. The overtones of f_{rod} with $f =$ 400 Hz or 600 Hz or 800 Hz etc. are brighter (louder) because f_{rod} is brighter (louder) and due to superposition of the present frequencies.

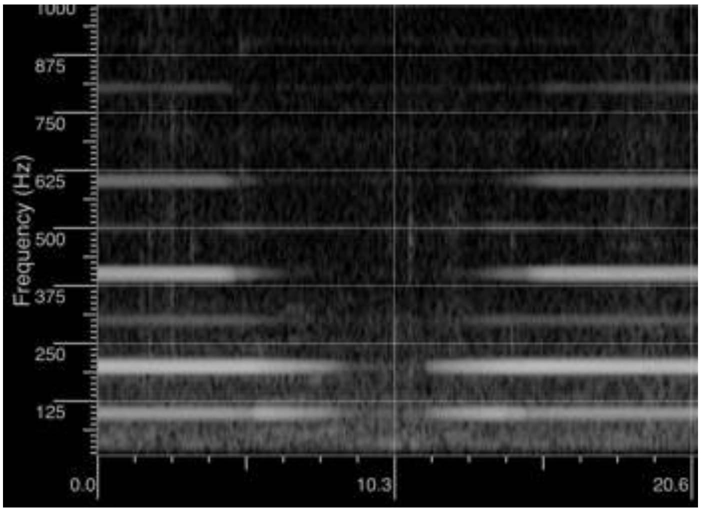


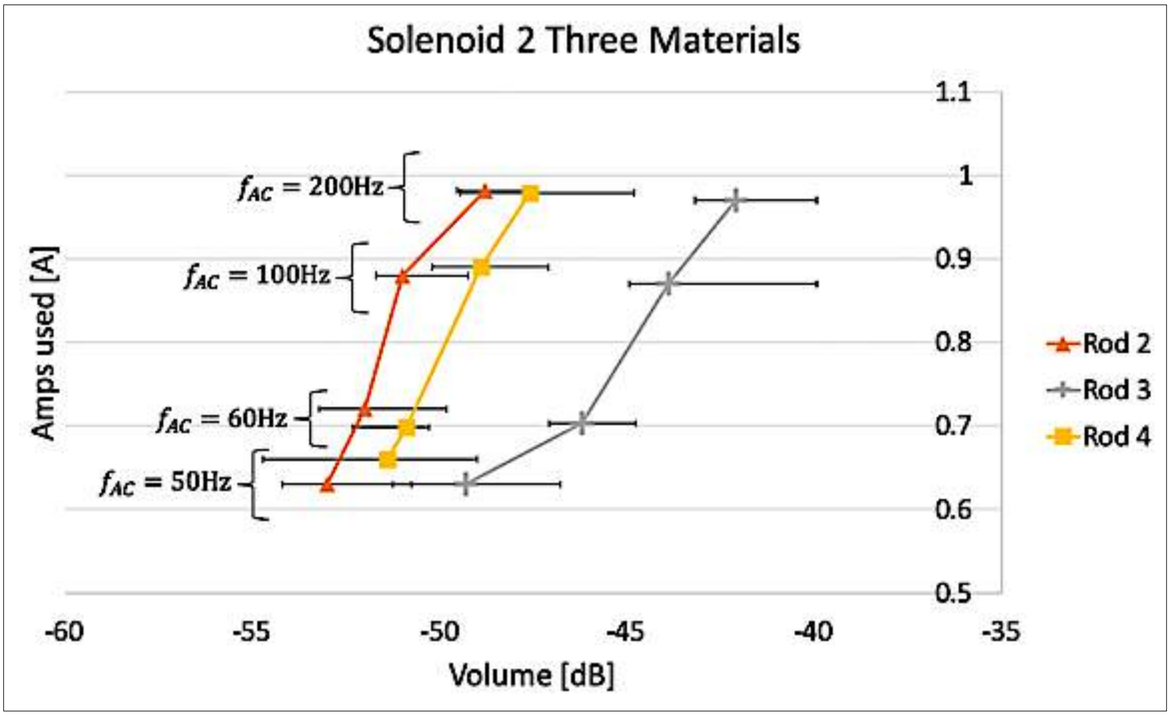
Figure 23: Example 2 of Frequency Spectrum by SpectrumView FFT

Results for observation of amplitude of AC (Hypothesis II) and different ferrite materials (Hypothesis IV)

Figure 24 (below) shows the results for Rod 2 (material 3C94), Rod 3 (material N27) and Rod 4 (material N87) which all have the same dimensions (length 93mm, width 28mm, height 30mm) but different ferrite material and parameters. Their different initial magnetic permeabilities μ_i are listed seen in Table 1 (above).

Figure 24 (below) shows a line graph for each of the three rods in Solenoid 2. The vertical axis refers to how much of the current [A] was used (drop of the current when rod was put into the solenoid). On the horizontal axis the created sound's intensity (volume, loudness and measured amplitude [dB]) is shown.

Each line graph connects four data points (horizontal: sound's amplitude, vertical: current used) for when the solenoid was fed with a current with frequencies f_{AC} = 50 or 60 or 100 or 200 Hz. The error bars a range from the “loudest” data point to the “quietest” of the data series.



label	material	μ_i [(Vs)/(Am)]	H_c [A/m]
Rod 2	3C94	2300 +/- 20%	18
Rod 3	N27	2000 +/- 25%	23
Rod 4	N87	2200 +/- 25%	21

Figure 24: Results of Experiments with Different Ferrite Materials of Rods

All line graphs are increasing. That means that the higher the f_{AC}, the more current was used (vertical) and the louder the sound was (horizontal). At all frequencies, Rod 3 is always the loudest, Rod 4 the next loudest and Rod 2 the quietest. Therefore, the sound's amplitude depended on the rod which in this case were made of different ferrite material. The same can be observed when the rods are in Solenoid 1 (Figure 25 below).

Results for different solenoids (Hypothesis I)

Figure 25 and Figure 26 below show line graphs for all five rods in Solenoid 1 and Solenoid 2, respectively. In both Figures, all lines are increasing and there is no overlap. For all experiments, a larger drop in current implies louder sounds.
Figure 25 and Figure 26 both show the same ordering of the rods from Rod 3 always being the loudest and then Rod 5, 4, 2, and 1 (albeit at different amplitudes).

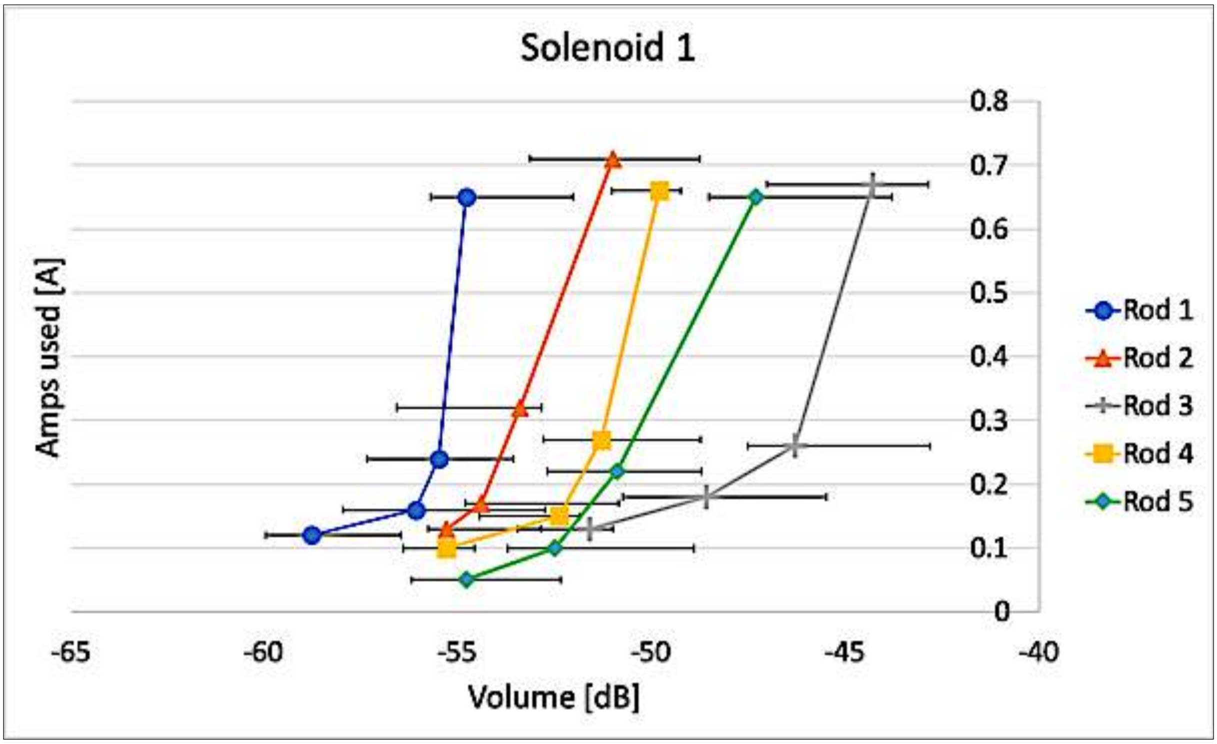


Figure 25: Results of Experiments with All Rods in Solenoid 1

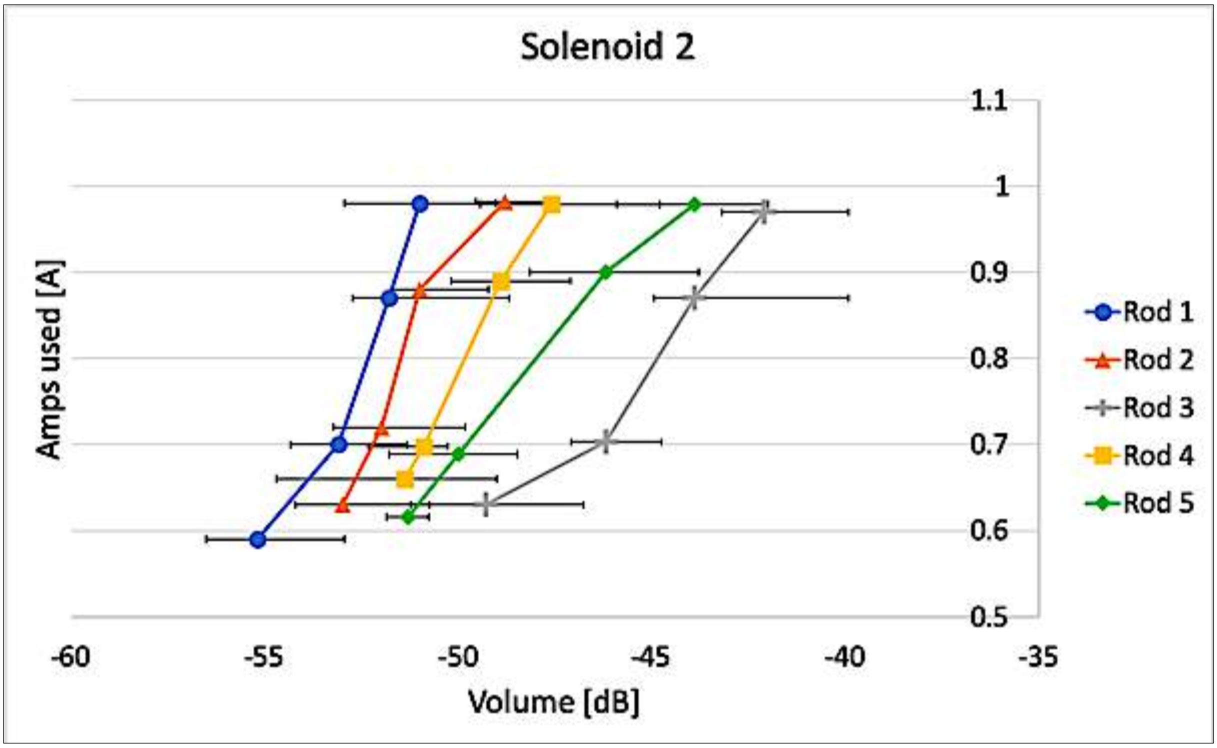


Figure 26: Results of Experiments with All Rods in Solenoid 2

Figure 27 below shows the graph of the averages of the differences in amplitude of the sound (shown on the vertical axis) for each different rod. This was calculated by subtracting the values of Solenoid 2 from those of Solenoid 1 at the same frequencies. Thus, a positive value means the average was higher for Solenoid 2 than for Solenoid 1 and a negative value means the opposite. The values are higher for each ferrite rod in Solenoid 2 than they were in Solenoid 1. In fact, not only were the averages higher for each rod, but every single value measured was as well. So, beyond reasonable doubt, it can be said that Solenoid 2 produces louder sounds than Solenoid 1.

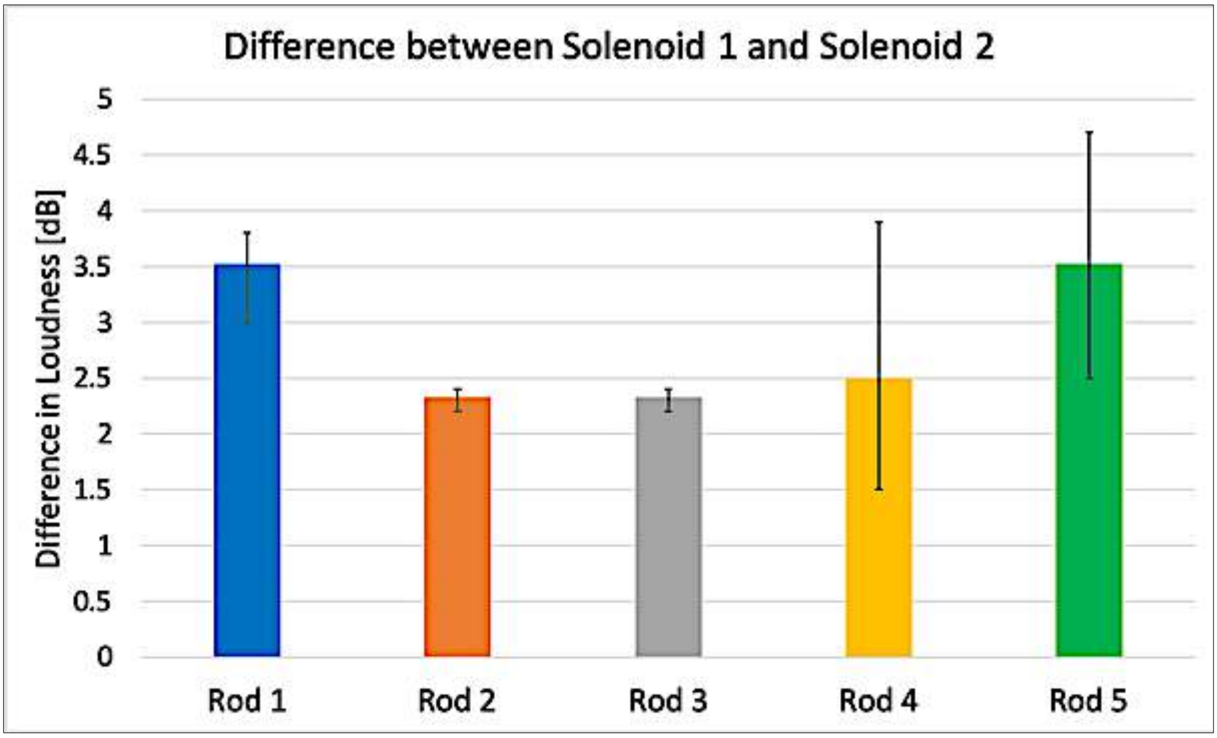


Figure 27: Results of Experiments with Different Solenoids

Results for different dimensions of the rod (Hypothesis III)

The ordering of the rods from loudest to quietest (Rod 3, 5, 4, 2, 1) is consistent throughout the data. The dimensions of the rods compare as shown in Table 2.

label	**material**	**length** [mm]	**width** [mm]	**height** [mm]	**volume** [m³]
Rod 1	**3C94**	100	25	25	6.25E-05
Rod 2	**3C94**	**93**	**28**	**30**	**7.81E-05**
Rod 3	N27	**93**	**28**	**30**	**7.81E-05**
Rod 4	**N87**	**93**	**28**	**30**	**7.81E-05**
Rod 5	**N87**	126	28	20	7.06E-05

Table 2: Dimensions of Ferrite Rods Used in the Experiments

Comparing different **lengths**:

Rod 4 can be compared to the **35.5%** longer Rod 5 made out of the same material. The line graph of the **longer** Rod 5 is further to the **right** meaning: it sounds **louder**.

Rod 2 can be compared to the **7.5%** longer Rod 1 made out of the same material. The line graph of the **longer** Rod 1 is further to the **left** meaning: it sounds **less loud**.

Comparing different **volumes**:

Rod 5 can be compared to the **11%** larger in volume Rod 4 made out of the same material. The line graph of the **larger in volume** Rod 4 is further to the **left** meaning that it sounds **less loud**.

Rod 1 can be compared to the **25%** larger in volume Rod 2 made out of the same material. The line graph of the **larger in volume** Rod 2 is further to the **right** meaning that it sounds **louder**.

3.3 Analysis

The outcome of the experiments versus the stated hypotheses are listed and commented on:

I. **Number of windings of solenoid: Increase triggers higher amplitude**
It was not surprising that the experiments clearly **confirmed** this hypothesis for the 2 solenoids that were compared (Figure 27 on page 38). The denser Solenoid 2 (600 windings, same length) has a higher magnetic field strength and causes more stress on the inserted ferrite rod. This results in faster deformation (more intense magnetostriction) and louder sound.

II. **Drop in current: larger drop implies higher amplitude**

The drop corresponds with the energy impeded by the rod. The rising graphs for all rods **confirm** that, as predicted, there is a positive correlation between the impeded energy and the amplitude (Figure 25, Figure 26).

III. **Dimensions of rod (length and volume)**:

The order of the rods from loudest to quietest was the same in both Figure 25 and Figure 26. The main reason for this is the material (see Hypothesis IV). But within one material we saw that the reason for this was different. For the material 3C94 it was the large difference in volume (25%) and for the material N87 it was the large difference in length (35.5%). This is not that conclusive though, so further experimenting would be necessary to get a better result. I would say that so far, the hypothesis is **confirmed**, because large differences in dimensions were a clear factor.

IV. **Ferrite material of rod**:

This hypothesis refers to the two material parameters μ_i (initial magnetic permeability) and H_c (coercive magnetic field strength) that shape the hysteresis loop. The order of the rods was, from loudest to least loud:

- hypothesis: order according to size of μ_i: 2 – 4 – 3 **not confirmed**
- hypothesis: order according to size of H_c: 2 – 4 – 3 **not confirmed**
- experiment (Figure 24): **3 – 4 – 2**

Why would soft ferrite materials with lower initial magnetic permeability create a louder sound than those with a higher magnetic permeability? One explanation of this could be that the rods with lower magnetic permeability can be penetrated more easily by the magnetic field, thus increasing the effect that field has on them. If the effect is larger, they would then deform faster and thus create a more concentrated pressure wave, which we would perceive as a louder sound.

Regarding H_c: Rod 3 has the largest H_c meaning that it is the hardest to be demagnetized (but only if the magnetic field acts the same way with all the rods). Since its permeability is so low however, the magnetic field would change much faster for Rod 3 than for the other rods, so H_c would be reached faster, even though it is a larger value. This was not predicted in the hypothesis, though, so it is **not confirmed.**

V. **Frequencies of AC and sound waves**:
The frequency spectrum analyzer showed that the experiments did **confirmed** the predicted frequencies as well as the loudest being f_{rod} (Figure 22 and Figure 23).

VI. **Lag of sound waves**:
not tested (reason: special measuring tools not available)

The above analysis shows, that the hypotheses that referred to parameters of the environment (solenoid windings, drop in current, frequency) were all confirmed. The ones with respect to the ferrite rod (dimensions and material) not. I think this is an indication that there were too many simplifications in my approach. Many more parameters might need to be considered, Also, how they interact with each other (multivariate approach) might be more relevant than expected. From the experiments we can tell that the theory used can be applied, albeit only for different proportionalities that were useful to predict the outcomes. Now that the analysis of the experiments is done, we can discuss the experiments on more of a meta level, talking about what could have been done better and what was done well.

3.4 Discussion

The performance of the experiments had the following advantages: not just one but a few parameters were varied (2 solenoids, 5 rods). There were many measurements taken, so I had a good basis for the analysis. The repeated trials showed consistency, which made me feel confident that the results might even be significant when taking more measurements.

A disadvantage for the experiments was that similar shaped ferrite rods were not as easily available as I assumed they would be. The idea was to use more ferrite rods, but the smaller ones that I purchased turned out to be useless. They were too small to produce any sound, which was disappointing. But, since getting larger ones with a similar shape was not possible and getting differently shaped ones did not seem reasonable to me, the measurements might not be comparable.

The quantitative theory was not extensive enough to predict a specific amplitude that would be created by a ferrite rod, which maybe could have been developed in tandem with the experiments.

My last comment is about the simplification in the theoretical explanations. Many different impacts on the system were neglected, such as the Lorentz Force. As discussed in the theory, there is always a force present when there is a magnetic field and moving electrons. This Lorentz Force could have acted on some of the electrons inside the ferrite rod, distorting the results without us knowing it. Also, the assumption that $\vec{E} = 0$ might not be applicable in the case of these experiments, as there is a driving force to make the electrons move around the solenoid, which could have an effect on the Lorentz Force on the ferrite rod yet again.

Considering these shortcomings, there are a few improvements that could be done to the experiments and this paper in general to better answer the research question:

- More differently composed ferrite materials could have been used
- There could be a deeper dive into the theory (mostly quantitative)
- More consideration to other effects could have been given (e.g. Lorentz Force)

4 Part C: Swiss Young Physicists' Tournament

The phenomenon of the "Musical Ferrite" is a perfect problem for the Swiss Young Physicists' Tournament (SYPT), because it:

- Is something that occurs in people's daily life
- Allows designing experiments with a relatively simple and affordable infrastructure
- Is an open-ended problem (no fully developed theoretical explanation, yet)
- Offers a lot of research opportunities regarding the many relevant variables

"Musical Ferrite" is a promising problem for some really good Science Fights (explained below), which are the core of the SYPT. There are currently 25 countries organizing national tournaments like the SYPT. The best national teams participate at the International Young Physicists' Tournament[25] (IYPT). The IYPT 2020 will be the 33rd international tournament.

As year 2020 will be my fourth time competing in the SYPT (and if I make it to the international team, my second year of that), the strategy I will discuss below comes from that of a veteran. I would like to mention, though, that the documentation is based on my personal view and experience and only contains recommendations.

4.1 Structure of the SYPT[26]

Tournament's Periodicity and Problem Set

The SYPT is an annual Swiss national physics tournament for high school students. Not only one but a total of 17 problems ("Musical Ferrite" corresponds with number 4) are debated. They are formulated by the International Organization Committee (IOC) of the IYPT and published every year for the following year directly after the IYPT concludes. The problems describe phenomena that are not fully researched and thus encourages participants to find their own solution.

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[25] Further details can be found on the official webpage https://www.iypt.org (IYPT, 2000)

[26] Further details can be found on the official webpage https://www.sypt.ch (ProIYPT-CH, 2004).

Tournament Rounds

At the tournament itself, a set of three teams compete in one Science Fight (SF), where individually proposed solutions to three problems (one per team) are debated. Several SFs are run parallel, depending on the number of teams participating. There are three rounds of SFs such that all participants have played each role (Reporter, Opponent and Reviewer as described below) once. The teams will be ranked according to their team points. The top three teams will compete in the Final.

4.2 Science Fights

In the SYPT, a team consists of three team members. Each team member chooses one of the 17 problems and studies it theoretically and experimentally. This preparatory work usually starts in December for the tournament occurring in the following summer. The goal is to create a 12-minute presentation about the individually developed solution. The presentation includes explanation of the theory, experiments and results. Each team member presents their presentation at a SF, where the other two team members play the roles of the Opponent and the Reviewer. A description of those three different roles during a SF is:

- *Reporter:* presents his or her solution to a problem
- *Opponent:* critiques the presentation of the Reporter of one of the two opposing teams
- *Reviewer:* judges the performances of Opponent and Reporter of the two opposing teams

A SF consists of three *stages*. During one stage, one of the competing teams plays the role of the Reporter, another team provides the Opponent and the last team is the Reviewer. The roles get switched for the next two stages. After three stages a SF is concluded. Regarding teamwork, it is important to know that when one team member is on stage, the other two teammates can assist him or her.

At the end of each stage, a Jury judges the performances. The Jury is comprised of people that are in the process, or have already finished, studying physics. They grade the performances of the contestants on a scale from 1 to 10, that are weighted with a factor as illustrated in Marking Scheme Column of Table 3.

Team A – Team Member 1			**Team A**	
Role	**Marking Scheme**	**Example**		**Example**
Reporter	**3** x (1 to 10)	3 x 7 = **21**	**Team Member 1**	39
Opponent	**2** x (1 to 10)	2 x 6.5 = **13**	**Team Member 2**	36
Reviewer	**1** x (1 to 10)	1 x 5 = **5**	**Team Member 3**	42
Team A – Team Member 1: Total		**39**	**Team A: Total**	117

Table 3: SYPT Marking Scheme

After the three *rounds* of SFs are completed, everybody has been the Reporter, the Opponent and the Reviewer, once. The points for each performance of a team member are totaled for his or her individual ranking (important for picking the national team members competing at the IYPT). This is shown in Table 3 for Team A – Team Member 1 having a total of 39 points. Similarly, the points for Team Member 2 and Team Member 3 would be calculated. Team A would end up having, for example, a total of 117 points as shown in Table 3. The three teams with the highest number of points compete in the Final.

The three Roles

Table 4 below gives an overview of the tasks for the Reporter, Opponent and Reviewer during one stage of a SF. The individual phases are explained further in the next paragraphs addressing the individual roles. The main focus is always on the preparation as a Reporter, as it is not known until shortly before the tournament (about one week) which problems are to be opposed or reviewed. Also, preparation for the role as a Reporter is the foundation for the other roles. Some thoughts during the presentation go toward what questions could be expected from the Opponent and the Jury.

Phase	Time (total 45')
Presentation of the Reporter	12'
Clarifying questions of the Opponent to the Reporter	2'
Preparation of the Opponent	3'
Review of the presentation (maximum 4') and discussion between Opponent and Reporter	11'
Summary of the discussion by the Opponent	1'
Questions of the Reviewer to the Reporter and the Opponent	3'
Preparation of the Reviewer	2'
Review of the performances of the Reporter and the Opponent by the Reviewer	4'
Concluding remarks of the Reporter	2'
Questions of the jury to all three teams	5'

Table 4: SYPT Description and Times of one Stage (ProIYPT-CH, 2004)

The Role of the Reporter

The Reporter is the key person in a SF of the SYPT and also gets the highest weight (3 times) on the points from the Jury. It is his or her presentation that is discussed by the Opponent and the Reviewer and subsequently questioned by the Jury, which means they have the burden of defending their position. Reporters have 12 minutes to present their findings uninterrupted and must explain everything they have done to the fullest extent possible. This will lead to questions from the Opponent and a discussion, in which the Opponent will attack parts of the Reporter's work and search for mistakes and missed points. A Reporter has to rectify himself or herself and show understanding of the topic to the fullest extent. A good presentation by itself will not score highly, the reporter must also be versatile in the topic. It is a fact that the better the preparation, the more success with the presentation.

The Role of the Opponent

The Opponent has the role of critiquing the presentation of the Reporter of an opposing team. Directly after the presentation, he or she has the opportunity to ask "clarifying questions" for 2 minutes. They are called **clarifying**, as they may not lead to a discussion of any sort, so just questions to further the understanding of the Opponent's team and the other members of the audience. Usually these questions are used to review specific slides again or ask about graphs or methods of experimenting.

Then comes the statement of the Opponent and the discussion (with a combined time of 10 minutes) after a quick break for the preparation of the Opponent. This is the real time for the Opponent to shine, with him or her first evaluating the presentation based on the performance of the Reporter and his or her reaction to the questions. During the discussion, both the Reporter and the Opponent "take the stage" to talk about the demonstration of the Reporter and the points made by the Opponent. It requires quick thinking on both sides and is seen as the most interesting part of a SF. After this phase, the Opponent gets one minute to summarize the discussion and make some final points.

The Role of the Reviewer

The Reviewer has been watching the entire time and now comes his or her appearance. He or she only gets one time period to interact with both of the other contestants and that is in a 3-minute session of questions to both the Reporter and the Opponent. (A little tip for anyone considering competing in the SYPT or IYPT: As a Reviewer, always ask the Opponent your first question, it will give you a significant bonus.) These questions are meant to understand any points made by the Opponent and the Reporter, mostly during the discussion and less about the presentation itself, unless the Opponent missed something glaring.

After another quick break for the preparation of the Reviewer, he or she takes the stage and has 4 minutes to explain his or her point of view on how the entire SF progressed. It is meant as a helping hand to the Jury, facilitating the final grading, by reminding the Jury of what happened in the SF so far and giving the Reviewer's own opinion on the events that transpired. Then, as a final statement, the Reporter can justify himself or herself for another two minutes followed by a five-minute Jury questioning period.

4.3 Creating a Presentation

SYPT presentations usually follow a simple model that is similar to the organization of a scientific paper:

- Demonstration of the phenomenon
- Theory
- Experiments (including the Set Up)
- Analysis of the Results
- Conclusion

There is one problem with just following a template set by scientific papers: They tend to be a bit boring as they are very factual. My experience has taught me the following rule: the minute your Jury falls asleep is what your grade is going to be. So, as Reporter, you have to keep the Jury engaged for **at least** 10 minutes out of the 12. Of course, ending a presentation on exactly 12 minutes is one of the most impressive things when it comes to being the Reporter, but it is very hard to be that precise.

Besides getting the timing right, it is great if the presentation contains something flashy, some sort of story throughout the entire presentation that will keep the jurors engaged.

Demonstrating the Phenomenon

This is a very creative part. It can be done by a short physical demonstration or short video clip, depending on the phenomenon. I think that this part, albeit being very important, should not take up too much time.

Explaining the Theory

The theory in an SYPT presentation is usually divided up into *qualitative* and *quantitative* theory, which is a very good option for the phenomenon of the "Musical Ferrite". On one hand, the discussion of magnetic anisotropy (qualitative theory) is very important, but so is the discussion of the frequency predictions (qualitative).

Something that always helps with the qualitative explanation of the phenomenon, is a good *animation* or *graphic* that showcases all the important factors in the discussed system. The creation of this starts with thinking of all the things that need to be present in the system for it to make sense, based on what needs to be known to understand the phenomenon. For magnetocrystalline anisotropy, which is the most important idea regarding the "Musical Ferrite", it would definitely be helpful to draw a ferromagnetic crystal to demonstrate all the different factors, such as the domains, the so-called “easy axis” and the magnetic field being applied to it in different directions. An example slide for this section can be seen in Figure 28 below.

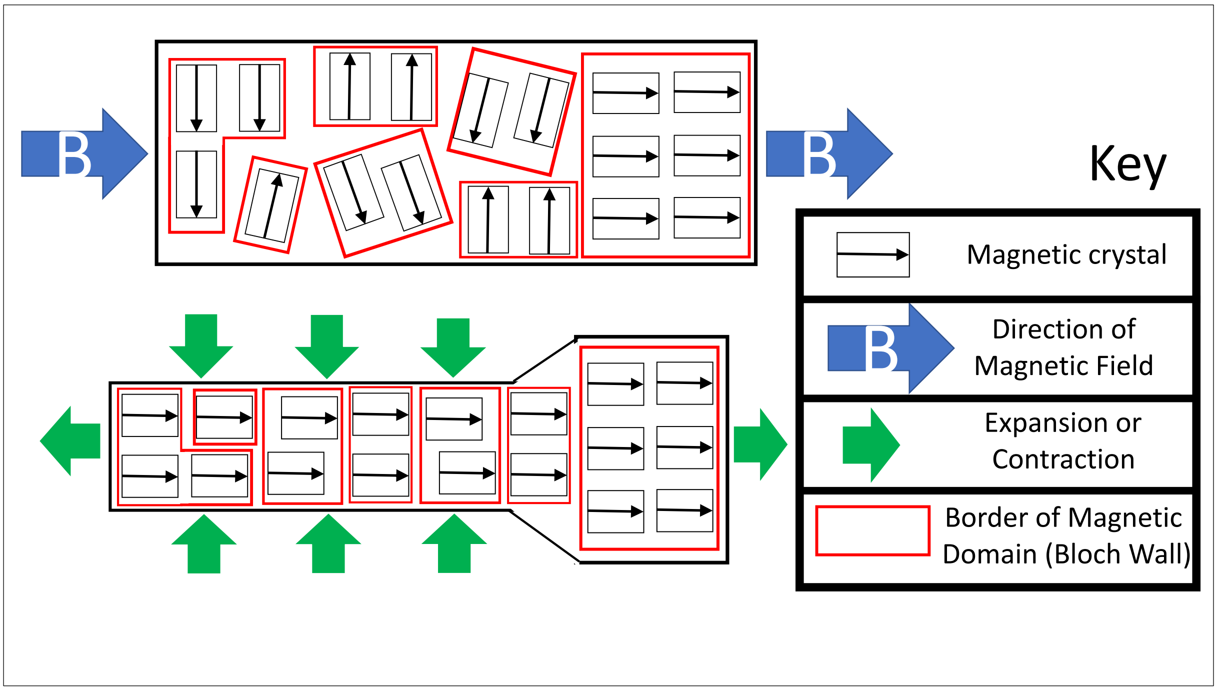


Figure 28: SYPT Presentation Sample Slide 1 (Theory)

Showcasing the Experiments

The first thing that has to be shown when presenting the experiments is the Set Up. The audience and the other students in the SF have to be able to understand what was going on in the experiments such that a fruitful discussion will follow with the Opponent. Regarding the "Musical Ferrite", the main pieces (solenoid, ferrite rod, multimeter and signal generator) have to be clearly visible on the picture. I usually create two pictures: one with all the pieces lined up next to each other (Figure 29) and one with the entire Set Up when conducting the experiments (Figure 30).

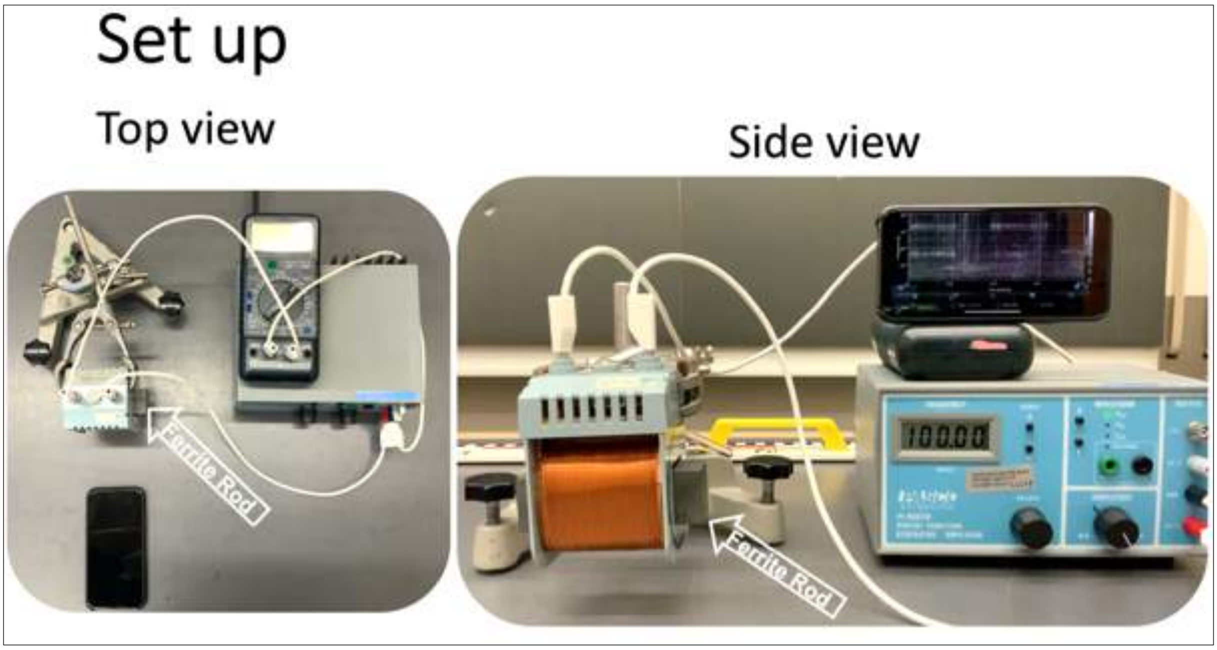
Set up

- Frequency Generator
- Multimeter
- Ferrite Rods
- Coils
- Stands and Clamps

Ferrite Rods

Figure 29: SYPT Presentation Sample Slide 2 (Set Up)

What I usually do during the presentation is animate the words listed in Figure 29 at the same time as the corresponding picture appears. This leads to a clear explanation of everything that is in the Set Up.



Set up

Top view

Side view

Figure 30: SYPT Presentation Sample Slide 3 (Set Up)

A great way to display the measurements and results of the experiments is with graphs. The key is not to only show nice graphs but to explain them well. When preparing the graphs, the first question one has to ask is: does the graph make sense? Does it transfer the message I want to communicate? Ideally, a graph is "easy" enough for someone to basically understand what it shows without much or any of the Reporter's input. How to do that is shown (and marked with all the arrows, that of course, are not shown in the graph when presenting it) in Figure 31. A good graph has, at the minimum, large enough axis titles, labeling and clear color differentiation. This might seem a bit obvious, but people forget it all the time.

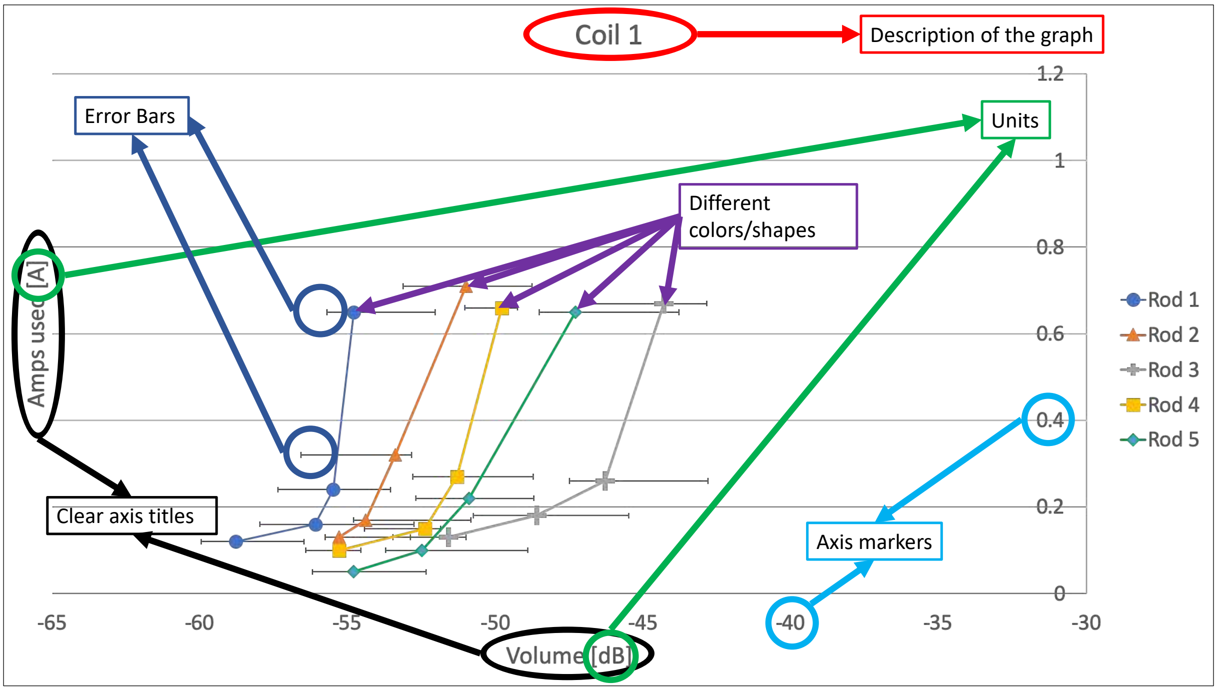


Figure 31: SYPT Presentation Sample Slide 4 (Results)

Formulating Hypotheses, Analysis and Conclusion

This part is very similar to the way it is done in a scientific paper. The hypotheses must be derived from your theory, they have to be logic and relate to the explained theory. For example, one of the crucial formulas for the "Musical Ferrite" is the relation between the magnetic flux density and the magnetic field strength.

It appears in the theory, the hypotheses and the experiments. It is important to comment the whole thinking process clearly.

The analysis has to have two distinct parts, just like in a scientific paper: A part where experiments are *compared* to the theory and another part *interpreting* why the results turned out the way they did. This includes *discussing* any errors that might have arisen in your experiments for some reason.

The conclusion is the most important part of a presentation (which is not really the same for a scientific paper), because the audience gets a reminder of what the Reporter actually created while investigating the phenomenon. Unlike in a scientific paper, it is not possible to go back and "read" a part of the presentation again. This puts the Reporter at a significant disadvantage when it comes to expecting the audience to remember what was demonstrated and analyzed. So, the best is to basically summarize the entire presentation in about one minute. This makes sure that what the Reporter said stays with the listener. It can be done by reviewing graphs, experiments or even some of the comparison (Theory vs. Experiments). However, a Reporter should make sure **not** to add anything new during his or her conclusion. It makes the presentation seem unpolished, because it looks like something was forgotten.

Creating Something "Flashy"

The basic idea of something flashy is to make the SYPT Presentation interesting. Generally, there are two ways to make the audience stay engaged throughout your presentation:

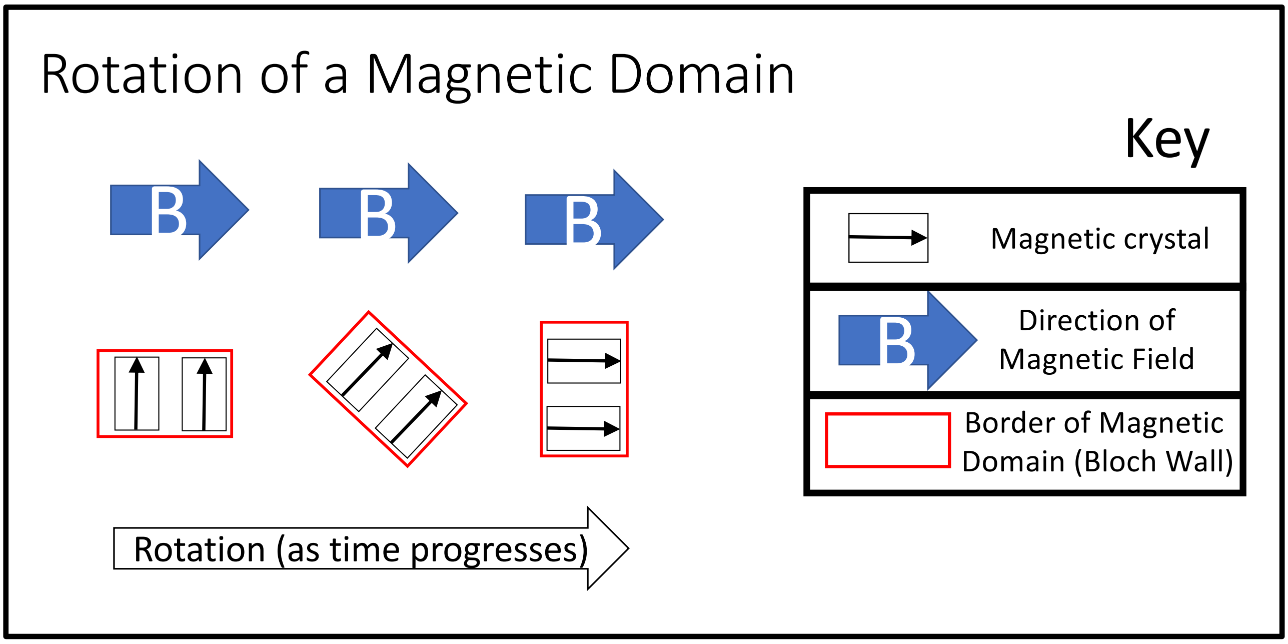
- An interesting spin on the topic.
- Something really impressive.

Example for interesting (unexpected) spin on the topic:

Demonstrate Helmholtz Theory (how bottles make sounds when you blow over them) by making a song with bottles. This is sure to show that your theory is actually applicable to real life situations. In the case of the "Musical Ferrite", creating a song with the ferrite rods is not really an option as the used frequency generator is not capable of switching the frequencies fast enough.

Example for something impressive:

An idea for the "Musical Ferrite" would be to create a comprehensive animation of the effect of magnetostriction. An important part of magnetostriction is, of course, the rotation of the magnetic domains, which can be showcased in a slide like this:



Rotation of a Magnetic Domain

Key

Magnetic crystal

Direction of Magnetic Field

Border of Magnetic Domain (Bloch Wall)

Rotation (as time progresses)

Figure 32: SYPT Presentation Sample Slide 5 (Theory)

This will lead people to understand the phenomenon easily, which is one of the flashiest things you can do.

As a final remark with respect to the SYPT presentation, I would like to point out that the Reporter has to keep in mind that, while physics is by far the most important part, a good presentation is a vital part to getting a lot of points. So, animations or visualizations like described above are integral to a successful SYPT presentation.

5 Conclusion

The research question I posed for this paper was the following:

To what extent can the vibrations of a ferrite rod inserted into a periodically changing magnetic field be described by physical theory?

To answer this question, I first went through all of the theory that is applicable to this topic, namely: Electromagnetism, Ferromagnetism, Magnetostriction, the Composition of Ferrites and Acoustics. The most relevant theoretical part was Magnetostriction, as it is the effect that makes the phenomenon possible. As shown, it causes specific materials to deform (e.g. ferrite), when a magnetic field is applied to them. This is because crystals in the material are more easily magnetized in some directions than others, so when a magnetic field is applied in the "wrong direction", the crystals will turn. If the magnetic field is periodically changing, the ferrite rod will start to vibrate. These vibrations of the object will push air molecules back and forth causing a sound wave to be created.

I used this knowledge to formulate hypotheses which I then tested with various experiments. Every hypothesis I postulated and tested was confirmed, except for the hypothesis about material (magnetic permeability μ_i and the coercive magnetic field strength H_c). I discussed why this hypothesis was not confirmed and formulated an alternate idea as to why my experiments turned out the way they did.

With the help of these experiments and the theory explained before, I can now answer the research question: The qualitative theory of how the phenomenon arises and which relations exist in the system is quite extensive and allows to predict many results. The quantitative theory, however, is quite lacking. Quantitative predictions are not possible (except for the frequency). So, we are partway there: we know what happens and why it does, but the full mathematical description is not complete. Neither this paper nor the current academic research has fully explained this phenomenon.

After documenting the theory, the conducted experiments and the answers to the research question, I discussed the SYPT. It was my inspiration for this project. I described why this phenomenon of the "Musical Ferrite" was a suitable SYPT problem and also gave tips on how to make a good presentation when competing at the tournament. I did this by going through my process of working on a SYPT assignment and showing example slides and displaying strategies. As an added bonus, working on this paper will provide an amazing basis for preparation for the SYPT, when I compete in it in March 2020.

6 Reflection

To reflect on this paper, I will go through it in its entirety, commenting on what worked and what did not work, and then propose some improvements.

A positive of this paper was certainly the extensive qualitative theory, which I think was explained well, with comprehensive visualizations. It was a great experience for myself to delve into electromagnetism and research about a new topic I never heard before: magnetostriction. It realized that it is a complex field and that the theory of the phenomenon of the "Musical Ferrite" is not fully understood. This is the reason that the theory became a substantial part and the strength of this paper.

The hypotheses I postulated were a logical derivation from the theory I could comprehend and did explain. They had to be very specific and focused with respect to the experiments.

A negative of this paper was that the experiments needed to be narrowed down to the available material (5 similarly shaped ferrite rods and 2 different solenoids and other material) and resources at the school's physics laboratory. The experimental results were a bit lacking, especially due to the fact that I did not conduct a large number of experiments. If I had done more, I could have been more confident in the results and thus my conclusions. I did, however, use and compare different ferrites and would have used even more if available in the time frame I had.

A positive was that the results of the experiments were sufficient to accept or reject the tested hypotheses and provided a basis to find answers to the research question.

The experiments' outcomes were described in the analysis which was not that comprehensive. The fact that there is no fully established qualitative theory about the phenomenon made any sort of precise comparison impossible.

The last part of this paper, the SYPT, was the best for me because I am very familiar with the tournament. I described the tournament and explained how to prepare as a contestant. I provided some sample slides demonstrating how the phenomenon of the "Musical Ferrite" could be presented. Also, I gave some tips of how to get ready for the different roles (Reporter, Opponent and Reviewer) any participant gets to play in the Science Fights at the tournament.

Some improvements that could be made to add to this paper are conducting more experiments with different ferrite rods, materials and measuring other variables. Also, trying to create a qualitative theory explaining the phenomenon could be done. New theoretical approaches could be derived from the results of the extra experiments. Of course, any additional research to understand the phenomenon more thoroughly would lead to better predictions or analysis as well.

All in all, this paper was an enrichening and satisfying learning experience for me. The aim was fulfilled as I could adequately answer the research question, despite the lack of many experiments and some quantitative theory. Additionally, I am already well prepared for the SYPT 2020.

7 Table of Figures and Table of Tables

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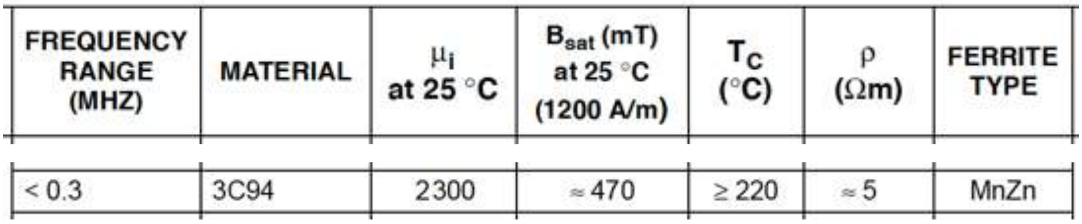
9 Appendices

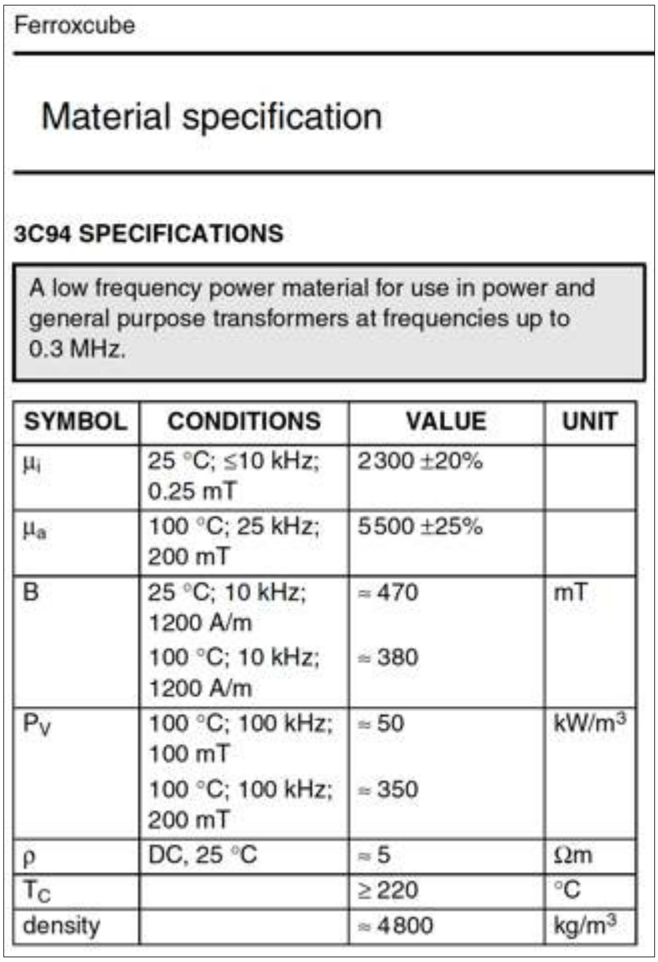
9.1 Appendix: Ferrite Material Specifications

3C94

Data Handbook, page 59 (Ferroxcube Corporation, 2013)



FREQUENCY RANGE (MHZ)	MATERIAL	μ_i at 25 °C	B_{sat} (mT) at 25 °C (1200 A/m)	T_C (°C)	ρ (Ωm)	FERRITE TYPE
< 0.3	3C94	2300	≈ 470	≥ 220	≈ 5	MnZn



Ferroxcube

Material specification

3C94 SPECIFICATIONS

A low frequency power material for use in power and general purpose transformers at frequencies up to 0.3 MHz.

SYMBOL	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.25 mT	2300 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	5500 ±25%	
B	25 °C; 10 kHz; 1200 A/m 100 °C; 10 kHz; 1200 A/m	≈ 470 ≈ 380	mT
P_V	100 °C; 100 kHz; 100 mT 100 °C; 100 kHz; 200 mT	≈ 50 ≈ 350	kW/m³
ρ	DC, 25 °C	≈ 5	Ωm
T_C		≥ 220	°C
density		≈ 4800	kg/m³

Data Handbook, page 92 (Ferroxcube Corporation, 2013)

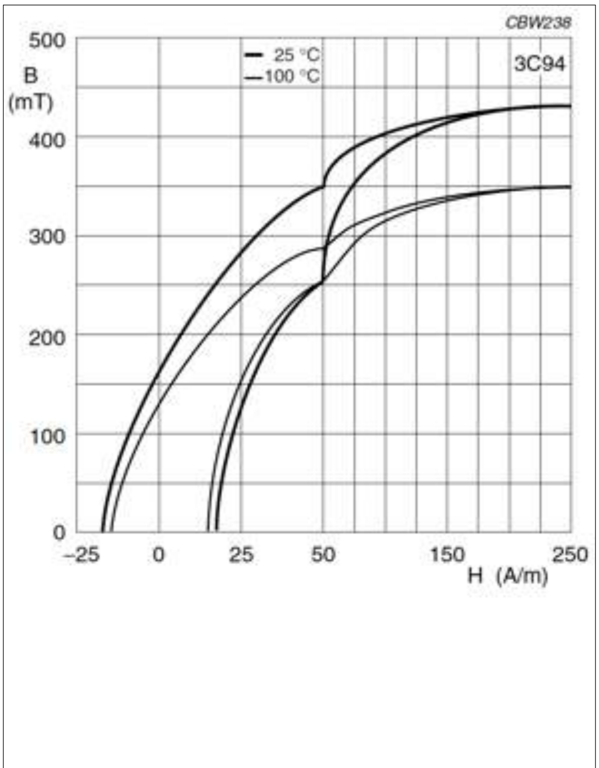
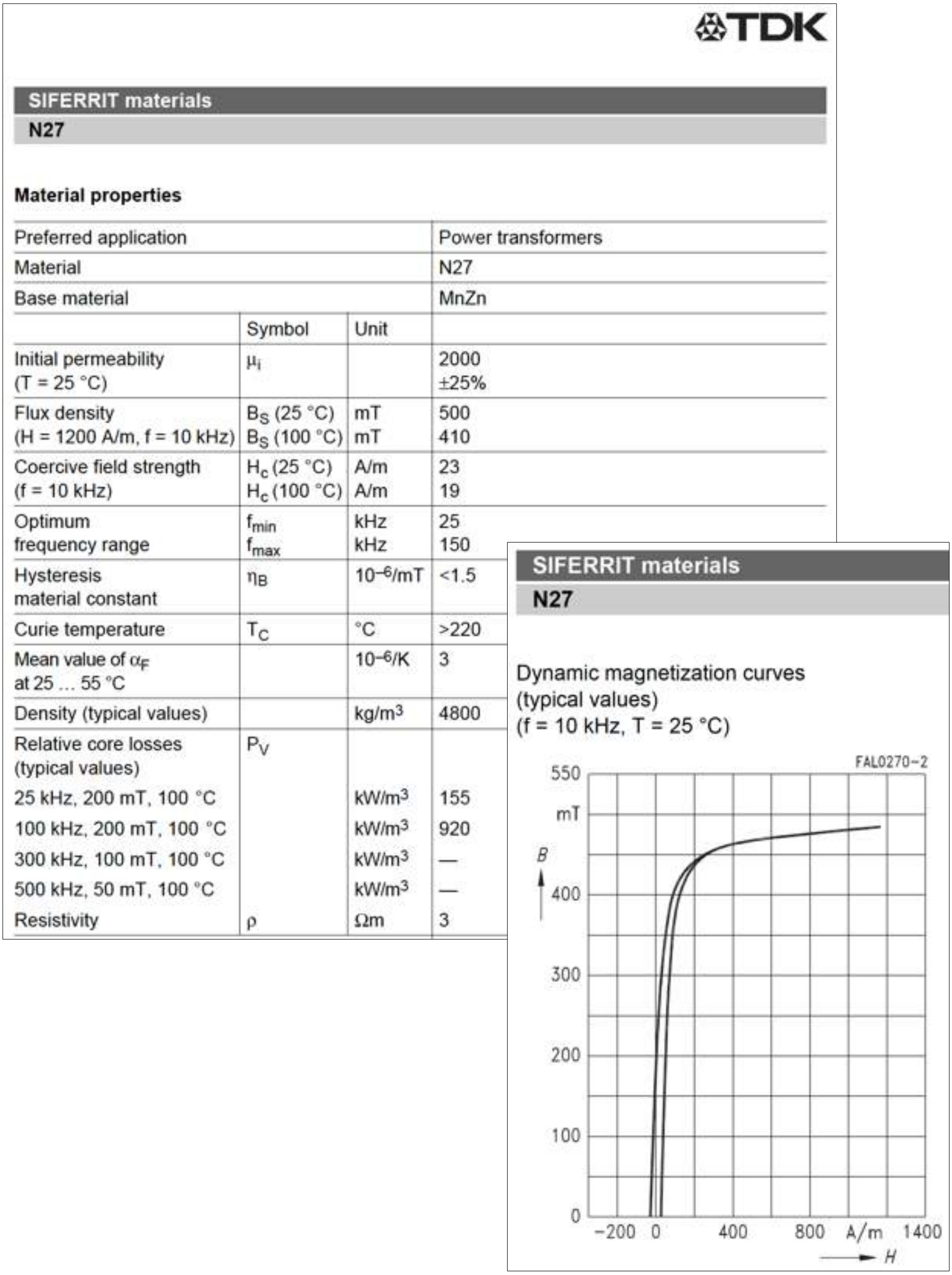


Fig.3 Typical B-H loops.

N27

Material Datasheet for N27, pages 2 and 4 (TDK Electronics, 2014)



TDK

SIFERRIT materials

N27

Material properties

Preferred application			Power transformers
Material			N27
Base material			MnZn
	Symbol	Unit	
Initial permeability (T = 25 °C)	μ_i		2000 ±25%
Flux density (H = 1200 A/m, f = 10 kHz)	B_S (25 °C) B_S (100 °C)	mT mT	500 410
Coercive field strength (f = 10 kHz)	H_c (25 °C) H_c (100 °C)	A/m A/m	23 19
Optimum frequency range	f_{min} f_{max}	kHz kHz	25 150
Hysteresis material constant	η_B	10^{-6}/mT	<1.5
Curie temperature	T_C	°C	>220
Mean value of α_F at 25 … 55 °C		10^{-6}/K	3
Density (typical values)		kg/m³	4800
Relative core losses (typical values)	P_V		
25 kHz, 200 mT, 100 °C		kW/m³	155
100 kHz, 200 mT, 100 °C		kW/m³	920
300 kHz, 100 mT, 100 °C		kW/m³	—
500 kHz, 50 mT, 100 °C		kW/m³	—
Resistivity	ρ	Ωm	3

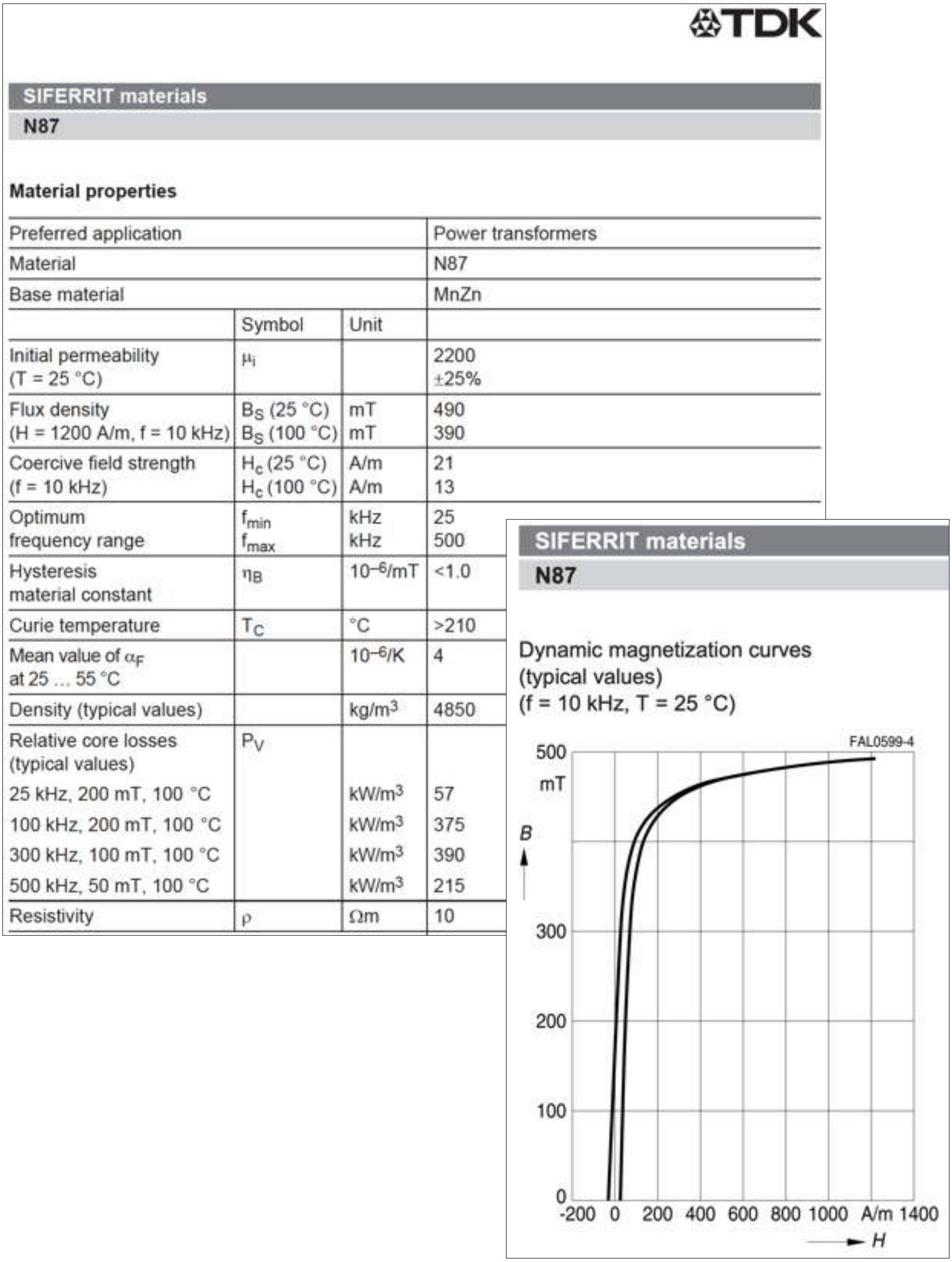
SIFERRIT materials

N27

Dynamic magnetization curves
(typical values)
(f = 10 kHz, T = 25 °C)

N87

Material Datasheet for N87, pages 2 and 4 (TDK Electronics, 2017)



TDK

SIFERRIT materials

N87

Material properties

Preferred application			Power transformers
Material			N87
Base material			MnZn
	Symbol	Unit	
Initial permeability (T = 25 °C)	μ_i		2200 ±25%
Flux density (H = 1200 A/m, f = 10 kHz)	B_S (25 °C) B_S (100 °C)	mT mT	490 390
Coercive field strength (f = 10 kHz)	H_c (25 °C) H_c (100 °C)	A/m A/m	21 13
Optimum frequency range	f_{min} f_{max}	kHz kHz	25 500
Hysteresis material constant	η_B	10^{-6}/mT	<1.0
Curie temperature	T_C	°C	>210
Mean value of α_F at 25 ... 55 °C		10^{-6}/K	4
Density (typical values)		kg/m³	4850
Relative core losses (typical values)	P_V		
25 kHz, 200 mT, 100 °C		kW/m³	57
100 kHz, 200 mT, 100 °C		kW/m³	375
300 kHz, 100 mT, 100 °C		kW/m³	390
500 kHz, 50 mT, 100 °C		kW/m³	215
Resistivity	ρ	Ωm	10

SIFERRIT materials

N87

Dynamic magnetization curves
(typical values)
(f = 10 kHz, T = 25 °C)

9.2 Appendix: Experiments Raw Data

	Solenoid 1					Solenoid 2			
Frequency	50 Hz	60 Hz	100 Hz	200 Hz	Frequency	50 Hz	60 Hz	100 Hz	200 Hz
Rod	Rod 1				Rod	Rod 1			
Trial 1	-57.5	-58.0	-57.4	-54.9	Trial 1	-56.5	-54.0	-51.9	-49.3
Trial 2	-58.6	-52.8	-53.8	-55.6	Trial 2	-53.8	-51.3	-52.7	-49.6
Trial 3	-56.5	-57.0	-53.6	-52.0	Trial 3	-53.0	-54.3	-51.5	-53.0
Trial 4	-59.2	-56.4	-55.8	-55.7	Trial 4	-54.7	-52.4	-48.7	-49.0
Trial 5	-60.0	-54.5	-54.1	-52.8	Trial 5	-55.7	-53.5	-51.7	-52.1
max	-56.5	-52.8	-53.6	-52.0	max	-53.0	-51.3	-48.7	-49.0
min	60.0	58.0	57.4	55.7	min	56.5	54.3	52.7	53.0
current difference (A)	0.1	0.2	0.2	0.7	current difference (A)	0.6	0.7	0.9	1.0
average volume (db)	-58.4	-55.7	-54.9	-54.2	average volume (db)	-58.4	-55.7	-54.9	-54.2
Rod	Rod 1				Rod	Rod 2			
Trial 1	-54.1	-52.4	-54.0	-52.6	Trial 1	-54.1	-53.2	-51.4	-48.5
Trial 2	-55.7	-54.8	-52.8	-48.8	Trial 2	-54.2	-51.0	-50.2	-47.6
Trial 3	-54.9	-50.8	-53.1	-53.1	Trial 3	-52.6	-52.6	-51.2	-48.4
Trial 4	-55.8	-54.4	-56.6	-50.5	Trial 4	-53.4	-51.5	-49.2	-49.6
Trial 5	-52.9	-53.9	-54.9	-52.2	Trial 5	-50.8	-49.8	-51.7	-47.7
max	-52.9	-50.8	-52.8	-48.8	max	-50.8	-49.8	-49.2	-47.6
min	55.8	54.8	56.6	53.1	min	54.2	53.2	51.7	49.6
current difference (A)	0.1	0.2	0.3	0.7	current difference (A)	0.6	0.7	0.9	1.0
average volume (db)	-54.7	-53.3	-54.3	-51.5	average volume (db)	-53.0	-51.6	-50.8	-48.4
Rod	Rod 3				Rod	Rod 3			
Trial 1	-52.1	-48.7	-45.0	-45.5	Trial 1	-46.8	-46.7	-42.5	-39.9
Trial 2	-52.3	-48.7	-47.5	-47.0	Trial 2	-51.3	-46.0	-43.0	-41.4
Trial 3	-53.5	-50.8	-45.5	-46.3	Trial 3	-47.8	-45.9	-43.3	-41.4
Trial 4	-51.0	-45.5	-46.1	-42.9	Trial 4	-50.0	-47.1	-45.0	-40.2
Trial 5	-51.5	-49.2	-42.8	-43.7	Trial 5	-46.9	-44.8	-39.9	-43.2
max	-51.0	-45.5	-42.8	-42.9	max	-46.8	-44.8	-39.9	-39.9
min	53.5	50.8	47.5	47.0	min	51.3	47.1	45.0	43.2
current difference (A)	0.1	0.2	0.3	0.7	current difference (A)	0.6	0.7	0.9	1.0
average volume (db)	-52.1	-48.6	-45.4	-45.1	average volume (db)	-48.6	-46.1	-42.7	-41.2
Rod	Rod 4				Rod	Rod 4			
Trial 1	-56.4	-54.4	-52.3	-50.4	Trial 1	-53.9	-52.3	-47.8	-45.3
Trial 2	-56.3	-54.0	-48.7	-49.6	Trial 2	-51.3	-51.9	-48.2	-49.4
Trial 3	-55.7	-54.1	-51.3	-51.0	Trial 3	-54.7	-51.6	-49.3	-44.8
Trial 4	-54.6	-53.5	-49.9	-49.3	Trial 4	-53.2	-50.3	-47.1	-49.4
Trial 5	-56.4	-51.9	-52.8	-50.7	Trial 5	-49.0	-51.3	-50.2	-49.0
max	-54.6	-51.9	-48.7	-49.3	max	-49.0	-50.3	-47.1	-44.8
min	56.4	54.4	52.8	51.0	min	54.7	52.3	50.2	49.4
current difference (A)	0.1	0.2	0.3	0.7	current difference (A)	0.7	0.7	0.9	1.0
average volume (db)	-55.9	-53.6	-51.0	-50.2	average volume (db)	-52.4	-51.5	-48.5	-47.6
Rod	Rod 5				Rod	Rod 5			
Trial 1	-54.7	-53.7	-51.8	-46.4	Trial 1	-51.9	-48.5	-48.2	-42.0
Trial 2	-52.3	-50.3	-52.0	-48.5	Trial 2	-51.7	-51.1	-46.8	-43.7
Trial 3	-54.4	-51.2	-52.7	-46.6	Trial 3	-50.8	-50.3	-43.8	-45.9
Trial 4	-56.2	-52.5	-48.7	-45.0	Trial 4	-51.9	-50.6	-48.0	-42.4
Trial 5	-53.4	-48.9	-51.9	-43.8	Trial 5	-51.4	-51.8	-47.6	-45.9
max	-52.3	-48.9	-48.7	-43.8	max	-50.8	-48.5	-43.8	-42.0
min	56.2	53.7	52.7	48.5	min	51.9	51.8	48.2	45.9
current difference (A)	0.0	0.1	0.2	0.7	current difference (A)	0.6	0.7	0.9	1.0
average volume (db)	-54.2	-51.3	-51.4	-46.1	average volume (db)	-51.5	-50.5	-46.9	-44.0

9.3 Appendix: Authentication

This physics paper contains solely the work of its author unless indicated otherwise.

Michael Klein