Soft Magnetic Materials for Audio Transformers: History, Production, and Applications*

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The history of soft magnetic materials is traced from 1000 B.C. to the present time. This includes a description of the work of Oersted and Faraday who invented the first transformer, and the gradual improvements in core material over the last 150 years. These cover soft iron, silicon iron, grain orientation, Hi-B steels, domain control by lasers, and spark ablation. Amorphous metallic glasses are also detailed. Finally the design and characteristics of a wide range of audio transformers and magnetic shields are discussed, in particular with regard to Mumetal, which with other nickel-iron alloys has been the author's lifetime occupation.

0 INTRODUCTION

The term "soft" relates to that class of metals or alloys which can be easily magnetized and demagnetized as opposed to "hard" magnetic materials used for permanent magnets. This paper deals exclusively with soft materials, particularly for audio applications.

As far back as 1000 B.C. certain iron ores were found, mainly in Magnesia, a district of Macedonia, pieces of which attracted and repelled each other. These contained Fe_3O_4 (magnetite) and became known as lodestone, from the Saxon "loeden," to lead or direct. Lodestones as found were permanently magnetized and their power was named "magnetism." Around 55 B.C. Lucretius wrote "I have seen Samothracean iron rings even jump up, and at the same time filings of iron rave within brass basins when the magnet stone has been placed under." Later Pliny observed that iron which has been well touched and rubbed with lodestone is able to take hold of other pieces of iron.

The first use of lodestone as a mariner's compass is attributed to the Chinese. Even before then, it was known that a piece of lodestone freely suspended always turns to the North. The first compasses were magnetized iron needles on floating straws, but pivoted devices were developed. While visiting the Chinese National Museum in Peking some 20 years ago, the author was shown the whole range of early Chinese compasses.

The first authentic treatise on the science of magnetism was written in Latin by William Gilbert of Colchester who had also studied electrostatics, a science dating back to about 600 B.C., when Thales, by rubbing amber with fur, gave the amber the power of picking up certain objects. The Greek word for amber was "elektron," and from this our word "electricity" is derived. Over the centuries considerable experimentation and the production of friction machines to generate electrostatic charges were completed and included capacitors and spark discharge devices. It was not until 1796 that Volta evolved the voltaic pile to generate a continuous flow of electricity. This consisted of copper and zinc disks placed alternately in column form but prevented from touching each other by means of pieces of moist cloth. This was later replaced by the voltaic cell which consisted of a copper and a zinc strip placed in dilute sulfuric acid and capable of being joined externally by copper wires to feed a load. As is known, hydrogen gathers on the surface of the copper strip and polarization takes place, limiting the current output.

1 OERSTED'S DISCOVERY OF ELECTROMAGNETISM

Before we consider transformers, the production of a magnetic field by the presence of current is fundamental. In early 1820 the Danish physicist Oersted gave a series of lectures on magnetism and electricity. He made the current from a galvanic trough (voltaic cells in series) pass through a platinum wire to illustrate the heating effect (forerunner of modern electric heaters). Adjacent was a compass covered with glass, and in the course of the demonstration, on making the circuit, in the presence of the audience, a slight flick of

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the compass needle was noticed. It was not considered to be of very great significance, but months later, in 1820 July, he resumed the research and confirmed that the needle did actually move. By putting the compass, above, below, and on the sides of the wire carrying current he established that the wire was surrounded by a magnetic field. He immediately published a fourpage quarto document in Latin, describing this epochmaking discovery, and sent it to all learned bodies and distinguished scientists.

When several turns of wire were wound on a magnetizable core, such as iron, the field was greatly enhanced, and in 1825 Sturgeon produced the first electromagnet. A typical example is the Royal Institution's great electromagnet illustrated in Fig. 1. Electromagnets were constructed by Franklin in the United States and G. I. Moll of Utrecht, Holland. Magnetizable materials known at that time were various steels, wrought iron, nickel, and cobalt. (It is interesting to note that the nickel-cobalt alloy Permendur, a 20th-century U.S. discovery now in production, has the highest saturation induction of all well-used commercial alloys, particularly for pole pieces. Some rare earth alloys with even higher saturations exist but are too expensive to come into general use.

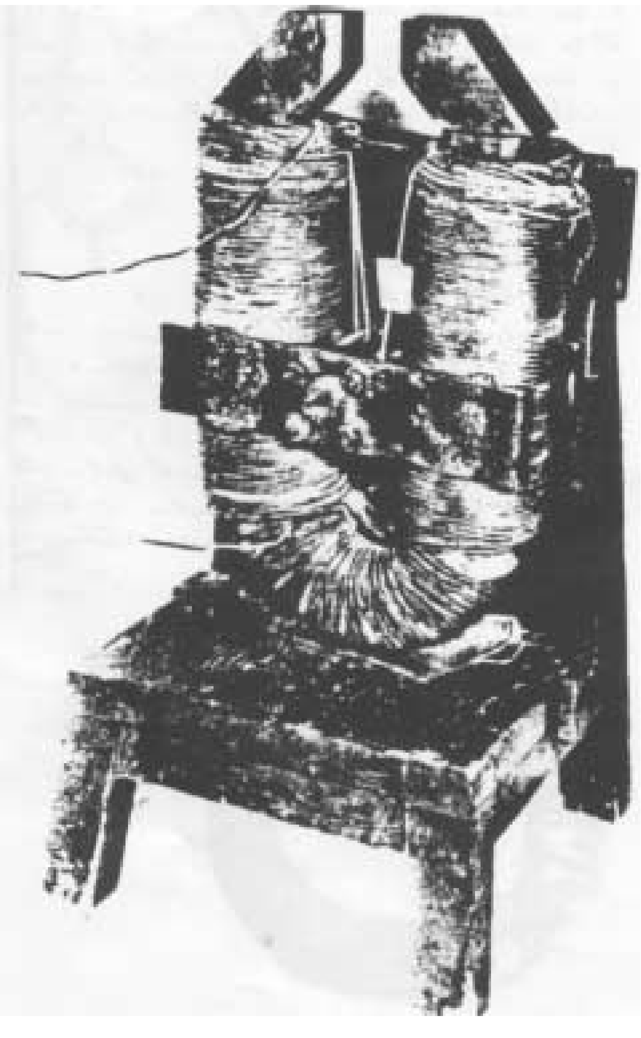

Fig. 1. The Royal Institution's great electromagnet.

2 FARADAY'S DISCOVERY OF ELECTROMAGNETIC INDUCTION

In the years 1821-1831 Michael Faraday became deeply interested in experimentation with electrically produced magnetic fields and in November 1825 came very close to discovering electromagnetic induction. He had five separate wires, each 5 ft long, adjacent to each other, and he passed a current through one of them trying to detect any effect on any of the neighboring wires. Unfortunately his galvanometer was not a delicate one and no effect was observable. At that time a galvanometer, or current-measuring device, was no more than a crude compass near a coil of wire.

On 1828 February 15, at the usual Friday evening gathering at the Royal Institution in London, there was held what could have been the first meeting of our Audio Engineering Society. The subject of the lecture was "Resonance or the Reciprocation of Sound." Music was demonstrated on instruments from Java, the jew's harp, and whistles, and a second meeting included sirens and stringed instruments. At the first lecture resonances were produced by the then well-known method of strewing sand on a circular disk and drawing a violin bow across the edge. The Chladni (1785) figures showed the natural resonances of the disk. A second disk of similar dimensions was placed under the energized one, which was similarly lightly covered with sand. It was then shown that the sand on the unenergized disk exhibited the same pattern of Chladni figures.

Michael Faraday was present at these demonstrations and he perceived that the mechanical work of bowing had been converted into sound energy and then reconverted into work on the second disk. This gave him a germ of inspiration to determine whether electrical energy might be converted into magnetism and then reconverted into electricity.

Incidentally N. W. McLachlan and the author, in 1930, made Chladni figures with sand and lycopodium powder on disks and wide-angled metal and paper cones to discover the natural resonances of loudspeakers by bowing. Subsequently energization of cones of many sizes and materials was made by passing audio frequency current through the moving coil attached to the cone and the sand studied. The frequencies at which these occurred were confirmed by bridge measurement of the variations of impedance and radiation resistance at each resonance [1]. It is worth recording that even the resonances of the actual moving coils were found to be audible by bowing, and the frequencies were measured.

Faraday, in 1831 August, did confirm that electric energy could be converted to magnetism and back to electricity by the following entry in his diary [2]:

Have had an iron ring made (soft iron) round and 1/8 inches thick and ring 6 inches in external diameter. Wound many coils of copper wire round one half, the coils being separated by twine and calico-there were 3 lengths of wire about 24 feet long and they could be connected as one length or used as separate lengths. By trial with a trough, each was insulated from the other. Will call this side of the side of the ring, but separated by an interval, was wound in two pieces together amounting to about 60 feet in length, the direction being as with the former coils; this side call B. Since the coil on A intensified the effect of the current it was logical to presume that coil B would intensify the effect of the forces in the ring. Coil A was capable of being connected to a trough and coil B was connected to a Galvanometer. When all was ready, connected the ends of one of the pieces on A side with battery; immediately a sensible effect on the needle. It oscillated and settled at last in the original position. On breaking connection of A side with battery again a disturbance of the needle wave apparently short and sudden.

This is exactly what Faraday wrote in his diary.

The discovery of electromagnetic induction resulted from many months of experimental research which he continued for almost 30 years.

Faraday's induction ring was the first transformer ever made, and his description of the toroidal core and windings does not differ greatly from that of a modern toroidal mains transformer now so extensively used in audio equipment (Fig. 2). He even had some idea of the effect of the turns ratio but suffered from the fact that covered insulated wire was not then available.

During the nineteenth century wire coverings of silk or cotton in single or double layers, impregnated papers, Gutta Percha for submarine cables, and rubber were utilized, to be followed eventually by enamel coatings.

It is worth recording that Faraday also invented the first dynamo, which gave a supply of direct current from a rotating disk (Fig. 3). This greatly enhanced the use of direct current for experimental and other purposes and basically led to the manufacture of highpower commercial generators.

Toward the end of that century considerable research was undertaken on soft magnetic materials for generators and power transformers. The latter, in some instances, consisted of toroidal copper windings with as many small-diameter iron wires as possible, forced through the central aperture and bent back on themselves to complete a magnetic core. Similar construction was used for small communication transformers for telephones. For power transformers an alternative construction was the use of soft iron plates bolted together, but these had appreciable losses and suffered from deterioration due to aging.

3 PRODUCTION OF NICKEL-IRON ALLOYS

In about 1890 J. A. Ewing had published a book entitled *Magnetic Induction in Iron and Other Metals* [3]. This is a most comprehensive study covering various magnetic measurements, including Weber's ballistic method, magnetization of iron rings and long wires, steel, cast iron, nickel, cobalt, and wrought iron wires. A chapter deals with hysteresis and the effects of vibration, together with magnetizing in weak and strong fields. He also studied effects of temperature and stress, torsion and twisting, with a final chapter on practical magnetic testing. Considering that the period was 1890-1900, it is astonishing that such comprehensive research was being carried out on so many magnetic materials.

Another reason for mentioning this treatise is that Ewing, Hopkinson, and others almost anticipated the discovery of modern high-permeability alloys such as Mumetal and Permalloy, so widely used in audio transformers. At that time tests were made on nickel-iron alloys containing 4.7% Ni, 25% Ni, 30% Ni, and 33% Ni.

Even the effects of annealing were observed, and had the nickel contents been increased further up to 80%, there would have been created elementary forms of Invar (35% NiFe), Radiometal (50% NiFe), and Mumetal and Permalloy (73-80% NiFe).

After leaving the university in 1922, the author's first laboratory work was to measure the magnetic properties of nickel-iron rods about 5 ft long and 0.25

Fig. 2. Page from Faraday's diary describing experiment and showing his induction ring, the first toroidal transformer.

in diameter, containing 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% Ni. These had previously been heated to about 1000°C and slow cooled. The test equipment employed, invented by Weber, is illustrated in Fig. 4, where a. ballistic galvanometer is used to measure flux.

These tests quickly indicated that as the nickel content was increased, there was an enormous improvement in magnetic properties around about 78% Ni content, which gave the optimum permeabilities.

High permeability is closely allied with low magnetostriction, and some years later the author made magnetostriction tests on a Mumetal rod, again using the Weber ballistic equipment. A 6-ft length of annealed thin Mumetal rod was inserted in the magnetizing solenoid, and one end was securely fixed in a large lead block. At the other end a 2000x linear magnification Reichert measuring microscope with oil immersion was focused on the grain boundary of a crystal exposed by etching with nitric acid. The first observations showed that the whole laboratory, situated within the works, was in a state of vibration due to the operation of hot and cold rolling mills and particularly a steam hammer. The result was that the measurements had to be made in the middle of the night when all was quiet. The magnetostriction movement on the grain boundary was on the order of one-millionth of its length for that particular specimen (Fig. 5). It is interesting to observe that had magnetostriction measurements been made on the aforementioned series of rods, the optimum composition for high permeability might have been confirmed.

Another test carried out by the author was to measure the permeability of a vertically suspended annealed Mumetal wire when various loads were applied to the lower end. This clearly showed that as loads were increased, there was first an improvement in permeability and then a decline. It is interesting to note that on modern Hi-B transformer steel a small tensile stress is obtained by using a glass surface coating applied at high temperature and then cooling. This reduces the losses and raises the permeability.

Fig. 3. Page from Faraday's diary showing sketch of first dynamo.

4 DISCOVERY OF IRON ALLOYED WITH SILICON FOR TRANSFORMER CONES

During the latter half of the nineteenth century considerable research on magnetic materials had been carried out by such persons as Ewing, Rowlands, S. P. Thomson, Steinmetz, and many others, and measurement techniques became well established. Many properties of wrought iron, steels, nickel, cobalt, and even some nickel-iron alloys were determined, and it is to be regretted that the full import of the results was not realized.

In the early 1900s that first major improvement in materials for transformers took place when Sir Robert Hadfield introduced iron alloyed with silicon which gave higher permeabilities and appreciably less loss than earlier steels. Various percentages of silicon were utilized and the alloys were sold under a variety of trade names. These were produced from hot-rolled sheets and had omnidirectional properties. Strain-relieving annealing was sometimes employed, and various coatings were used to reduce eddy current loss.

These sheets were used in the form of butt lapped strips for the magnetic cores or power transformers and had only about half of the previous iron losses. The most popular alloy was 3-4% SiFe. Larger values of silicon content were investigated even up to 7%, which was found to have superior magnetic properties, but the material was brittle and not easily machinable or stamped.

As an indication of the quality of silicon iron available in 1915, reference is made to an IEE paper by N. W. McLachlan on Stalloy plates 0.5 mm thick for instrument transformers [4]. He found by measurement at 50 Hz that at 0.01 T the complex permeability was 780 and at 0.1 T, 2760. At 0.5 T the value was only 3000.

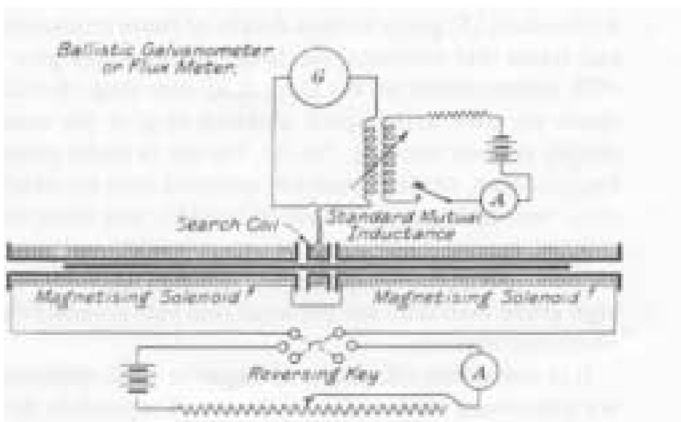

Fig. 4. Connections for testing iron rods by search coil method due to Weber.

5 GRAIN-ORIENTED SILICON IRON

Silicon irons with a number of improvements were utilized for transformers until the late 1930s when a breakthrough occurred due to the introduction of grainoriented silicon iron. This was the important invention of N. P. Goss, who termed the product Goss iron [5].

This was achieved by altering the silicon content in the steel, cold rolling the strip to the desired thickness, followed by high-temperature annealing at 1200°C to evolve secondary recrystallization. Large grains were produced, oriented in the rolling direction and resulting in greatly improved magnetic properties along the strip. More loss, however, arose across the strip, and this led to considerable research on mitered joints, butt joints, and methods of utilizing as far as possible constructions where the flux went along the grains. Obviously toroids here had a big advantage, and subsequently C cores and E cores were introduced, particularly for small transformers.

While improvements were taking place prior to the 1960s such as making thinner Goss material to reduce eddy currents, research was continuing to produce better steels. Japan came to the fore and patented their Hi-B Steel which is extensively used today. Here larger grains are evolved and a small tensile stress is imparted to the steel by using a glass surface coating applied at high temperature and resulting in reduced electrical loss.

6 RECENT DEVELOPMENTS

Even in the last few years significant improvements in electrical steel production have been obtained. As is well known, magnetic losses in a core consist partly of hysteresis, which varies linearly with frequency, and eddy current loss, which is proportional to the squares of sheet thickness, frequency, and induction, but inversely proportional to resistivity. There is however a third loss, mentioned by the author in 1941 [6], which was termed disaccommodation loss or Nachwirkung loss. It has been found that this loss depends on the distance between domain walls, and recently by a process of scribing and laser treating the surface of the strip, losses can be reduced by as much as 10%. Richardson [5] gives further details of these treatments and states that electrical steels developed today give a 40% improvement on the Goss 0.35-mm strip. British steels are now using spark ablation to give the same results as laser scribing. So far, for use in audio transformer cores, several grades of oriented strip are available, termed M grades, from M2 to M7, and these are utilized for the production of small toroids and laminations. For these purposes the aforementioned very high grade materials are not available yet, possibly for economic reasons.

It is noted that all efforts to improve steel materials are concerned with reducing losses. Fortunately low loss usually means higher magnetic permeability, which in the case of audio transformers is a most desirable feature to obtain high inductance with the smallest number of turns. The latter is required to minimize the capacity effects, as described later.

7 METALLIC GLASS OR AMORPHOUS SOFT MAGNETIC ALLOYS

One final development in magnetic materials over tile last 20 years has been the production of metallic glass, or amorphous soft magnetic alloys: These are like glass and have no crystalline structure. They are produced by continuous casting and rapid continuous quenching, which results in a quick transition from the fluid to the solid phase. The virtue of these materials is that thin strips, such as 0.05 mm thick (and up to 1 m wide in one instance), can be made directly from the casting line, thus avoiding the usual hot rolling, cold rolling, and intermediate annealing processes. Unfortunately, like glass, they are hard and very brittle which makes handling and cutting uneconomic.

The composition of metallic glasses may consist of some of the following: iron (Fe), boron (B), phosphorus (P), nickel (Ni), carbon (C), copper (Cu), and molybdenum (Mo), a few of these elements constituting a particular brand. Table 1 gives the properties of metallic glasses that existed a few years ago, but research continues [7].

Amorphous metal has been employed in small distibution transformers, and a 16-kVA unit which has only 20% of the loss of normal oriented silicon steels has been constructed. Amorphous metal is unlikely to be used in large power transformers owing to its low saturation induction, but in due course there is a possibility for its use in audio transformers if it can be considerably reduced in price as compared even with Mumetal.

8 THE ORIGIN OF MUMETAL

In the early 1920s Mumetal was developed to act as a loading material for submarine telegraph cables. It was produced in high-frequency induction furnaces (the original microwave oven principle), and the 20-lb ingots were used to make wire 0.010 in diameter. In 1926 for the Pacific submarine cable between Bamfield and Fanning, 3370 nautical miles in length, thousands of miles of this Mumetal wire were drawn for wrapping around the central copper conductor to increase its inductance. This involved subsequent annealing to develop the high permeability required. The effect of the Mumetal wire was to reduce greatly the attenuation of the signals and increase the word-handling capacity. By passing the loaded copper through a continuous furnace at about 900°C in a nitrogen atmosphere it also meant continuous measurements of inductance by the author and others on a definite length of conductor after passage through the furnace.

[1] Mumetal is a registered trademark of Telcon Metals Ltd., Crawley, Sussex, UK.

It is worthy of mention that since so much Mumetal wire was required, quite a number of firms were engaged in its production. It was found that the wire from one firm always had higher permeabilities than any other, and it transpired that they used fewer passes between intermediate softenings. It was thus proved that cold working or work hardening produced better magnetic qualities, the forerunner of grain orientation.

To cover the improvement in permeability a world patent was taken out (British Patent 366523, Smith, Garnett, and Randall, 1930) and subsequently sold to the U.S. company engaged in the production of oriented silicon iron.

In the early 1930s the demand for loaded submarine cables slackened and fresh fields for the utilization of Mumetal were explored. Magnetic shields began to be required and Mumetal toroids for precision instrument transformers soon became the fashion. In addition a demand arose for shielding cathode-ray tubes, particularly for oscilloscopes and eventually radar equipment.

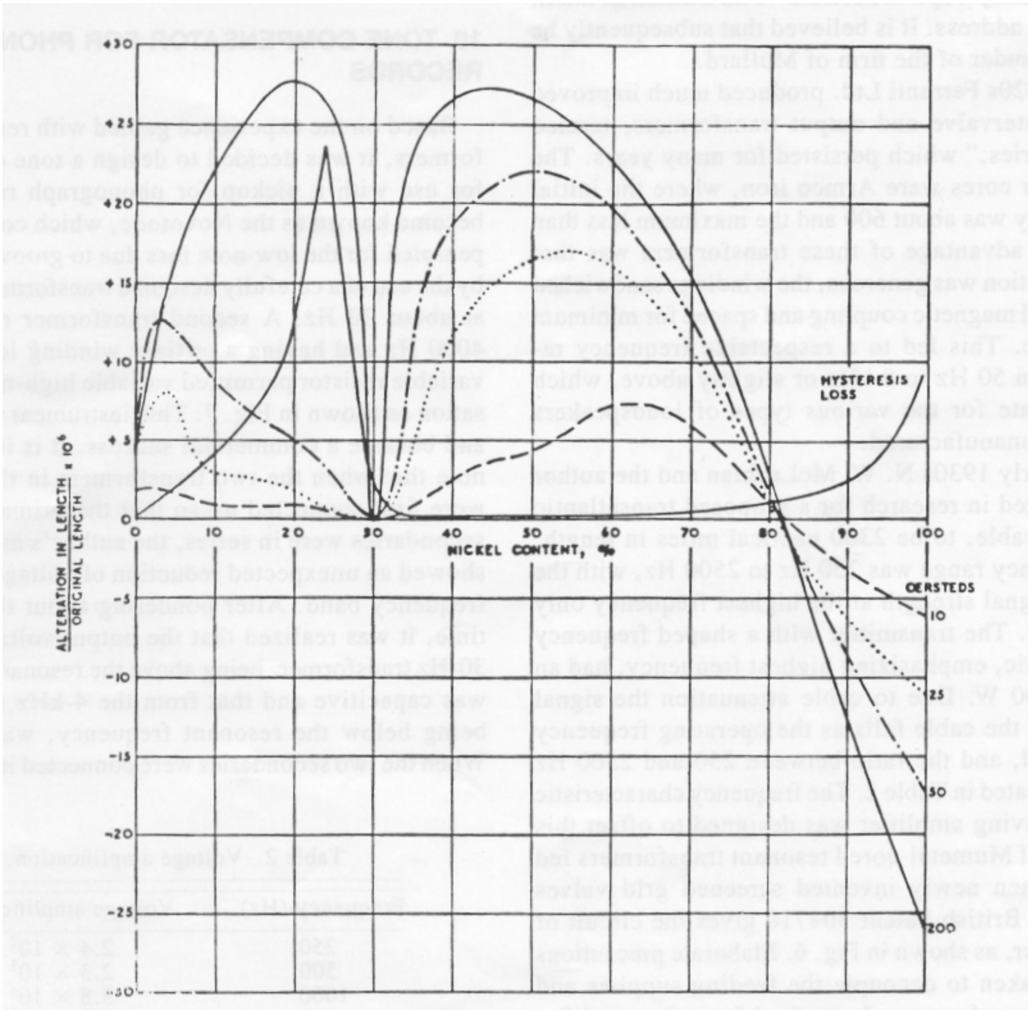

Fig. 5. Longitudinal magnetostriction effect in nickel-iron alloys.

Table 1. Properties of metal glasses.

Material	Composition (%)	Permeability μ_4 at 50 Hz	Coercivity (static) (A/cm)	Saturation flux density (T)	Density (g/cm³)	Resistivity $\left(\frac{\Omega \cdot mm^2}{m}\right)$	Curie temperature (°C)
Metal glasses[1]	80 Fe, 20 B						
	80 Fe, 16 P,						
	3 C, 1 B	—	0.04	1.6	7.4	1.4	375
	40 Fe, 40 Ni,	—	0.04	1.5	—	1.5	290
	14 P, 6 B	40 000	0.01	0.83	7.5	1.6	250
Classical alloys	50 Fe, 50 Ni	12 000					
(for comparison)	14 Fe, 77 Ni,	50 000	0.04	1.55	8.25	0.45	440
	5 Cu, 4 Mo	to 130 000	0.004	0.78	8.7	0.55	400

[1] Values from T. Egami, P. J. Flanders, and C. D. Graham, Jr.: *Appl. Phys. Lett.*, vol. 26, pp. 128–130 (1975); F. E. Luborksy, J. J. Becker, and R. O. McCary: *IEEE Trans. Magnetics*, vol. mag-11, pp. 1644–1649 (1975). In addition, see: T. Masumoto, K. Hashimoto, and H. Fujimori: *Sci. Rep. Ritu.* A, vol. 25, pp. 231–244 (1975); F. Haberey: *Elektro-Anzeiger*, vol. 29, pp. 537–539 (1976).

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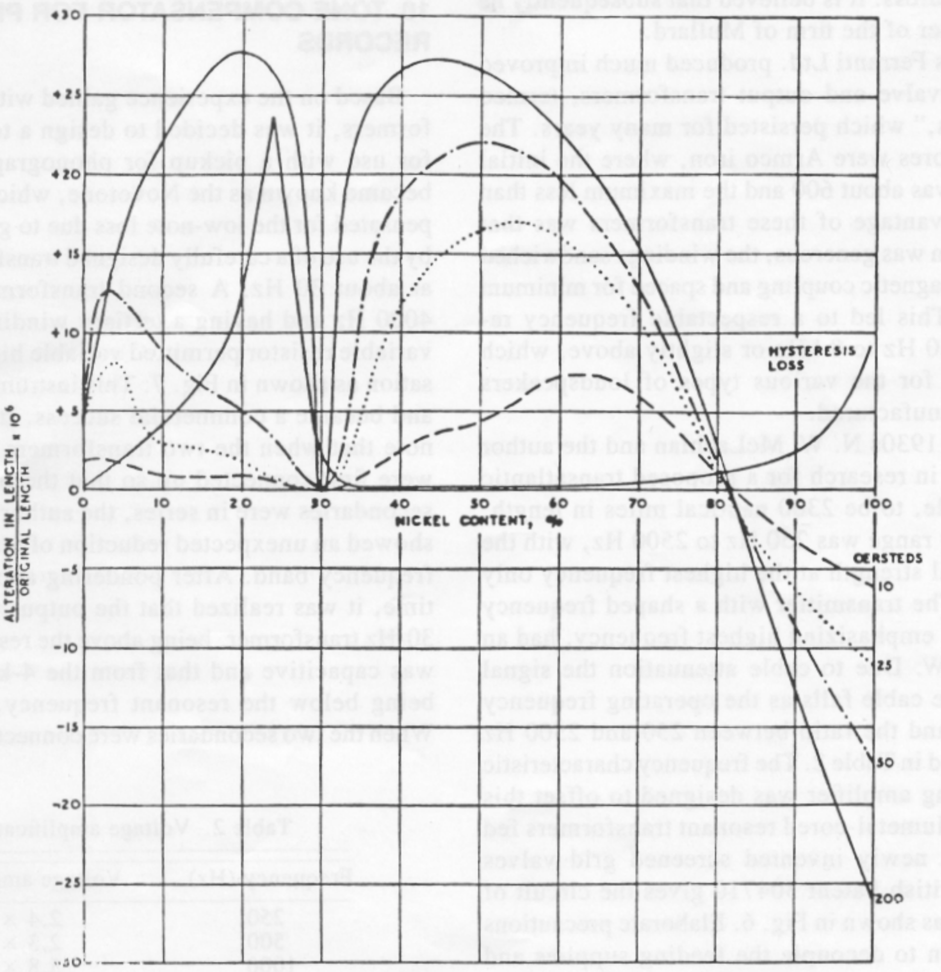

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9 HISTORY OF AUDIO FREQUENCY TRANSFORMERS

The author's first experience with audio transformers was in 1919 when he examined a war surplus audio amplifier which used "R" bright emitter valves and contained three kinds of audio transformers. These were inlet, intervalve, and output types and were all about 2 in^{3} with Stalloy (4% silicon iron) cores. It is of interest to note that a small brass plate on the amplifier case stated "made by Captain Mullard" with a South London, Streatham, address. It is believed that subsequently he was the founder of the firm of Mullard.

In the 1920s Ferranti Ltd. produced much improved types of intervalve and output transformers, termed the "AF series," which persisted for many years. The transformer cores were Armco iron, where the initial permeability was about 600 and the maximum less than 4000. The advantage of these transformers was that the core section was generous, the windings sandwiched to give good magnetic coupling and spaced for minimum capacitance. This led to a respectable frequency response from 50 Hz to 8 kHz or slightly above, which was adequate for the various types of loudspeakers then being manufactured.

In the early 1930s N. W. McLachlan and the author were engaged in research for a proposed transatlantic telephone cable, to be 2300 nautical miles in length. The frequency range was 250 Hz to 2500 Hz, with the received signal strength at the highest frequency only about 1 uV The transmitter with a shaped frequency characteristic, emphasizing highest frequency, had an input of 200 W. Due to cable attenuation the signal strength on the cable falls as the operating frequency is increased, and the ratio between 250 and 2500 Hz was as indicated in Table 2. The frequency characteristic of the receiving amplifier was designed to offset this by the aid of Mumetal-cored resonant transformers fed from the then newly invented screened grid valves (Tetrodes). British Patent 304710 gives the circuit of this amplifier, as shown in Fig. 6. Elaborate precautions had to be taken to decouple the feeding supplies and screen the transformers. In its final form the amplifier had six stages, and the following amplification figures (which include amplification due to the input and output transformers) were obtained by measurements made by the author and given in British Patent 304710.

The input transformer with a Mumetal core operated at such a low level that "noise" had to be minimized and the winding resistances were reduced by immersing this transformer in liquid air. Due to the Wall Street crash, the transatlantic telephone cable could not be financed, but the project worked well in the laboratory using artificial lines which corresponded to the proposed cable.

10 TONE COMPENSATOR FOR PHONOGRAPH RECORDS

Based on the experience gained with resonant transformers, it was decided to design a tone compensator for use with a pickup for phonograph records. This became known as the Novotone, which correctly compensated for the low-note loss due to groove limitations by the use of a carefully designed transformer resonating at about 30 Hz. A second transformer resonating at 4000 Hz and having a tertiary winding loaded with a variable resistor permitted variable high-note compensation as shown in Fig. 7. This instrument was patented and became a commercial success. It is interesting to note that when the two transformers in the Novotone were first connected up so that the primaries and the secondaries were in series, the author's measurements showed an unexpected reduction of voltage in the midfrequency band. After pondering about this for some time, it was realized that the output voltage from the 30-Hz transformer, being above the resonant frequency, was capacitive and that from the 4-kHz transformer, being below the resonant frequency, was inductive. When the two secondaries were connected in opposition,

Table 2. Voltage amplification.

Frequency (Hz)	Voltage amplification
250	2.4 x 102
500	2.3 x 103
1000	5.8 x 104
1500	6.8 x 105
2000	5.4 x 106
2500	1.1 x 10'

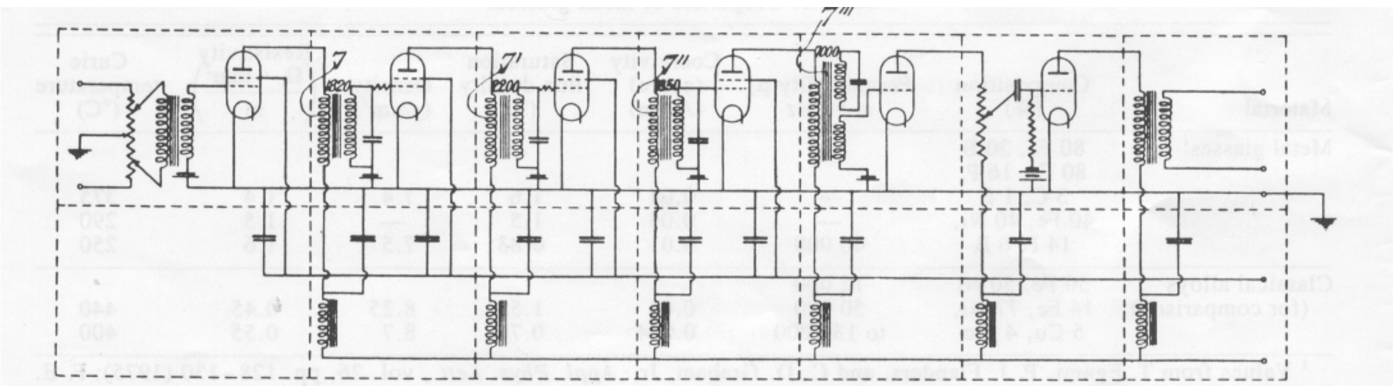


Fig. 6. Amplifier with "resonant intervalve transformers" to give voltage amplification of 240 at 250 Hz and 11 million at 2500 Hz (British Patent 304710).

the performance curve in Fig. 7 was achieved. It should perhaps be stated that to get the exact frequency characteristics of the resonant transformers, a considerable amount of research was required.

By the early 1930s, nickel-iron alloys such as Mumetal, Permalloy C, Radiometal, and others were firmly established as materials for audio frequency transformers. A very large variety of sizes of laminations became available and eventually led to the formation of a committee which produced a document giving the preferred types, particularly for government departments. Many of these sizes are still being manufactured.

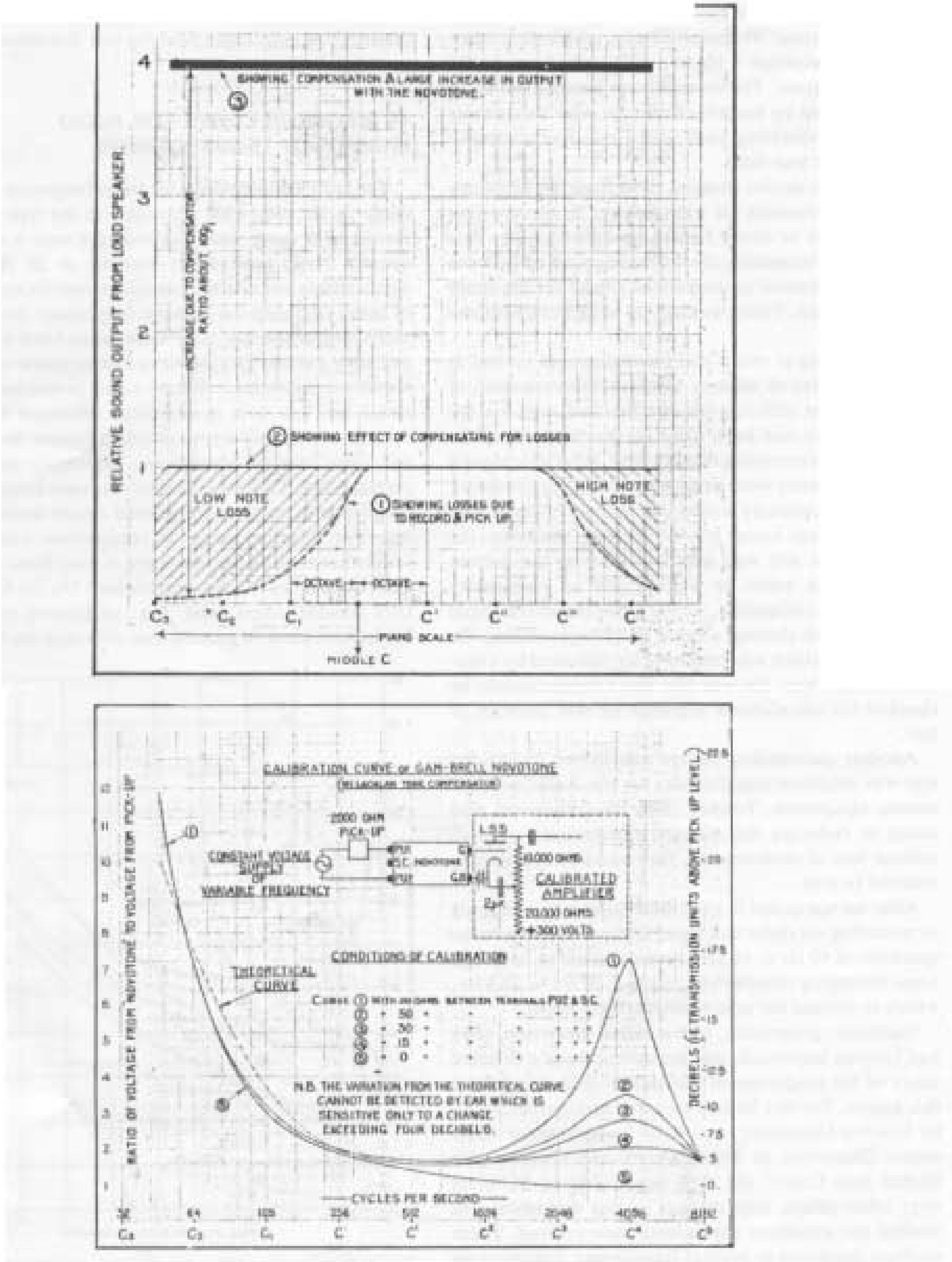


Fig. 7. McLachlan Novotone compensator for electrical reproduction of disk records using resonant audio transformers

During World War II, munitions and communications made great demands on these high-permeability laminations, but a few unusual types of transformers are worth mentioning. Thus the Royal Aircraft Establishment at Farnborough was interested in determining the vibration frequencies and their amplitudes on the mainly wooden aeroplane, the Mosquito, specially designed to avoid radar. In conjunction with the De Havilland Company, which built Mosquitos, the author designed and manufactured Mumetal-cored transformers operating over the range 4 Hz to 1 kHz, which suited the R. A. E. program. The transformers handled the small voltages set up by nickel-chromium wire transducers glued to the vibrating parts and a six-channel amplifier-recorder was built.

After this, a similar demand arose from the Wellcome research laboratories for transformers to operate over 4 Hz to 1 kHz or above for the encephalograph. This is a device for measuring the tiny voltages set up between electrodes gummed to the patient's head for the study of brain tumors. Today as many as nine electrodes can be utilized.

It is amusing to recall that the author was invited to the laboratories to witness the first demonstration of the equipment utilizing an anesthetized dog, on the head of which had been fixed electrodes feeding the amplifier and a recording oscilloscope. Rhythmic signals at low frequencies were being observed when the doctor in charge facetiously asked the author, "Would you like to have your brains tested?" Fearing the worst, the author agreed and was asked to observe the pattern on the screen when he worked out an elementary mathematical calculation. To his astonishment he found that the record showed a burst of voltages during the calculation, which was immediately followed by a second similar burst. He was told that subconsciously he checked his calculations although he was unaware of this.

Another outstanding device considered during the war was modified transformers for the Asdic antisubmarine equipment. Toward 1945 the author was also asked to redesign the normal transformers so that, without loss of performance, they could be appreciably reduced in size.

After the war ended in 1945 there began improvements in recording on disks and tapes and a frequency range spectrum of 40 Hz to 16 kHz became common, although some recording companies specified 20 Hz to 20 kHz, which is normal for many transformers today.

Harmonic generation, today called distortion, then had become important, and the author made a detailed study of the properties of the nickel-iron alloys from this aspect. For this he was awarded an external Ph.D. by London University, his thesis being entitled "Harmonic Distortion in Transformers and Chokes with Nickel Iron Cores" [8]. The superiority of Mumetal over other alloys with respect to low distortion was studied and distortion coefficients were evolved. These enabled designers to predict transformer distortion on finished transformers, provided the associated circuit parameters were disclosed. In the thesis the importance of uniform flux density throughout the magnetic circuit was shown to be essential if distortion is to be minimized. Fig. 8 illustrates the distortion coefficients of various magnetic materials in the form of interleaved assemblies of laminations. These coefficients are directly proportional to the resulting distortion, and the superiority of Mumetal is apparent. Fig. 9 gives the distortion coefficients for Mumetal in forms other than laminations and emphasizes the low distortion of highpermeability spiral cores.

11 MAGNETIC CORES FOR AUDIO FREQUENCY TRANSFORMERS

The desirable properties for audio frequency magnetic cores varies somewhat according to the type of transformer. For those handling voltages over a wide frequency band, particularly starting at 20 Hz, highpermeability cores are essential to restrict the number of turns and keep the leakage inductance down. High resistivity of the magnetic material and low hysteresis and eddy current loss are desirable so that overall core losses are minimized. Where actual power handling is small and low cost is desirable, Mumetal 0.38 mm thick is mostly employed, although thinner laminations can offer certain advantages, especially as regards permeability. This is particularly the case for very small transformers required for printed circuit board mounting. For this the range of laminations available is somewhat limited but can vary in size from about 10 mm ^{2} up to a few square centimeters. On the Continent DIN standard sizes exist. Fig. 10 gives a few of the lamination sizes in general use, although for high per

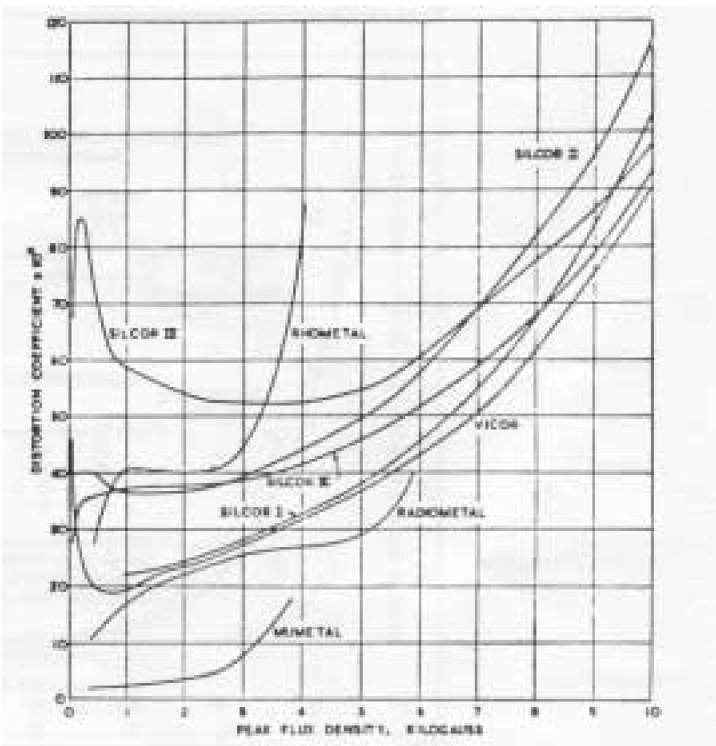


Fig. 8. Distortion coefficients of various magnetic materials in the form of interleaved assemblies of laminations.

performance or appreciable audio output larger sizes are available.

Laminations are generally in the form of Es and Is (to make up a rectangular form) or Ts and Us, and care must be taken in assembly to avoid excess compression or bending since the permeability is easily reduced thereby. There are advantages in higher permeability by using single E laminations (Fig. 11). Impregnation can have undesired effects, and immersion in incorrect grades of wax can lead to microphony, that is, minor voltages set up in the windings generally due to relative movements-of windings and cores.

It will be noticed that generally the core sectional areas are such that uniform flux density throughout the magnetic circuit is obtained. This is most important to minimize harmonic generation, and the presence of holes for bolts for fixing purposes does cause nonuniform flux concentration. Laminations are normally interleaved to form a stack, but when this is the case, a striking phenomenon is observed.

Referring to Table 3, which gives the latest properties of the various grades of Mumetal, it will be observed that the saturation flux density is 0.77 T. Now by examining the manufacturers' curves for Mumetal laminations type 187 (Fig. 12) it will be seen that the permeability falls rapidly beyond 0.3 T, or less than half of the ferric induction saturation. This obviously limits the practical maximum induction at which the transformer can operate since high distortion starts at this density. Fig. 13 shows the wide range of permeabilities found over a number of batches of laminations, as sold, which shows initial permeability varying from 16 000 to 27 000 and a comparable divergence over the whole useful range of flux density. This must be taken into account when designing. The reason for the limitation of maximum working induction is given in detail in [9], from which Figs. 14 and 15 are taken. Basically it is due to the crowding of flux at the imbricated joints in the lamination assembly, which is discussed in detail in this paper.

12 DISTORTION IN AUDIO TRANSFORMERS

Referring to Figs. 8 and 9 it will be noticed that distortion increases as the flux density is raised so that wherever there are flux concentrations, additional distortion is produced. With an audio transformer the highest operating flux levels are at the lowest frequency, and here the maximum distortion occurs. As frequency is raised, for a definite operating voltage, the flux is progressively reduced so that harmonic generation falls. For the higher frequencies in the audio range there is the "skin effect," that is, the flux tends to concentrate on the outer surface of the laminations, which accounts for the fall in effective permeability, as shown in Fig. 16. Obviously for best operation at high audio frequencies thin material, such as 0.1 mm thick, has advantages as regards both inductance and distortion, but it is expensive.

13 INCREMENTAL OPERATING CONDITIONS

The passage of direct current through winding carrying audio, frequency currents causes magnetization which results in a severe diminution in permeability and limits the audio output. This is of particular importance with transistor amplifiers where heavy direct current can be available in the output.

In one case encountered by the author, a 300-VA

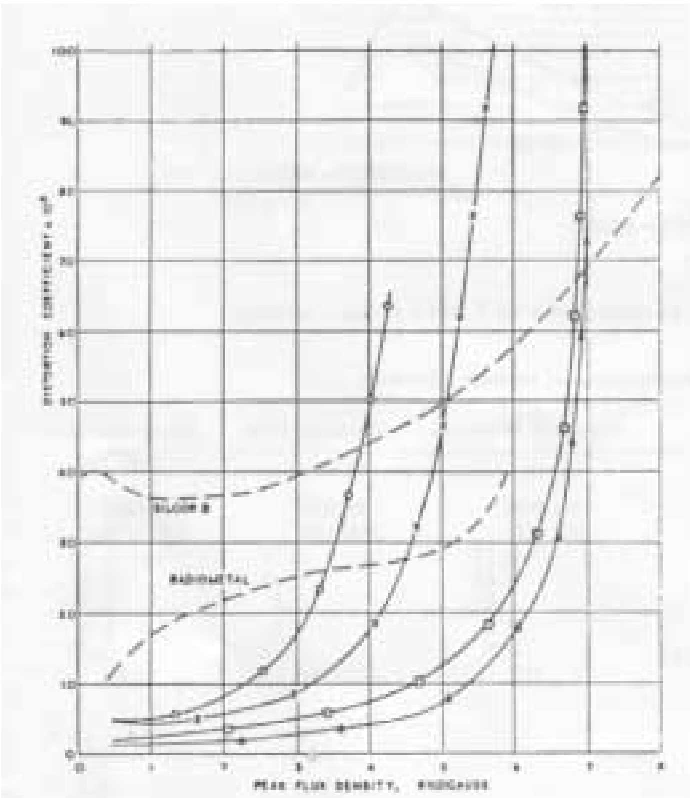


Fig. 9. Distortion coefficients of Mumetal. O-cut ring stampings with interleaved joints; x-ring-stampings; 0-spiral core; A-high-permeability spiral core.

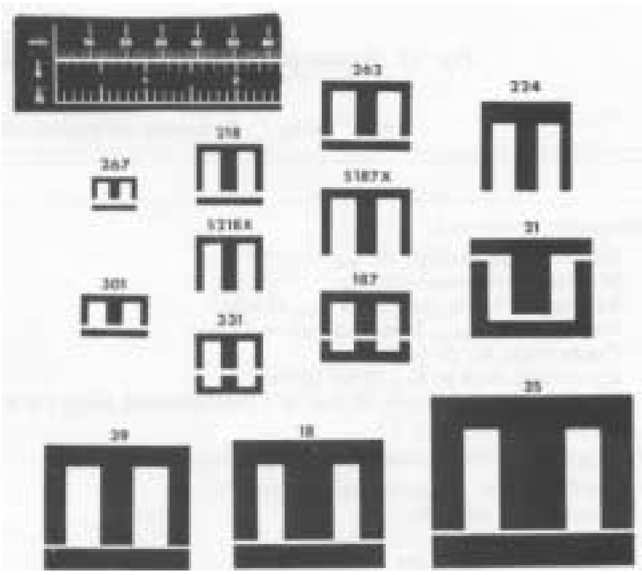


Fig. 10. Sizes and types of some of the laminations used for audio frequency transformers.

push-pull audio output transformer designed by him and fed from two transistor amplifiers was said to have been balanced to eliminate any direct current. In fact it was found to be unbalanced and passing 2 A direct current through the primary winding, and the effect on the quality of the speech and music, to put it mildly, was most pronounced. When the unbalance was found, there had never before been such a rush to put two 10 000-RF capacitors in the lines. Here was a case of enormous distortion, and the author was reminded of a wartime requirement of a large number of transformers he designed especially to create maximum distortion for radio transmitters to jam unwanted radio reception.

14 DEMAGNETIZATION OF SOFT MAGNETIC MATERIALS

When a transformer has been subjected to large values of direct current or has been in the vicinity of a strong permanent magnet, such as too near a loudspeaker, it will assume a polarized state or become magnetized. Fortunately this seldom has a permanently harmful effect on the core material, although in its magnetized state it will have higher distortion and reduced audio output. The process of demagnetizing is quite simple and consists of applying to one winding an alternating current (for example, at 50 Hz) of value appreciably exceeding

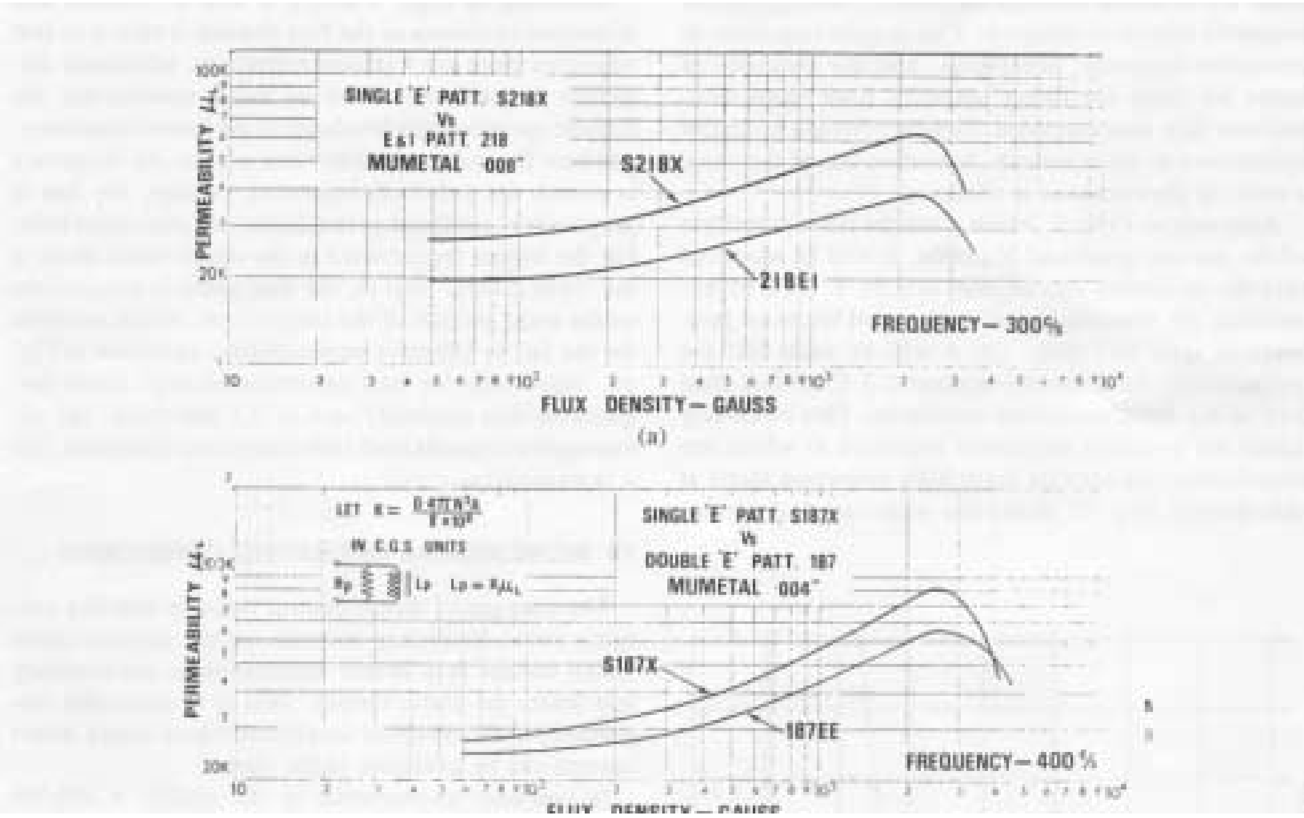


Fig. 11. Higher permeability of E laminations as compared with E and I of same material.

Table 3. Summary of typical characteristics of modern Mumetal.

	Standard Mumetal	Mumetal Plus	Supermumetal
Magnetic properties			
Initial permeability* do 114	60 000	80 000	140 000
Maximum permeability do	240 000	300 000	350 000
Saturation ferric induction Bsat (Tesla)	0.77	0.77	0.77
Remanence, Brem from saturation (Tesla)	0.45	0.45	0.5
Coercivity, H° do (A/m)	1.0	0.8	0.55
Hysteresis loss at Bsat (J/m3 cycle)	3.2	1.3	0.9
Total loss at 0.1 Tesla 50 Hz, 0.1 mm spirated cores (mW/kg)	0.7	0.55	0.35
Curie temperature (°C)	350	350	350
Physical properties (similar for all grades)			
Coefficient of linear expansion, per °C			13 x 10-6
Resistivity, uOhm . m			0.6
Specific gravity			8.8
Thermal conductivity, W/m . °C			33
Specific heat, J/kg . °C			440

* u4 is measured at 0.4 A/m.

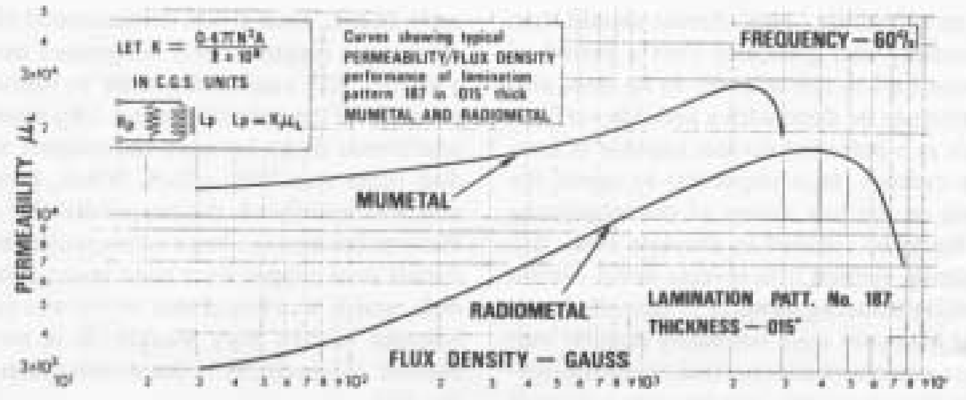


Fig. 12. Increase in permeability with flux density and reduction at about half saturation.

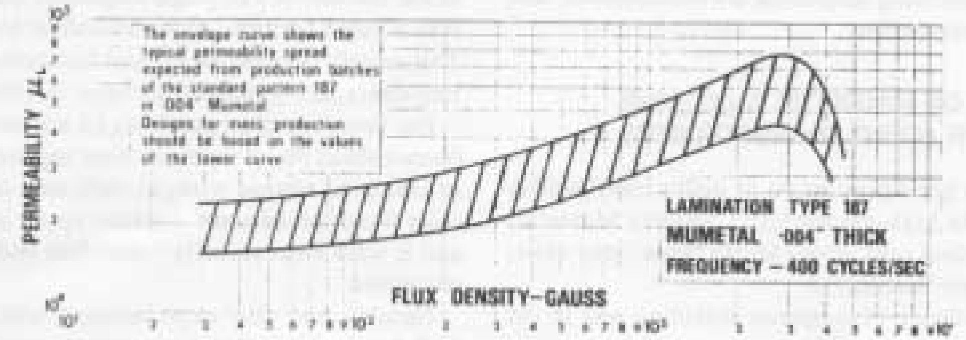


Fig. 13. Typical permeability spread on lamination batches as purchased.

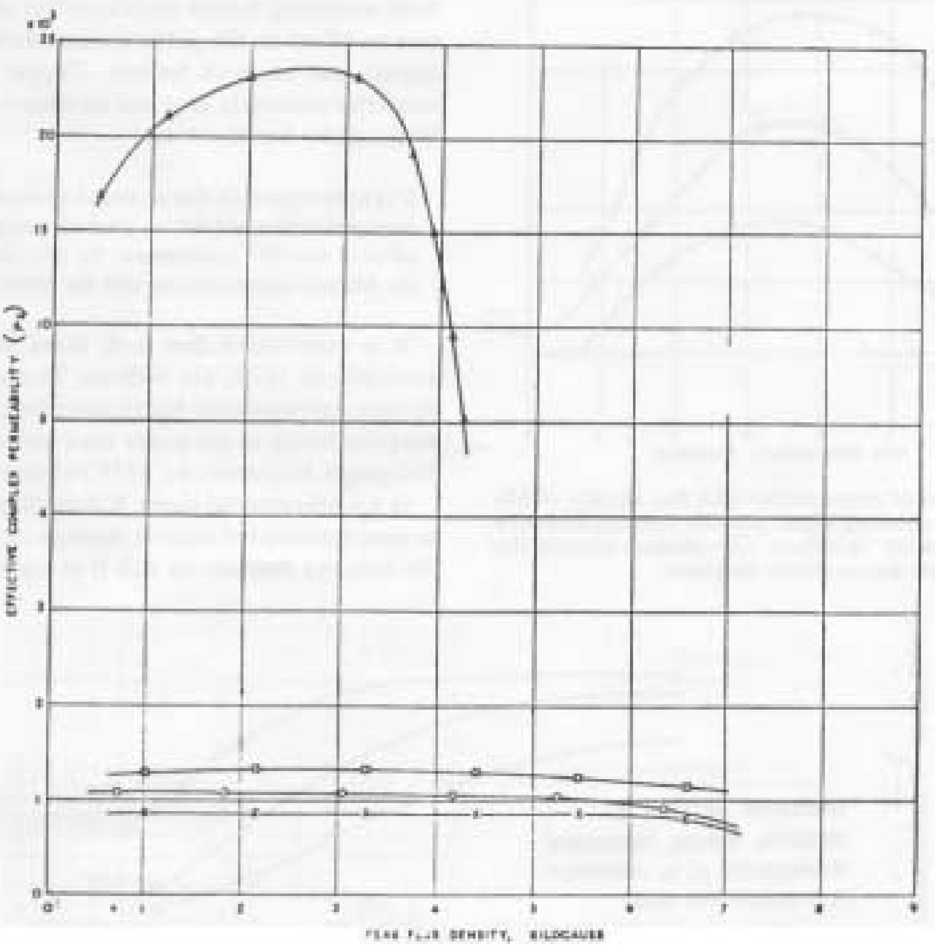


Fig. 14. Variation of permeability of interleaved laminations with flux density as compared with butted and gapped assemblies. 0-interleave 0-butted; O-with 0.001-in gap in one outer limb and butt joint in the other; x -with 0.001-in gap in middle and in both outer limbs. Note change of scale of ordinate at [L5-5000.

that required for saturation. This current should then be reduced smoothly and gradually over a period of time, such as one-half to one minute. In its most elementary form this can be done with a suitable variable resistance, such as a potential divider capable of handling the large current. It is important to spend the bulk of the time on the low values of demagnetizing force, which should be reduced to absolute zero. Another demagnetizing method is to reverse direct current continuously while reducing its value to zero. It should be stressed that Mumetal does not easily acquire unidirectional magnetization under normal operating conditions. Silicon iron, however, can become polarized to a small extent if low-frequency ac signals or pulses of values approaching saturation are encountered, and this increases distortion.

15 HISTORY OF MAGNETIC SHIELDING AS USED FOR AUDIO TRANSFORMERS

Nowadays a good proportion of audio transformers are contained in high-permeability (usually Mumetal) magnetic shielding cans where 50-Hz "hum" may exist, and these are most effective.

The first evidence of magnetic shielding was in the early 1820s, when it was demonstrated that a horseshoe permanent magnet freely suspended and rotated over a copper disk caused the latter to rotate. (This is the principle of the induction motor.) By interfacing various nonferrous disks between the magnet and the copper disk there was little effect. When, however, an iron disk was interfaced, the copper disk did not move, and this was the first evidence of magnetic shielding. Other metals than copper were tried instead for the rotatable disk, and it was found that silver was comparable but bismuth reacted very weakly. It is now known that electric conductivity is the desideratum for motion of the disk.

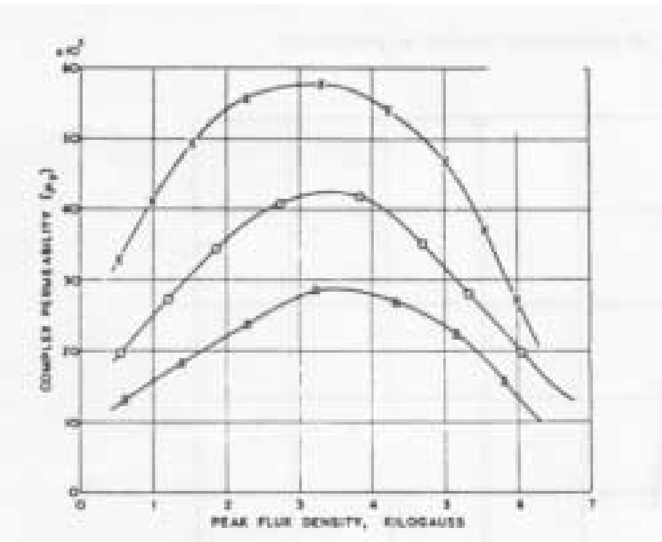


Fig. 15. Variation of permeability with flux density of Mumetal spiral cores showing higher possible working densities. x-high-permeability specimen; O-medium-permeability specimen; A-low-permeability specimen.

On 1883 November 8 Willoughby Smith, as president of the Society of Telegraph Engineers and Electricians, read a paper entitled "Volta-Electrical Induction" [10]. This society became the present Institution of Electrical Engineers (IEE) some years later in 1888.

For demonstration purposes he utilized two wooden frames about 36 in 2 in which were supported flat helices of insulated copper wire, as indicated in Fig. 17. The coils were placed some distance apart, and switches D and E were mechanically controlled and could be synchronized.

Faraday had also experimented with similar coils with hand-operated static switches as in Fig. 17(b) and found that when the space between the coils was filled with insulating bodies such as sulfur and shellac, there was no effect on the galvanometer deflection when the circuit was made or broken. Copper and other nonmagnetic materials also had no observable effect, and Willoughby Smith wrote:

> It is to be regretted that so sound a reasoner and so careful an experimenter had not the great advantage of the assistance of such suitable instruments for this class of research as the Mirror-Galvanometer and the Telephone.

It is noteworthy that both these instruments were available in 1879, Sir William Thomson's mirror reflecting galvanometer being described in detail by Willoughby Smith in his paper read before the Society of Telegraph Engineers on 1879 February 12 [11].

In his presidential paper Willoughby Smith was able to send interrupted current through coil A and measure the induced currents in coil B at various frequencies.

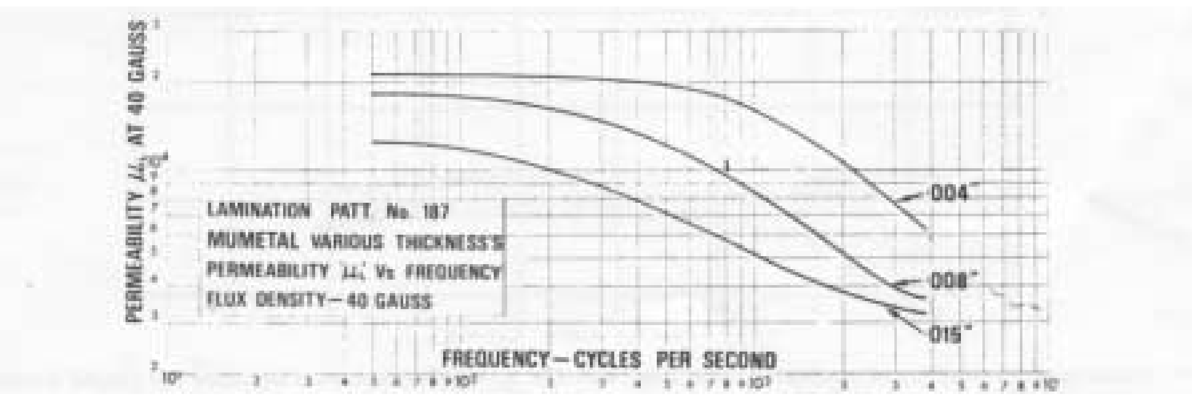


Fig. 16. Curves stressing fall in permeability with increasing frequency and showing advantage of thin laminations.

The results of his tests by placing between the coils sheets of copper, zinc, tin, iron, and lead show wide differences in shielding effects and particularly variations as the frequency increased. (This author found all this equipment some 40 years later in his company's stores.)

A more scientific series of shielding tests was carried out by Constable and Aston at the National Physical Laboratory some 40 years ago, and results are given in Table 4. It will be noted that at 50 Hz Mumetal is easily the most effective, but while copper 1/32 in thick has a value of 4 dB at 50 Hz it becomes 26 dB at 3200 Hz.

With the passage of time and research on the effects of impurities in Mumetal, the permeabilities have greatly improved, and comparatively thinner thicknesses for shields are employed. It is even possible to obtain some degree of shielding by wrapping a transformer in very thin Mumetal tape, 0.05 or 0.1 mm thick, but the uses are limited.

For shielding audio frequency transformers the author, in the 1930s, devised about 10 deep-drawn cylindrical Mumetal cans, and many of these sizes have persisted up to the present time. The normal reduction in hum by the use of these cans is 30-40 dB, but where 50-Hz fields are intense, it is customary to use double shields or even a Mumetal shield encased in a second shield having a higher saturation induction, such as Radiometal 50% Ni-50% Fe alloy.

When low- and high-frequency audio fields are to be minimized it is possible to copper plate Mumetal shields, although an inner lining of copper foil is preferable.

The usual method of measuring hum reduction is to

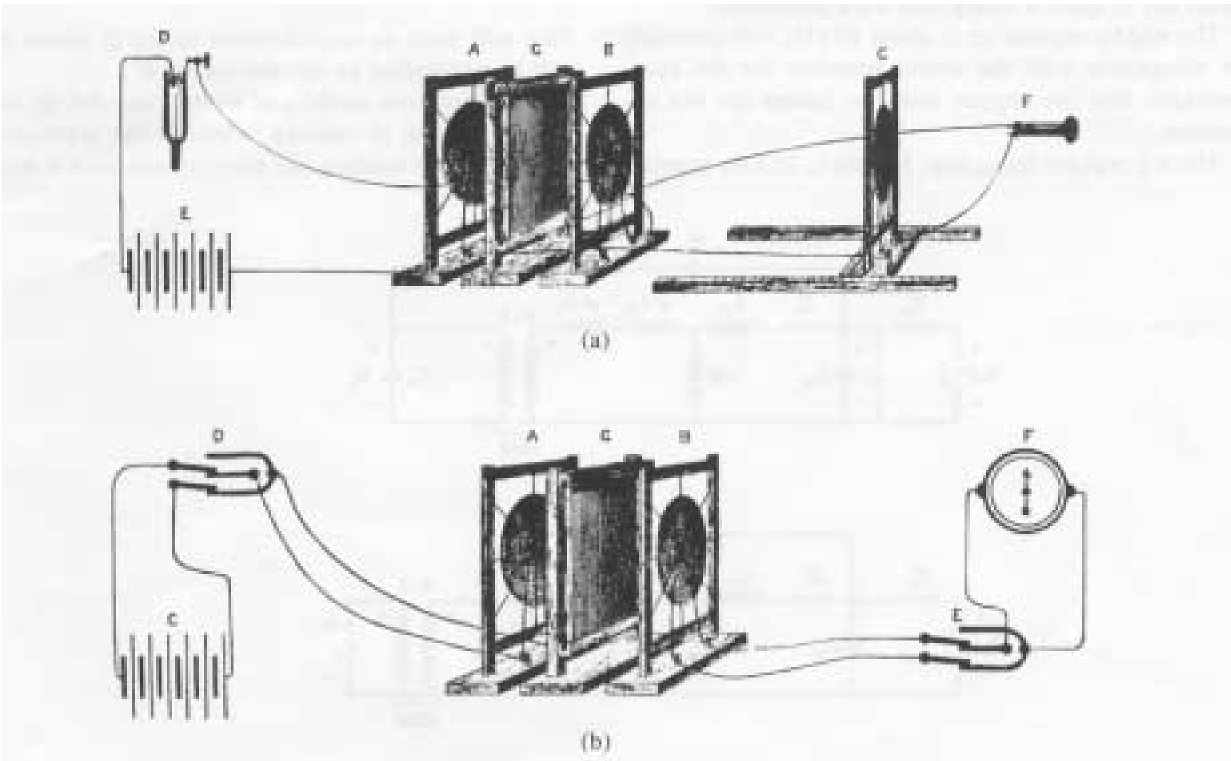


Fig. 17. Magnetic shielding measurements by Willoughby Smith in 1882.

Table 4. Screening effects of various materials compared with Mumetal.

Frequency (Hz)	Transformer iron thickness 1/64"	Steel thickness 1/16"	Copper thickness 1/32"	Lead thickness 1/2"	Brass thickness 1/4"	Aluminum thickness 1/4"	Cast iron thickness 1/4"	High permeability alloy thickness 1/16": Enclosing pickup transformer	High permeability alloy thickness 1/16": Enclosing exciting transformer
	d.b.	d.b.	d.b.	d.b.	d.b.	d.b.	d.b.	d.b.	d.b.
50	4	6	4	4	10	12	12	36	30
100	5	6	5	7	12	17	13	37	28
200	4	6	8	10	16	20	16	36	29
400	4	7	12	16	22	26	24	35	29
800	4	7	18	24	30	32	41	34	30
1600	6	8	24	32	40	31	33	32	29
3200	6	6	26	22	30	20	20	26	22
6400	8	6	13	8	15	8	8	20	8

create a uniform 50-Hz magnetic field by the use of Helmholtz coils and to measure the voltage setup in a transformer first without a shield, then when encased in a shield.

For some applications, particularly for electromedical purposes or electron-microscope observations or where the earth's field is to be minimized or eliminated, it is possible to line a room with a Mumetal sheet, or even to make a Mumetal cabin capable of housing an operator.

16 SOME NOTES ON FREQUENCY RESPONSE OF AUDIO TRANSFORMERS

The lower register of the frequency response is obtained by the correct selection of the grade and size of the magnetic core and by the number of primary turns. The maximum operating flux density must be chosen to keep within the acceptable distortion range, and this generally is quite a straightforward procedure.

The middle register up to about 10 kHz will generally be acceptable with the above provisos for the bass, provided that the copper and iron losses are not excessive.

The top register from, say, 10 kHz to 20 kHz depends to a great extent upon the number of sections in the windings and the minimization of capacitance between coils and other parts of the transformer. The magnetic coupling between primary and secondary windings is of considerable importance since this controls the leakage inductance, and high permeability of the core material is helpful in effecting this. At high frequencies it can be assumed that the self- and mutual coil capacities, and those between the windings and the core, and electrostatic and magnetic shields, can be regarded as lumped together to form capacitance C20 in the equivalent circuit (Fig. 18a). If L' represents the leakage inductance and R' is the generator resistance plus the equivalent resistance of the transformer, this forms a series resonant circuit whose frequency is

$$f = \frac{1}{2\pi\sqrt{L'C'_{20}}} .$$

This will have an amplification factor Q whose value will be controlled by the resistance R'.

An alternative method of controlling the Q, which causes the rise in voltage output at the resonant frequency, is by loading the transformer with a resistor

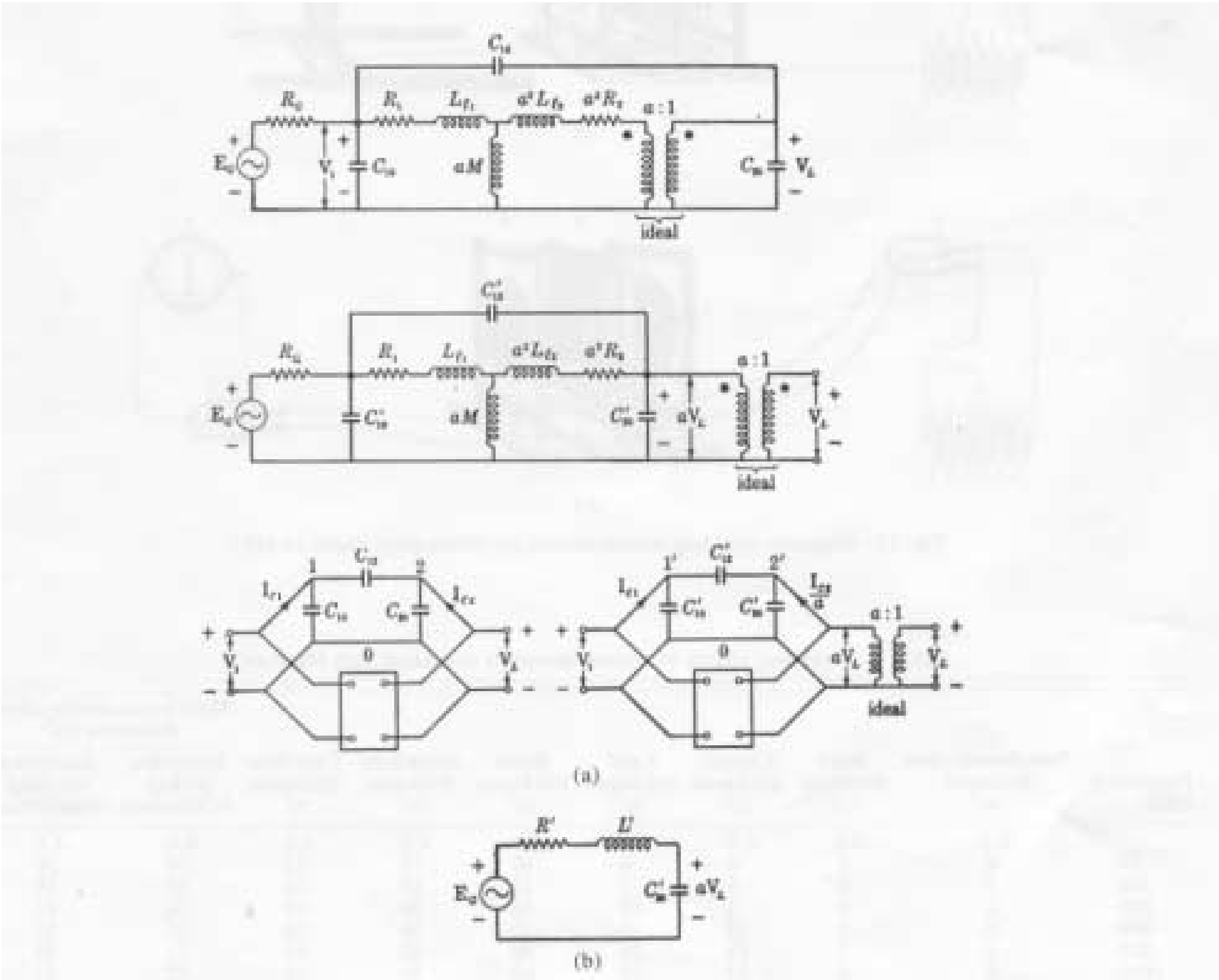


Fig. 18. (a) Equivalent circuits of audio transformer at high audio frequencies. (b) Simplest form of equivalent circuit of audio transformer at high audio frequencies.

or increasing the secondary winding resistance. Fig. 19 is a series of curves showing the frequency response of a very old (1944) fairly bad input transformer for different loading resistances. With modern transformers the leakage resonance is usually above 20 kHz, but loading the secondary gives similar effects. The type of loading on a very high grade input transformer can have astonishing effects where the frequency response can be made to extend from 20 Hz up to beyond 100 kHz, as indicated by the curves in Fig. 20. This transformer was designed by the author for Dolby Laboratories and was extensively used by them for their broadcast equipment.

17 PERFORMANCE REQUIREMENTS FOR AUDIO FREQUENCY TRANSFORMERS

A specification could include all or a great deal of the following, much of which depends on the magnetic core.

1) Frequency response, for example, 20 Hz to 20 kHz generally, although 2 Hz to 10 kHz has been specified for vibration study transformers and 320 Hz to 320 kHz for high-speed cassette-copying equipment

2) Maximum operating level at the lowest operating frequency

3) Turns ratio

4) Copper resistance

5) Inductance of primary or secondary at a specified frequency and value of excitation and sometimes leakage inductance

6) Permissible transmission loss and whether correction is to be made by turns adjustment

7) Source impedance

8) Load or loads

9) Insulation test on winding to winding and to magnetic core and housing

10) Flash test at prescribed voltage

11) Permissible distortion or harmonic generation

12) Balance or common-mode rejection

13) Mechanical size with any limitations for insertion in a module

14) Type of mounting, such as printed circuit board, one-hole fixing, or grommet

15) Color-coded leads or terminal blocks

16) Electrostatic interwinding shields if required

17) Magnetic shielding, usually by Mumetal can and being of the order of 30-40 dB at 50 Hz

18) Freedom from microphony

19) For large transformers, such as 300 VA, freedom from acoustic noise generated by core and winding

20) For telecommunication transformers, return loss

21) Isolation test (such as 1500 V rms at 50 Hz for 1 minute), between windings and metal parts with subsequent insulation test

22) Maximum voltage permissible if core accidently saturated.

A few of the specialized requirements encountered are:

1) To operate at 90°C at bottom of oil well drilling

2) To operate in liquid nitrogen at 77 K

3) To operate inside diver's helmet with compensation for loss of bass

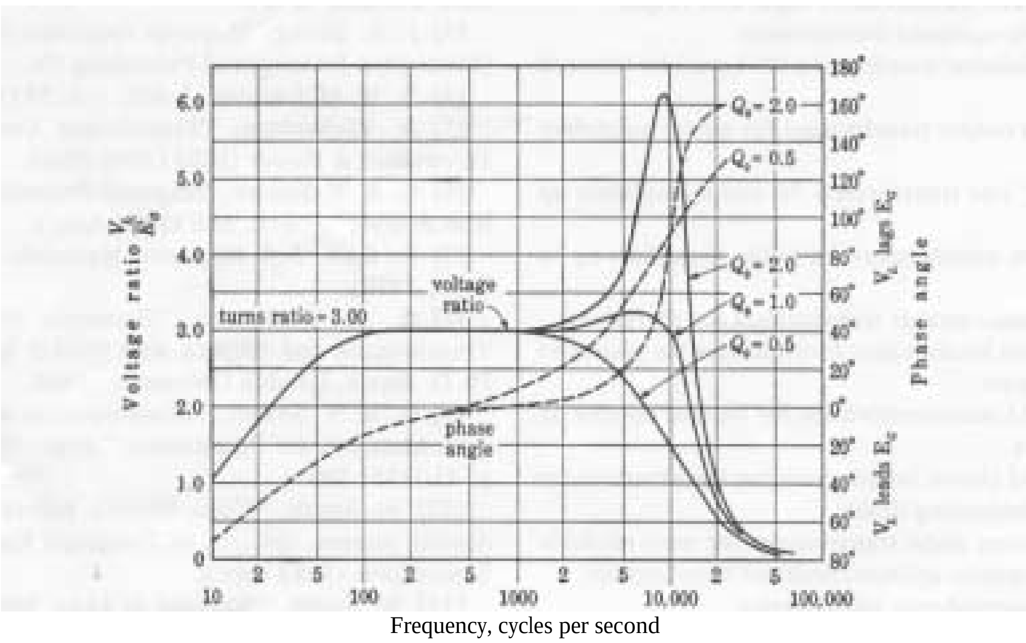
4) Very low power bridge input transformers

5) Audiometric transformers to medical specifications

6) High-ratio transformer in liquid helium for noise research.

18 RANGE OF AUDIO FREQUENCY TRANSFORMERS

It is not normally realized that there is a very large number of different audio frequency transformers; the following list covers some of those in general demand:



Frequency, cycles per second

Fig. 19. Frequency and phase characteristics of a circuit containing an input or interstage transformer, showing the effects of varying the secondary resistance.

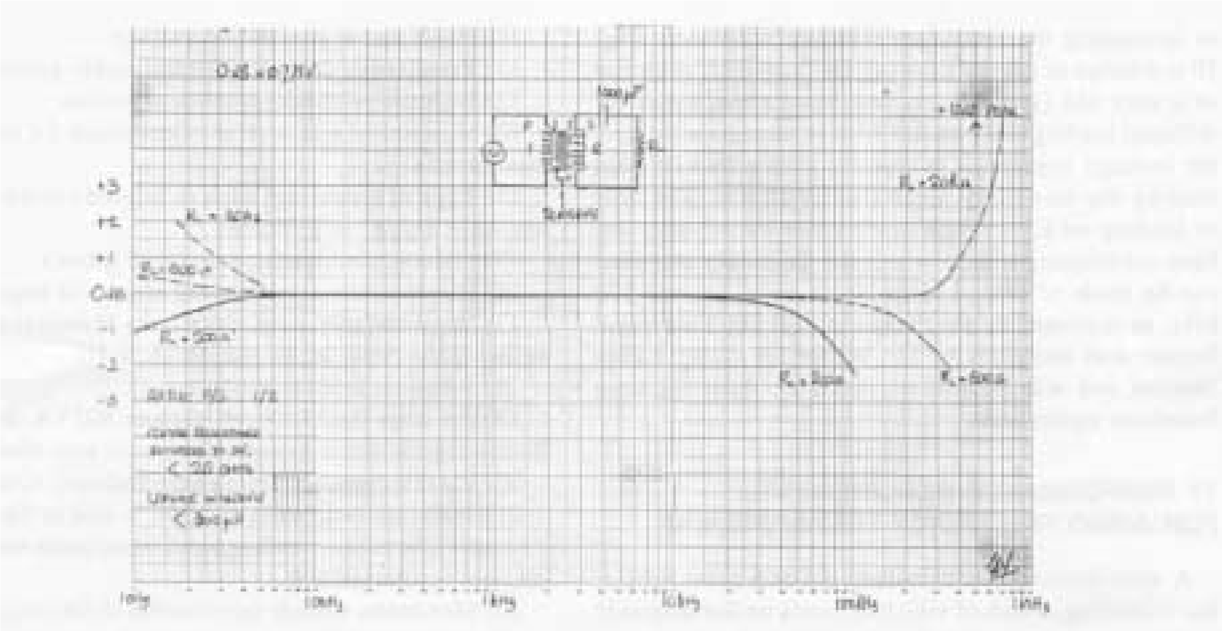


Fig. 20. Typical performance of wide-band audio transformers showing effects of different secondary loadings.

1) Microphone transformers (all types), including those for phantom powering
2) Transformers for dynamic and moving-coil pickups
3) Input transformers (all types)
4) Output transformers for mixers
5) Multisecondary output transformers
6) Bridging transformers
7) Line transformers
8) Line transformers to isolating test specifications
9) Impedance matching transformers, including those for high-power loudspeaker distribution
10) Balanced transformers, input and output
11) Double-screened transformers
12) Experimental transformers (all types) for research projects
13) Audio output transformers for power amplifiers up to 1 kW
14) 100-V line transformers for audio amplifiers up to 1kW
15) Output transformers for valve amplifiers up to 500 W
16) Hi-fi loudspeaker transformers for all ratings
17) Column loudspeaker transformers for plain and focused outputs
18) Tapped autotransformers for volume control on loudspeakers
19) Printed circuit board mounting transformers for mixing and recording desks
20) Miniature audio transformers for most modules
21) Microphone split!er/combiner transformers
22) Antimicrophonic transformers
23) Low-frequency pulse transformers
24) Vibration study transformers (2 Hz upward)
25) Direct injection transformers (for guitars, etc.)
26) Transformers for electrostatic speakers up to 2000 V do
27) Hi-fi output transformers for Compact Disc reproduction
28) Induction loop transformers (all ratings).

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THE AUTHOR

G. A. V. Sowter was born in London, U.K., and educated at London University, where he was awarded his B.Sc. in engineering in 1922. He then joined the Telegraph Construction and Maintenance Co., which made and laid the first Atlantic submarine cable, and he was engaged in research on magnetic materials. This included the early work and evolution on Mumetal and kindred alloys by the team. In the early 1930s, he worked with N. W. McLachlan, the celebrated pioneer of moving-coil loudspeaker research, and developed a transmitter and receiver for a projected transatlantic telephone submarine cable. The economic world depression of the 1930s terminated this project and laboratory work on moving coil loudspeakers was undertaken.

A number of technical papers were published by Dr. Sowter and Dr. McLachlan on loudspeaker articles in the *Philosophical Magazine*. During this period the standard textbook *Loudspeakers* by N. W. McLachlan was published, based on the extensive measurements carried on by Dr. Sowter. Dr. Sowter became chairman of the measurements division of the Institution of Electrical Engineers, was on the council for a number of years, and served on many of their committees. He received a fellowship of the I.E.E. Previously he had been Chairman of the Council of the British Institution of Radio Engineers (now I.E.E.I.E.) and still enjoys his ham radio-his callsign G20S being allocated in the early 20s. He has chaired a number of British Standard Committees on magnetic materials and has written several technical papers on this subject. He became Group Commercial Director of several Telcon Metals companies which included factories producing Mumetal and other alloys.

Prior to World War II Dr. Sowter spent several years teaching at Higher National Certificate level as well as managing Telcon Metals Ltd. This resulted in the award of an external Ph.D. degree at London University, where his thesis was on "Harmonic Distortion in Transformers and Chokes with Nickel Iron Cores."

In the late 1930s he became consultant to Sowter Transformers, Ipswich, U.K., which produces every type of audio frequency transformer. He is still active in this capacity and has made hundreds of designs resulting in the sale of thousands of transformers handling from a few microwatts up to a kilowatt. His expertise in the properties and applications of high-permeability magnetic alloys led to the design of transformers for the Royal Shakespeare Co. Barbican, Royal Opera House Covent Garden, BBC Studios, Dolby Laboratories, plus many others.

Dr. Sowter has traveled extensively, including a visit to China 25 years ago. He is treasurer and member of the "Dynamicables" Club, which has celebrated its Centenary recently and consists of the 100 outstanding British Electrical Engineers.

He is also a registered chartered engineer by the British Engineering Council. At the 73rd Convention of the Audio Engineering Society in Eindhoven, Dr. Sowter was awarded a fellowship in recognition of his achievements in the audio field. The citation, approved by Ray Dolby, chairman of the AES Awards Committee, reads: "For contributions to audio transformer and loudspeaker design, particularly the optimal employment of magnetic materials."