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Addie Lopshire-Bratt
addie.lopshire-bratt@pop.belmont.edu

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The Perceived Effect of Transformer Core Metal on Musical Sounds

Addie Lopshire-Bratt

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Mike Porter Date: 3/27/2020

Mike Porter

Date: 3/28/2020

Dr. Eric Tarr

Scott H Hawley Date: 4/15/2020

Dr. Scott Hawley

Accepted for the Honors Council and Honors Program:

___________________________ Date ____________

Dr. Bonnie Smith Whitehouse, Director
The Honors Program

THE PERCEIVED EFFECT OF TRANSFORMER CORE METAL ON MUSICAL SOUNDS

A. LOPSHIRE-BRATT

Abstract. Transformers are an electronic component used to change the voltage from one part of a circuit to the next. They appear in most audio equipment from the earlier eras but left a sonic signature on the sound waves passed through them. Most research conducted on the “sound” of transformers has focused on their effect on simple sine waves passed through the component, not complex–musical–waves. This thesis seeks to organize the research available about transformers and simple sine waves and compare it with the gamut of opinions that audio professionals hold about their sound.

1. Introduction

Transformers are an integral component in the construction of audio equipment.They appear in many iterations of famous microphones, direct input (DI) boxes, preamps, compressors, and other common gear. However, none of these pieces of gear function the same, thus the use of the transformer must be adapted to suit the purpose.

Date: April 20, 2020.

The purpose of a transformer is to change the voltage from one part of a circuit to the next. The transformer may be a step-up transformer (boosting the voltage from one part to the next), a step-down transformer (cutting the voltage), or one-to-one (maintaining the same voltage on either side to be used for isolation) [1], [2]. The transformer is built by a single core with two enamel insulated wires wrapped around it. The two wires never touch and function off the principle of mutual induction, in which the alternating current of the primary coil (the windings of one wire) induce a magnetic field that then causes a voltage across the secondary coil (the windings of the other wire) [1]. The ratio of a transformer describes how many windings on the primary coil as compared to the secondary and thus tells what the effect on the voltage will be [3]. This property is the defining point of a transformer's function.

Many types of transformers exist, but several appear most often in audio. The two most used transformers are input and output transformers. There are also isolation transformers which are used for–predictably–isolation by the removal of electro-magnetic interference via common-mode rejection [4]. Essentially, the isolation transformer separates noise generated by anything that is not the desired input from the signal by passing only the desired signal to the secondary coil. Input transformers are used to boost the signal to a level that is recognizable to the piece of gear the signal passes through. Output transformers are used for line-driving, to connect a line level signal to an amplifier [4]. Line level refers to the level at which sound is both audible and reproduced most effectively and efficiently.

There are two main areas to develop with transformers: the conductor and the core. The conductor is typically electrolytically pure copper, so researchers have long thought there is no real need for improvement outside of its insulation, though there may be some merit to testing different platings [5]. Over the years of transformer innovation, the effects of the metal used to make the core, around which the coils are wrapped, have been studied extensively. Particularly in reference to audio, the ability of certain metals to maintain high or low frequency fidelity has been thoroughly examined. The goal here is to reduce distortion and improve fidelity–the typical definition of “good” quality audio [5], [6]. However, these studies primarily focus more on the hypothetical or scientific situations surrounding these core metal effects, such as hysteresis loss or eddy current loss, which affect high and low frequencies respectively, and will be discussed at length in later sections. Furthermore, most of these scientific studies do not use complex waveforms as the test input, which affects the results when applied to real-world applications [7]. The lack of information regarding complex waveforms outlines a hole in the existing research field.

Complex waveforms, in this case, refer to frequencies that are not made up of a single sine wave. When testing gear for specifications such as frequency response, a standard sine wave of a single frequency is run through the component, typically at octave intervals (250Hz, 500Hz, 1kHz, 2kHz, 4kHz, 8kHz, and 16kHz). For reference, the human hearing range is 20Hz to 20kHz, 20Hz being lowest and 20kHz being the highest. These frequencies correspond to the perceived pitch; low frequencies are low pitches, high frequencies are high pitches [8]. The key difference is that frequency is the measurement of cycles per second that a waveform has; pitch is only the perception of the frequency.

Figure 1 represents a simple sine wave, the typical test signal for audio studies. Musical signals are–thankfully–not single sine waves because they are made up of a fundamental frequency, and then multiples of that frequency called overtones and harmonics. These harmonics are each at different amplitudes–essentially volume–and give the signal its specific timbre. Harmonics are why the note A 440 (the A commonly tuned to which has a fundamental frequency of 440Hz) sound different on piano to violin [8]. Figure 2 shows a complex waveform, 1f referring to the fundamental frequency, then 2f and 3f being the harmonics on top. Their sum represents a combination of constructive and destructive interference–reinforcement and cancellation of sound–that forms the sound we recognize of a musical instrument and known as the complex waveform. In reality, there are far more than three frequencies combined in commonly recognizable musical sounds, but the principle is the same.

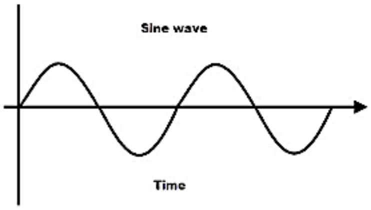

Figure 1. Example of a single sine wave–the usual test subject for audio equipment evaluations

Source: Electronics Hub

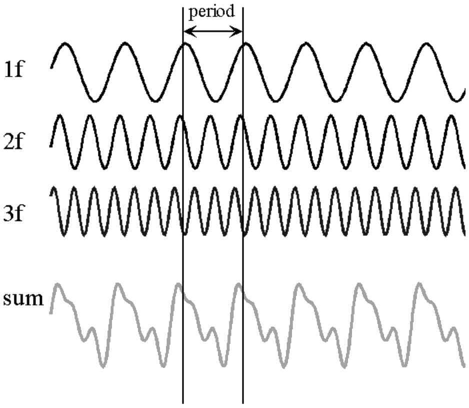

Figure 2. Example of a complex waveform

Source: Physics Department of UConn

Few studies exist that scientifically analyze the changes complex waveforms undergo when passed through a transformer. This type of research would be very difficult to attain because of the amount of variables added by the combined signals. To illustrate the differences that adding a single frequency makes, Eric K. Pritchard built a model of audio processing distortion caused by an output transformer. His study was performed in the context of the signature "tube" sound. He built a model to mimic an output transformer in a tube circuit and ran a single low frequency and a single high frequency through it separately. The low frequency had some soft clipping, but the high frequency was mostly the same. However, when he combined the signals, the light clipping on the low frequency wave affect the shape of the high frequency wave, too, proving that testing individual sine waves is only so effective in determining performance [9]. This effect further illuminates the complexity of musical research.

A pitfall of these purely scientific research projects is that they operate under the impression that reduced distortion and more even frequency response means the component is the best [6]. In actuality, many audiophiles, musicians, and other professionals appreciate an imperfect device; for example, tube-based amplifiers and microphones are not only still common but appreciated as the optimum gear for certain performances, yet the tube adds noise and its output transformer distorts low frequencies [9], [10]. Like the example cited in the Pritchard study, these characteristics people appreciate can be caused by something deemed undesirable. The phenomenon described in Pritchard's work is called Intermodulation Distortion (IMD), in which harmonics playback incorrectly [9]. IMD is a type of nonlinear distortion that adds frequencies that are not multiples of the original signal (harmonics being multiples of the fundamental frequency) [10]. As I mentioned earlier, the goals of transformer design are to reduce distortion and increase frequency response, but people will enjoy a distorted sound anyway. Both factors–complex wave research being hard to procure and humans being unpredictable–make it impossible to decide a transformer's core metal as the "best," so the mission becomes to document the perceived characteristics of the components to be best put to use in the desired situation.

A diverse array of opinions exists pertaining to which transformers sound "warm" or "bright" or "gritty" [11]. These terms may seem strange when applied to the sound of a piece of gear, but they, among others, are common language between music professionals. These out-of-place terms describe a shifty quality of audio: timbre [12]. The basis for these opinions is rarely, if ever, scientific data addressing the hypothetical high and low frequency degradation.

We know there are different qualities of core metal specifications, but that same place where research that solidifies the timbral qualities also implies a need for proof that there is a difference at all. Much of audio engineering is opinion-based, which in more scientific terms means it is perception-based. The problem arises in the slight differences between human auditory systems; no one perceives the same sound the exact same way, so before examining the specific qualities of different transformer metals, the existence of a difference at all must be documented.

These two issues–are there differences and what do they sound like–are the foundation for this thesis. This thesis seeks to consolidate the existing information on transformers to prove that they do, indeed, sound different and begin to scientifically document what they do sound like.

2. Background and Scientific Studies

A variety of research exists about transformers. Since Michael Faraday's experimentation with an induction ring in the late nineteenth century, transformers have been in continuous use [13], [1]. Power transformers are the basis for the world's power grid and can be found in any device plugged into the wall. Power is transferred via power lines and distributed at high voltages throughout any neighborhood. By stepping down the high voltage power line in the street before delivering it to plugs where it is accessed, the transformer is the key component in safely powering every electronic device we use.

Transformers in audio processing function in the same manner but with specific characteristics to cater to their usage. Audio transformers are broadband devices, which carry a large frequency range and have a magnetic core coupling over 0.75 [2]. In order to cover the audible frequency range (20Hz-20kHz), transformers need to include an additional octave on either end to avoid dropping off at either polar end [5]. The key to the optimal core metal is permeability–the inductance (ability to induce a magnetic field) of one turn wound on the core [14], [5], [15]. More permeable metals concentrate magnetic flux, which, in turn, creates high primary inductance (the inductance of the primary coil) [16]. The permeability of air and other non-magnetic materials–aluminum, brass, paper, etc–is 1.00, but the permeability of ferro-magnetic (easily magnetized) materials is much higher [16]. For example, ordinary steel is 300, 4% silicon transformer steel is 5,000, and nickel-iron-molybdenum alloys are in the 100,000 range [16]. Magnetism is the key to transformer function.

Transformers are wound on a metal core of laminated strips. The lamination process involves thin sheets of some kind of metal–which type depends on the purpose–stamped into shapes [1]. These strips are then wound around a–typically–rectangular core [1]. A comprehensive discussion of audio transformers by Bruce E. Hofer describes the specifics of audio transformers. Input transformers typically have a ratio between 1:2 and 1:10 when used to couple a microphone to a preamp to boost the signal to a level that is recognizable [4]. Output transformers are used to drive line level signal to amplifiers; for instance, the output of a stereo music player passes through an output transformer to reach a pair of speakers [4]. One of the most common uses for transformers is in DI–direct input–boxes, which couple instruments to mic level (significantly lower than line level signal). These transformers typically have a ratio of 10:1, a step down transformer, that is used to match the output impedance of the box to the input impedance of the next device in the signal chain [4]. Electric guitars, instruments often used with DIs, have reactive pickups, which require a higher output load impedance [17]. So, while the level produced from an electric guitar may be high enough to call "line level," the power is significantly reduced and incapable of passing long distances [17]. Then direct boxes handle the signal straight from the instrument plugged into it–high impedance and unbalanced–but when it passes through the transformer it becomes a balanced, low-impedance signal that is capable of passing longer distances without interference or significant degradation, i.e. additional, undesired noise.

Many factors and fields are important to the design of transformers, including geometry, magnetics, dielectrics, and design principles of weight and reliability [1], [18]. These factors must be balanced in order to mitigate the most common issues encountered in audio transformers: series resonance and core saturation [2].

Series resonance is the resulting resonance between the first turns of the primary coil and the capacitance in the center which creates a low impedance, thus boosting the resonant frequency as much as ten times its original value [2]. Series resonance can also be referred to as eddy current loss and is unique to high frequencies [14]. By boosting the high frequencies, eddy current loss is responsible for much of the low frequency degradation in transformers [19]. High permeability metals–the ideal for transformers–are natural electrical conductors, which becomes an issue as they induce small currents in the cross section of the core material–eddy currents [16]. These issues are typical in audio because of the higher signal peaks (the highest amplitude the input signal reaches) and lower RMS–a form of average–values present in musical signals [2]. This loss can be remedied by the laminations mentioned earlier because stacking and insulating them individually makes eddy currents insignificant [16]. They are insulated with Faraday shields. A study conducted in 1977 by E. Peterson and L. R. Wrathall determined that the thicker the laminations, the more effective the core at preventing eddy current loss and that low permeability is directly proportional to the thinning of laminations [19]. This type of loss is merely one of two.

Core saturation depends on the input voltage and frequency but is a form of waveform distortion most commonly observed in low frequencies when the electrical energy is lost as heat, also known as hysteresis loss [2], [14]. Saturation results from a high intensity magnetic field and decreases the permeability until it becomes 1–or completely non-magnetic [16]. Unfortunately, high permeability generally means that saturation occurs at a lower flux density, varying inversely with frequency [16]. Essentially, magnetic hysteresis is a magnetic memory effect; a high hysteresis remains strongly magnetized even after the force is removed. Magnetically saturating zero-hysteresis materials have no residual magnetism when the force is removed, and thus is the goal for audio uses [16]. This non-linearity of hysteresis loss causes the low frequency distortion it is known for [16]. More specifically, the magnetic hysteresis energy losses decrease sound pressure most at the fundamental frequency of the input signal [20]. To reduce hysteresis loss, certain metal alloys can be heat-treated through special processes [16]. Hysteresis loss is more commonly understood than eddy currents and is often easier to hear.

The hysteresis of a certain metal is expressed using a B-H loop. For high hysteresis metals, there is a wide or square B-H loop. At the origin of the graph–the zero point–is the zero hysteresis point [16]. Smaller AC signals travel less of the loop than the larger AC signals, which then approach the saturation points. Signal distortions are caused by the curvature of the loop towards the end points and are symmetrical producing odd-order harmonics [16]. Essentially, the louder the input signal, the higher the risk of magnetic saturation [20]. Thus, the louder the instrument, the more audible the transformer.

Figure 3 is an example of the B-H loop for silicon steel. It clearly has a lower magnetic hysteresis because it is a narrower loop. Comparatively, Figure 4 is a nickel-iron alloy, a highly permeable material, that has a much wider–therefore higher–magnetic hysteresis. The higher the hysteresis, the more likely saturation. These graphs clearly demonstrate the tradeoff between low or high frequency fidelity. Of course, magnetic hysteresis is lowest at the resonant frequency [20].

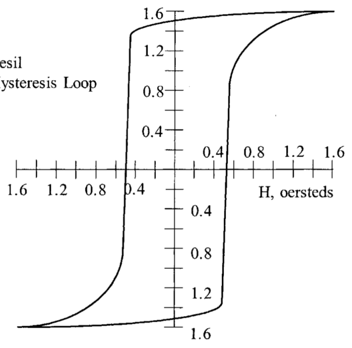

Figure 3. B-H Loop of silicon-steel

Source: Marcel Dekker, [21]

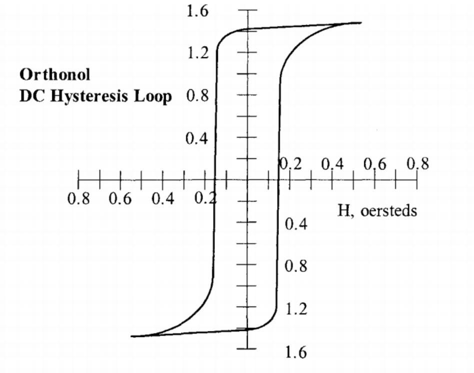

Figure 4. B-H Loop of nickel-iron alloy

Source: Marcel Dekker, [21]

The ideal construction of a transformer keeps a minimum turns ratio (as permitted by core metal) while maintaining the necessary open-circuit inductance and power-handling for low and high frequency fidelity [5]. Transformers are often referred to by their core metals to differentiate between two of the same operation or ratio. The core is the material inside the coil that provides its support; being so close to the coil, it is important to have a magnetic material but its qualities affect the signal [16]. Several factors define the quality of the core metal, but their effects are intertwined. Specifications for core metals relate to their efficiency in dealing with the aforementioned common malfunctions. If the frequency range is meant to start at 20Hz, it is necessary to keep the number of turns low [13]. A metal with high permeability is desirable because it controls the loss. Losses, as mentioned before, include hysteresis loss or eddy current loss. To keep loss low, the metal should have fewer turns with a higher inductance value [14]. The majority of harmonic (waveform) distortion is in the low frequency range [13]. However, designing audio transformers is difficult because the materials and techniques that protect low frequency fidelity tend to harm the high frequency fidelity [16]. This tradeoff further complicates transformers' presence in audio devices.

In 1987, G.A.V. Sowter compiled a thorough history of the experimentation of core metals in audio transformers. Softer metals are more flexible in the magnetization and demagnetization process that rules transformers. The late nineteenth century was devoted to comprehensive studies of soft metals–iron, steels, nickel, cobalt, among others. Higher nickel content was discovered to boost magnetism

[13]. Nickel alloys were instrumental in improvements to low-level transformer design [5]. In the early twentieth century, silicon-iron alloys became the focus for high permeability and low loss, since minimizing losses had become the focal point of experiments. Metallic glass, which has no crystalline structure, had a resulting 20% lower loss than the preceding metals [13]. These discoveries led to the next big trend in transformer design: mumetal.

Mumetal was originally intended to increase signal strength and reliability in telegraph cables, but by the 1930s Mumetal was the main focus for audio transformers [13]. Mumetal is a nickel-iron alloy that has a high magnetic permeability, thus making it resistant to losses. Mumetal is a type of ferromagnetic–easily magnetized–metal but is among several other types, including ferrites. Ferrites are another classification of ferromagnetic metals, which have a very permeable core that is best suited to high frequencies and thus make the ultra-high frequency, UHF for short, range accessible [14]. Silicon steel was also a later development. The key of this metal was keeping the flux in line with the grain [5]. This metal was more detail-intensive than others because it had to be heat treated and rolled in one direction while slowly cooling to keep a unidirectional grain [5], [13]. Sowter's paper marks the end of a long period of core metal experiments that wrapped up in the 1950s and 1960s. At this point the ideal metals were identified and most of the scientific improvements were documented; all that was left was personal opinions and changing the construction of the transformer itself [15]. As the 1970s rolled in, engineers' opinions turned towards more realistic sound as they sought ways to reduce the amount of introduced noise in the signal path, targeting transformers.

As observed by the term "realisitc," human listeners rarely describe sound as having high permeability so much as seemingly vague terms like "warm" or "bright." We tend not to listen to music from a one-dimensional angle; the quality that pushes us to call it something as non-musical as "warm" is called timbre [12], [22]. Timbre is more than just tone color–spectral properties–and sound quality [12]. Timbre, at its most simple, is how listeners differentiate between two signals without factoring in pitch, loudness, or duration; that is to say, timbre is what makes music recognizable [12], [10]. For reference, timbre is the quality through which we differentiate vowels when speaking [10]. Essentially, timbre is the combination of the spectral content, spectral balance, and amplitude envelope of a sound source [10]. Fortunately, a rather large body of research has been devoted to pinpointing and defining these terms.

Sticking to the example of warmth versus brightness–as the two definitions overlap significantly–brightness correlates closest to the spectral centroid [12], [22]. The spectral centroid is the point in the frequency spectrum where the energy of the signal concentrates, yet rarely, if ever, do musicians tell their engineers they would like the spectral centroid to be in the mid-high range [12]. Warmth is slightly harder to pin down. A 2011 study presented at the AES Convention by Asteris Zacharakis and Josh Reiss found warmth to be related to the spectral centroid, but only in the first third of the frequency spectrum [22]. A later study in 2015 by Duncan Williams found warmth to include perception of the spectral slope, which refers to the approximate shape of the frequency spectrum [12]. These studies both attempted a larger body of work in progress: building a usable universal metering system for timbral qualities. However, a wider knowledge of these timbral definitions is necessary to move forward with scientific categorization of transformer sound.

3. Subjective Ideas

This thesis does not include a formal listening test but instead is intended to lay groundwork for a future listening test to compare and describe transformer differences. Again, regardless of previous literature and studies, most musicians and audio engineers do not need to know the permeability rating or the amount of hysteresis loss inherent to a certain transformer, yet these are the people using audio transformers the most. What matters is more the interaction with the source passing through the transformer.

According to the informal website for custom transformers Butler Windings, nickel is the ideal choice [23]. The author chooses nickel because of its high permeability but admits that it lacks the low frequency fidelity of steel [23]. Ferrites are comparable to nickel, however, they saturate at lower levels [23]. However, steel and silicon-iron alloys, along with other ferromagnetic alloys still appear in modern transformers for what are typically subjective reasons.

According to the Lundahl Transformer website, Kevin Carter claims that the differences between core metals is subtle, but the "detail and tonal shading differences are easy to hear with the appropriate recordings" [24]. In his case, he examines two transformers, one with a mumetal core and another with an amorphous–another name for the aforementioned metallic glass–metal core. He determines–through casual listening tests by himself–that the amorphous core is more transparent and detailed, while the mumuetal core had more "body" [24]. These types of informal tests suggest that there is an identifiable and audible difference in core metals.

In 2014, Brian Fox of Fox Audio Research conducted an informal study examining the frequency responses of different name-brand transformers to determine their usefulness in microphones. Like Carter, he concludes that there are subtle differences between transformers, but not enough to completely fix the sound of a bad microphone the way something like a capsule change would [25]. He found that the Cinemag 2480, using a high nickel core, resonated with his circuit's capacitor at 15kHz, which would change depending on the size of the capacitor but would still yield a resonance [25]. Cinemag 9766, also using a high nickel core, had the superior bass frequency response, which Fox attributes to the 12:1 ratio [25]. Finally, the AMI

T14–a nickel alloy core–had the weakest bass response, which is why it is useful in microphones intended to be bright [25]. Fox's study is a simpler version of this one in that there was no control over the windings ratio or insulation, and the transformers were used in tube circuits, which naturally colors the sound as well.

Grant Carpenter of Gordon Instruments has strong feelings on the sound of transformers. In a 2020 interview, he described the transformer in a signal path as an "FX switch," the common audio engineer shorthand for "effects" [26]. It should be noted that Carpenter designs and builds mic preamps, so the transformer character is important to his work. It seems obvious that because signal is being passed directly through the transformer, then it will leave a sonic signature just because of its handling. However, Carpenter does not give the transformer all the credit for the color–distortion, according to him–but instead ascribes the effect to the overall pathology of the signal [26].

The design business is inundated with the idea of matching impedances between devices in the signal path, an idea Carpenter wants to move away from. He posits that the best scenario is a low output impedance, as close to zero as possible, and a high input impedance, as close to an open circuit as possible [26]. Because of the bidirectional nature of the transformer, the device affects signal both "upstream and downstream" in the signal path [26]. If the output stage feeding the primary coil of the transformer is overdriven trying to meet the low input impedance of the transformer, then the transformer starts to distort the signal [26]. The issue with overdriving the output stage lies in maintaining enough bandwidth and bias–hot Class A, in Carpenter's words–to reliably pass the entire dynamic range of the input signal, otherwise the output amplifier distorts [26]. Class A, in this case, refers to the constant output of a complete signal with no crossover switching. Even though taking the transformer out of the signal path would remove the distortion, it is not directly the fault of the transformer [26]. That resultant distortion is called color and known as the specific sound of a transformer, but this pathology theory suggests that the assumed sound of a transformer–let alone that of a specific core metal–is not necessarily accurate.

To further complicate the idea of transformer sound, impedance is AC resistance specified at a certain frequency [26]. So, even if an output or input stage match Carpenter's theory of ideal impedances, the use of a transformer is further complicated by the signal being a complex waveform composed of multiple frequencies. Therefore, even if the transformer met the requirements of a high input impedance, that impedance value would vary along the frequency response, resulting in some resonances or losses at different frequencies.

Distortion itself is a complicated topic. Distortion through transformers is made up of two main issues: harmonic distortion and loss of information (LOI) [26]. Carpenter generalizes all transformers in his description of the LOI, claiming they lose definition of the signal by rounding it out and muddying up the tail [26]. In classic audio engineer form, his description is full of those subjective, loosely defined words. He ultimately ascribes "phase smearing" to be the root issue [26]. Phase smearing, according to Carpenter, does not affect the stereo image left to right, but does affect the depth of the sound–the front to back perception–by causing the sound to move around and be harder to localize [26].

To justify his bias against transformer use, he brought up a story of his own work. When designing a preamp, he had placed it in a mumetal box but had to remove it for servicing. When it was out of the box, he liked the sound better, but back in the box it changed again. He switched to an aluminum box, which is still conductive but not magnetic, and blocked the RF signals (as the case is supposed to do) but lacked the effect of the mumetal box [26]. When passing a signal through a conductor, it creates a magnetic field around that conductor, but introducing another magnetic material around that field will bend the signal field and distort the original signal [26]. If merely bringing magnetic material close to the signal alters it audibly, then Carpenter reasons that running the signal through magnetic material–the basis of transformer design–would alter it even more [26]. This experience is ultimately what prompted Carpenter to avoid transformers in his design, "as nature intended" [26]. However, even this effect is not specific to any one core metal. As covered earlier, any effective core metal is highly magnetic, so they would affect the signal.

That said, it stands to reason that differences in magnetism would change the effect on the sound.

Though Carpenter does not use transformers in his own work–his business signature is the sonic traceless preamp–but he mentioned that isolation transformers are "somewhat benign" [26]. Isolation transformers remove ground noise because of the one-to-one connection, which prevents common mode current from being accepted as differential current that would be passed through the transformer as signal instead of noise [26]. His belief that isolation transformers do little to transform the sound–though he concedes there is some coloration–is based on the turns ratio; because they do not step up or down the voltage, they do not greatly affect the signal passing through them. He cites the ratio as being more of the decider in a transformers sound, though both the core metal and the ratio are variables, because there is not as broad a selection of core metals per type of transformer [26]. When deciding what the main factor in transformer sound differences is, he seemed to run into the same issue: there are just too many variables to isolate any given one.

Mastering engineer Eric Cohn is less particular about his transformers than Carpenter. The transformers present in his Nashville studio are similar to the FX switch Carpenter describes, but Cohn uses them as primarily a tool [27]. They are in line with the console, but optional "free gain," when engaged they add 6dB without having to adjust much to the sound [27]. Cohn does concede that they do color the sound, but they only make a little bit of difference compared to the usefulness of the tool [27]. Contrary to Carpenter, Cohn does believe the color depends on the transformer and the load applied to that transformer; different loads will change the produced color from the transformer output [27]. Cohn does admit his opinion is not that of a professional and merely the user.

Though, Cohn does point out that the audio industry is an industry of opinions. Trying to determine exact sound characteristics of any specific transformer will be difficult purely because of the diverse amount of opinions and differences in engineers' hearing [27]. While frustrating for a researcher, Cohn finds comfort knowing that the opinions do not really matter because they will always be different [27]. So while he does agree transformers have both a sonic signature and differing signatures based on their use or design, he also does not think it is possible to pinpoint objective sound characteristics of different transformers.

An article featured on the Neumann company's Microphone data page discusses if microphones sound better with transformers or without them. Transformers first appeared in condenser microphones to balance the output and simplify their circuits [28]. In the 1970s and 1980s, the trend switched to a focus on "literal" and "direct" audio, leading to transformerless microphones becoming the ideal recording technology [28]. However, the author notes that "audio transformers do indeed color the sound image, but not as much as people tend to think," especially apparent in

Carpenter's great disdain for transformers [28]. This article posits that transformer microphones do have a "smoother" top and a "deeper" bottom end, citing the reason as well-designed transformers being able to pass frequencies beyond the range of human hearing, which provides the air at the top end of the frequency spectrum as well as lower frequency resonances that give a bass boost [28]. There are few studies on whether or not hearing above 20kHz does actually change the experience of sound, given that very few humans can hear beyond 20kHz. That being said, transformerless microphones do have a broader frequency response and can handle higher levels without distortion that comes from saturation [28]. Although, the article ultimately concludes that "90% of a microphone's sound is in the capsule." [28]. So, while transformer sound is interesting and a necessary consideration for designers, it is not the main focus.

The Shure website also addresses when to use transformers. This article's ideas are less complex than the former because it focuses on what transformers do rather than how they sound but does also admit a difference in transformer sound. However, this article focuses on the differences between expensive and inexpensive transformers, claiming that expensive transformers will have a flatter, broader frequency response and distort at higher levels than their inexpensive counterparts [29]. This source is the only one to draw a distinction among prices.

Many more ideas about transformers exist in the audio industry, but as Cohn said, the industry is full of different opinions. The sheer amount of professionals who interact with transformers and transformer-based devices on a near daily basis who also have strong ideas about their sound does suggest that they do affect the sound. Clearly, there is disagreement as to what extent and in which ways, as is there a missing piece of measurable comparison.

4. Facts Versus Ideas

The question of transformers' signature sound lies in two places: if there is a differentiable sound between any two transformers and what that difference specifically is. The first part is easier to answer.

The mere existence of Section 3: Subjective Ideas proves that trained listeners can indeed differentiate sound between transformers. While none of the information in that section is scientific research, it represents a larger trend in the audio industry of anecdotal evidence that any professional would validate. All of the sources in that section reflect this idea in some way. Carter claims they make a subtle difference but are only noticeable in high quality recordings in the details, which bolsters Brian Fox's claim that there is not enough of a difference in transformer sound to fix a bad microphone design. The Neumann article reaffirms both of these researchers' points because it claims that there is not as much of a difference as they are said to be.

However, Carpenter's visceral reaction to the transformer shows a flipside of that idea: the differences might be subtle, but if your career is spent developing a specific and sensitive tone, it is your job to note those subtle changes that a transformer can cause. Carpenter argues that though a transformer might not be strong enough to fix a bad microphone design, it is enough to damage a good one. The opinion presented in the Shure article is not shared by many in the industry, as the Neve microphone preamps are widely known to have a distinct sound and a very expensive output transformer, the Marinair LO1166, which sells today for as much as $2200. To illustrate the signature sound of these preamps, Carpenter's preamp is known as the "anti-Neve" because of the lack of a signature. This signature contradicts the idea that the more expensive a transformer, the less apparent the sonic signature because of its presence. Even with the concession that the differences are subtle, all of the sources do seek to describe the differences for the relatively few people who are like Carpenter.

The Neumann article offers both that transformerless microphones do sound different in that they have more of a "direct" sound and the documented data that transformerless microphones have a broader frequency response and more headroom before distorting. Moving away from microphones, Cohn mentioned his set of in-line transformers that give "free gain" do add color, but he thinks their usefulness outweighs the potential change in character of the sound. Carpenter's broad theory of phase smearing from any transformers is most relevant to his field of amplifiers, but he does assume that is just the difference between a transformer or lack of one. Carpenter best describes the simple inference that because magnetic boxes affect the sound–and they are not directly in the signal path so much as near the signal–passing the signal through magnetic metal, the essence of a transformer, would alter the sound. Though Carpenter is not convinced that core metal is the main difference, as he ascribes the sonic signature to the function of a transformer: changing the voltage of a signal. Fox's experiment echoes some of Carpenter's speculation because he credits the 12:1 ratio of the high nickel core transformer he tested as the key to the sonic signature. The explanation for this change differs depending on the source, though.

This thesis began with the intention to identify the difference in transformer sound around core metal, but with the difficulty to isolate even one device in an audio signal path–let alone one part of a transformer itself–it became apparent that there are simply too many variables to determine what one specific variable does. That being said, some of the variables in both the signal path and transformer itself are worth examining, including level and frequencies and the transformer's ratio and core metal.

In terms of level, all scientific sources agree that louder signal is easiest to distort, which is easily observed in the B-H loops construction: higher level approaches the saturation point. The Neumann article shows the subjective experience of this fact by citing the transformerless microphones as having more headroom and being more "direct." Carpenter takes this level theory a step further in that he applies it to the level across the whole path, not just the transformer. His pathology idea, that the upstream device overdrives and causes the transformer to distort, aligns with this level issue because it is true that removing the transformer would solve that distortion, even though the added sound is the fault of the level of the signal path, not the transformer's construction. Thus, the transformer creates a sonic change, but it is not solely responsible though the change would disappear for the absence of the transformer.

Frequency response and losses also colors the signal, even if it is not specific to ratios or metals. To reiterate: eddy current losses (series resonance) cause low frequency degradation and hysteresis losses (core saturation) boost the low frequency and harm the high frequency fidelity. Sowter concludes the relatively obvious assumption that the majority of transformer distortion happens in the low frequencies. However, Bill Whitlock of Jensen Transformers encountered the paradoxical issue of transformer design: the measures to protect low frequency fidelity often harm high frequencies and vice versa.

Pritchard's finding that low frequency distortion changes the high frequency response when the signal is complex illustrates the issue of frequency response. This issue can be explained by a combination of factors: impedance and IMD. Impedance is AC resistance at a specific frequency, but when multiple frequencies, even just two, combine to form a new waveform, IMD results from the differing impedance levels. This phenomenon concisely represents why it is so difficult to determine scientifically what a musical signal will sound like through a transformer. The transformer could perform perfectly when a high frequency is isolated, but the addition of many other overtones complicates the signal exponentially.

In microphones, the Neumann article says that transformer microphones have a smoother top and deeper bottom, which can be explained by transformer function. In his 1953 paper, Howard explains that transformers need to provide an extra octave band on either end of the targeted frequency range–in this case 20Hz-20kHz, the human hearing range. Neumann cites this extra band as providing the air on the top that makes it smooth, as well as the saturation in the core as the resulting bass boost.

The level and frequency response are strong proof for the idea that transformers do change the sound from its original source to what listeners hear. As for differences from transformer to transformer, the ratio and core metal appear the most often as the causes.

The ratio describes how the transformer changes the voltage of a signal. Carpenter cites the ratio as the biggest decider of sonic signature in a transformer.

Howard claims that the lowest amount of turns is ideal, which Sowter agrees with since the lowest number of turns is ideal for a frequency response as low as 20Hz. However, the number of turns is not necessarily the ratio, but it is part of the same concept. Fox's study found the Cinemag 9766–a high nickel content core–to have the best bass response. Despite the other transformers in the study also having high nickel cores, this specific transformer had a 12:1 ratio, which Fox credits as the reason for this response. The study does not say how many literal turns there were in the core, but based on Sowter's and Howard's conclusions, the transformer likely used as little turns as possible to achieve that ratio.

Carpenter's idea that the ratio is the biggest factor is mostly supported by isolation transformers. He claims they are "relatively benign," as they just remove ground hum, but also claims that a design needing an isolation transformer to sound right has bigger problems than transformer choice [26]. Isolation transformers have a ratio of 1:1, since there is no need to change the voltage from one part of the circuit to the next.

Both the conclusions that turns and the overarching ratio from multiple sources suggest that ratio is a significant part of what characterizes the transformer sound. However, this thesis began with the intention to study core metal, which also comes up frequently in reference to transformer character.

Overall, most sources seem to point to the benefits of a nickel core. Nickel appears often in any transformer construction because of its high magnetism, as shown in Sowter's studies. One of the earliest discoveries in transformer design experimentation was that higher magnetism made the core more effective and that nickel is extremely magnetic. Butler Windings directly states that nickel is the best core because of its high permeability, but true to the paradox of transformers, it does lack the low frequency fidelity that steel has. Butler Windings also supports the use of ferrites, but since they have a lower saturation level than nickel, they are not the pick for ideal core material.

Fox's research found that the Cinemag 2480–another high nickel content core–saturated at 15kHz. While inside the human hearing range, realistically few humans could recognize a resonance at 15kHz, since most adults hear to about 14kHz outside of optimal conditions. This saturation does prove Carpenter's point that the few people who matter will notice, though. The engineer's job is to maintain the tone of the recorded instrument, so in context of the music industry, this resonance is extremely important and will degrade the low frequency response as well and change the subtleties of the tone. Fox's research also found the AMI T14 as having the weakest bass response, but the core was a nickel alloy. As an informal study, there is no information about what the nickel is alloyed with in the core, but assumedly it is something else highly permeable that would degrade the bass frequencies. It is also possible that this transformer just has too many turns as well and it is not a core metal issue at all. This transformer, the T14, is actually a replica of an extremely famous transformer in the ELAM251 microphone manufactured by AKG. Since that microphone is tube-based, it is possible that transformer was utilized for its weaker bass response since the tube would provide for a warmth the transformer lacked.

Mumetal is an alloy of nickel and iron. Carter describes his mumetal transformer as having more body. Reflecting back to Figure 4, the nickel-iron alloy has a narrower B-H loop, which means it has a higher hysteresis point so more likelihood of saturation. This saturation is likely what causes the low frequency boost associated with "body." Body, being another one of those shifty timbral terms, in this case refers to that low end base boost, creating a curvature in the frequency response that looks like–predictably–a body.

The strongest link between core metal observations and research is in amorphous cores (metallic glass). Carter notes that the amorphous transformer sounds transparent and direct–terms that appear in the Neumann article and from Carpenter to describe transformerless sound. Sowter documented that experimentation with amorphous metal proved 20% lower losses, meaning it is more accurate to the original sound. Since Carter's conclusion was reached by comparison to a mumetal transformer with the same turns and ratio, it stands to reason that metallic glass does actually provide a clearer sound.

5. Conclusion

Combining both the facts and the ideas about transformer sound, it is reasonable to assume that transformers have an effect on musical signals that pass through them. The general consensus among individuals in the audio industry is that they do make a difference, but disagreements exist as to what extent the difference is made. When comparing a transformer to the lack of a transformer, the most apparent effects on the resultant sound are caused by level or frequencies of the signal. High level distorts quicker through a transformer, and–depending on the transformer–the low end distorts at varying pressures.

The characterization of that effect is more hazy through the available data. Unfortunately, the character of the sound is where this thesis leaves off. However, there are enough differences between known and recognizable transformers to assume there is a difference from transformer to transformer. The two biggest factors are ratio and core metal. This study began with a focus on core metal, only to find that it is impossible to isolate just the core metal without also recognizing what the transformer's function in the signal path is, which lies in the ratio and number of turns.

Both the formal studies and opinion pieces do admit that a lower number of turns is ideal, so it is reasonable to conclude that the number of turns does affect the signal. The ratio appears in Fox's research when he ascribes a bass boost to a 12:1

ratio, as well as Carpenter's lack of animosity towards isolation transformers since they do little to the actual sound. The number of turns is related to the ratio, so it can be considered a sub-category of the larger consideration of design: the ratio.

As for core metal, the different properties of each metal, especially the B-H loop, note that they behave differently when exposed to different levels. As musical signals are just many frequencies combined at different levels, each frequency would activate the magnetic hysteresis differently and alter the sound. This alteration becomes apparent with opinions like Carter's and Butler Windings, where the only difference drawn between the transformers is the core material.

Though this thesis determines a strong likelihood of a difference between any given transformer, more research is necessary to define the character of different transformers.This data could be captured using a blind ABX listening test. Using transformers of different core metals, ratios, or number of turns and presenting identical recordings through each transformer to a listener and using a Likert scale to describe the sound would work. The challenge is maintaining uniformity across all variables other than the target of the test, as many manufacturers do not make identical transformers with more than one or two core metal choices or turn numbers. Essentially, this kind of test would require custom materials.

Although this study focuses on the core metal, the study of transformers is dynamic and complex. Even more so than just core metal and ratio. Carpenter suggests even changing the geometry of the conductor–a hitherto ignored factor–because a rectangular wire could present less issues than a round wire in reference to air gaps [26]. This idea suggests the sheer amount of possibilities for improvements to transformers.

That being said, most modern development and trends are steering away from transformer usage outside of necessity, as in the case of a DI box. Many engineers value the "direct" sound that transformers inhibit because of the flexibility in mixing provided by digital tools. There are many emulators that can recreate the sound of a transformer-based piece of gear that can be removed when undesirable. The sound attributed to most transformers is mostly perceived as "vintage" and most useful in microphones or microphone preamplifiers from early eras that create a nostalgic feel, but these devices are used stylistically for artistic flair and not so much the pure usefulness of a transformer. Ultimately, the sonic difference a transformer makes is subtle and not noticeable to the untrained ear. However, to the designers and curious college seniors, their sound can be vital to their goals.

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