INDUCTORS

1. Fundamental Laws of the Magnetic Field

Like the electric field the magnetic field describes the forces between matter, which are experienced under certain conditions. Under practical conditions the forces produced by the magnetic field are much stronger than those produced by the electric field. The knowledge about the existence of the magnetic field is already very old.

The magnetic field plays an important role in audio electronics, as it is involved in many equipment like:
- generators
- transformers
- motors
- inductors
- microphones
- tape recording, etc.

1.1. Magnetism of Permanent Magnets

Permanent magnets are made of iron or of alloys containing materials like nickel-cobalt, aluminium a.o.. Nowadays also sintered mixed oxides, so called hard ferrites, are used.

If a permanent magnet is mounted movable, it will aline itself, so that one pole points towards north.
This side is called the NORTH POLE, the other side the SOUTH POLE.

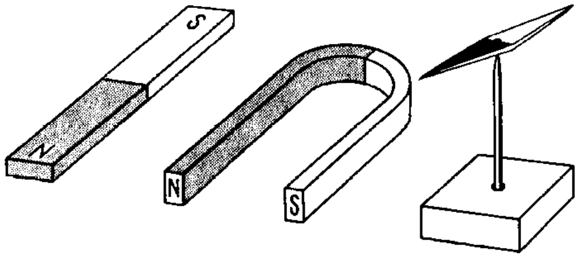

Fig. 1.1.1.
Some shapes of permanent magnets.

The forces realized between permanent magnets are described by the magnetic field. The magnetic field can be made visible in an experiment. Similar to the electric field, field lines are used to describe the magnetic field.

The properties of the magnetic field can be described by the following characteristics of the field lines:
- Magnetic field lines form a closed loop,
- Magnetic field lines try to be as short as possible,
- Magnetic field lines repel each other.

This will explain the well-known property of permanent magnets:

Equal poles repel, opposing poles attract each other.

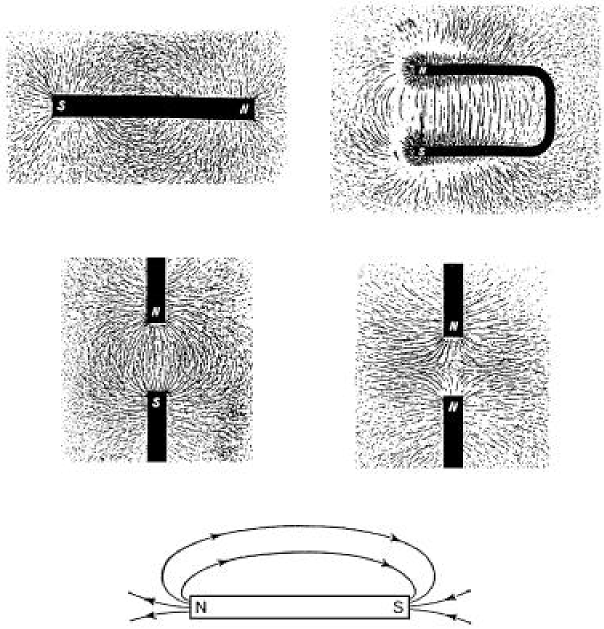

Fig. 1.1.2.
Magnetic field lines are used for the schematic description of the magnetic fields.
Each magnet has two poles, North and South. The shapes of magnetic fields can be made visible using iron dust.

By definition the direction of the magnetic field lines is such, that the field lines leave the north pole and enter the south pole. The direction is indicated by arrows.

The higher the density of field lines, the stronger the forces produced by the magnetic field.
The quantity for the magnetic field, graphically represented by the total number of field lines, is called the
MAGNETIC FLUX Φ.
Its unit is WEBER (Wb)

The quantity used to describe the effect of the magnetic field on a certain point is the
FLUX DENSITY or MAGNETIC INDUCTION B.
Its unit is TESLA (T).

The term "induction" comes form the idea, that the magnetism is "induced" (brought into) at a certain point by the magnetic field.

Magnets attract iron, steel, nickel, cobalt and alloys containing these metals. These materials will become magnets themselves as soon as they are exposed to a magnetic field (induced magnetism). They are thus called magnetic materials. Depending on the kind of material and the strength of the magnetic field, the magnetic materials will keep or loose their magnetism as soon as they leave the magnetic field.

Magnetic materials play an important role in electronics and will be discussed in detail later.

1.2. Magnetic Field and electric Current

When a current flows in a conductor, a concentric magnetic field builds up around this conductor.

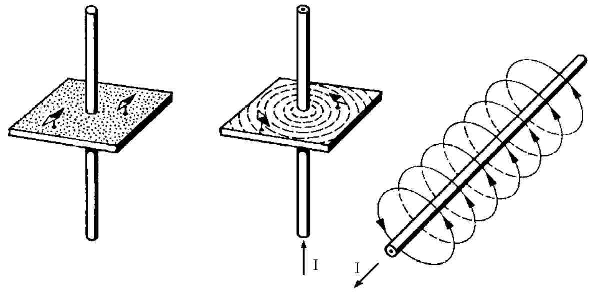

Fig. 1.2.1.
The presence of a magnetic field around a current through a conductor can be shown in an experiment and can be represented by concentric field lines around this conductor.

The forces between magnetic fields of conductors and other magnetic fields are mutual, this means conductors will produce forces on permanent magnetic fields and vice versa.

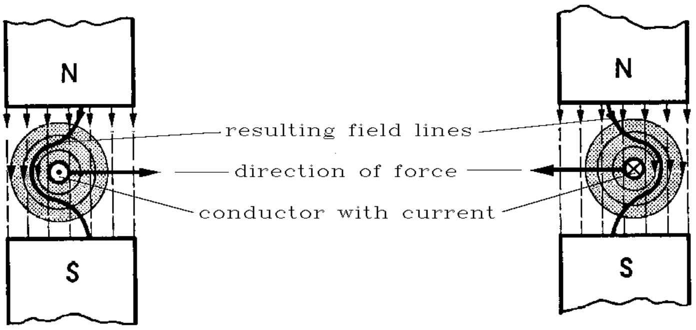

Fig. 1.2.2.
Mechanical force affecting a conductor (with current) when this conductor is placed in a magnetic field. On one side of the conductor the magnetic fields add up, on the other side they are opposed in direction and must be subtracted from each other. The mechanical force acting upon the conductor is vertical to the direction of the current, and vertical to the direction of the field lines.

Note that any current produces a magnetic field, even if it is not flowing in conductor. E.g. the electron beam in a CRT represents a current which has a magnetic field, so this beam can be deflected by other magnetic fields.

If the conductor is wound to form a coil, the neighbouring conductors carrying equal currents add up their individual magnetic fields. The resultant magnetic field is thus approximately increased by the number of turns. Such a magnetic field has the same properties as experienced with permanent magnets.

The direction of the magnetic field produced by current in a conductor depends on the direction of the current and the direction of the winding. It can be memorised by applying the "right hand rule".

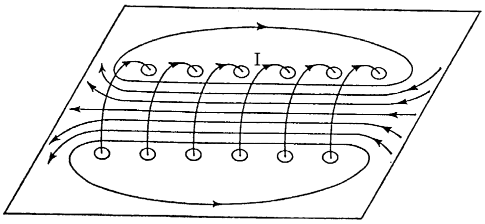

Fig. 1.2.3.

Several turns of wire make up a coil. This produces a concentration of magnetic field lines inside this coil, which now behaves like a permanent magnet (bar magnet).

The quantity for the strength of a magnetic field produced by a coil is the
MAGNETIC FIELD STRENGTH H.

The magnetic field strength depends on the current and on the physical properties of the coil:

$$H = I * \frac{N}{l}$$ **unit: A/m**

With:
I: current through the coil,
N: number of turns of the coil,
l: mean length of the magnetic field lines (difficult to determine)

Conclusion:
H increases when I increases and when the number of turns N is increased.
H decreases, when the turns are stretched, so that the length of the coil and thus the length of the field lines increases.

There is a direct relationship between the flux density and the field strength:

$$\mathbf{B \sim H}$$

A proportionality constant can be introduced to make an equation of the proportionality. This constant is called
MAGNETIC CONSTANT μ_o.

$$\boldsymbol{\mu_o = 1.257 * 10^{-6}\ T*m/A}$$

μ_o is thus relating the electrical and the magnetic quantities.
Thus the relationship between B and H becomes:

$$\boldsymbol{B = \mu_o * H}$$

1.3. Coils with Core

Certain core materials, e.g. soft iron, when placed in a coil, increase the strength of the magnetic field of this coil. This can be explained by the fact, that the magnetic field of the coil will magnetize the core and the fields of the core and the coil will add up.

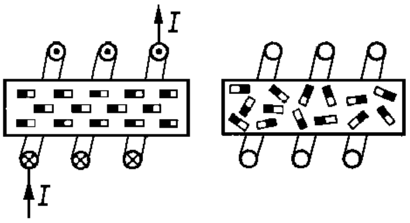

Fig. 1.3.1.

Showing molecular magnets in a core material. When no magnetic field is present, these molecular magnets are in disorder. Therefore the sum of their magnetic effects (to the outside) is zero. Under the force of a magnetic field they become orientated. Thus the iron core itself becomes a magnet, which supports the field of the coil.

In soft iron cores, this orientation of the molecular magnets disappears practically completely when the current (I) is switched off.

The flux density in a coil with a core is stronger than it is in a coil without core. The factor by which B is increased is described by the

RELATIVE PERMEABILITY μ_r.

It has the unit of 1. μ_r is a property of the core materials.

The flux density in a coil with core is thus:

$$\mathbf{B = \mu_r * \mu_o * H}$$

The permeability of the core material has the same importance for the properties of the coil, as the dielectric has for the capacitors.

Practical values for μr of different materials range from 1 for all non-magnetic materials to appr. 200 000 for special core materials. The permeabilities of magnetic materials depend strongly on their purity and on their mechanical treatment.

Magnetic Materials:	**μ_r:**
Pure Cobalt	70
Pure Nickel	250
Pure Iron	1000
50%NiFe	10 000
75%NiFe	100 000
Ultraperm 200	200 000

The relationship between H and B can be shown in a diagram. For a coil without a core (air coil) the characteristic is a straight line. The slope is constant for all values of H. Equal changes of field strength ΔH correspond to equal changes of flux density ΔB.

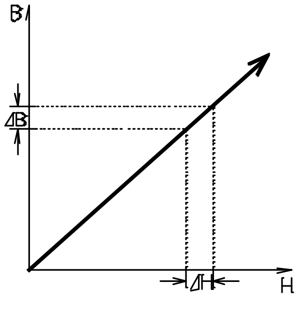

Fig. 1.3.2.
Relationship between field strength and flux density for an air coil.

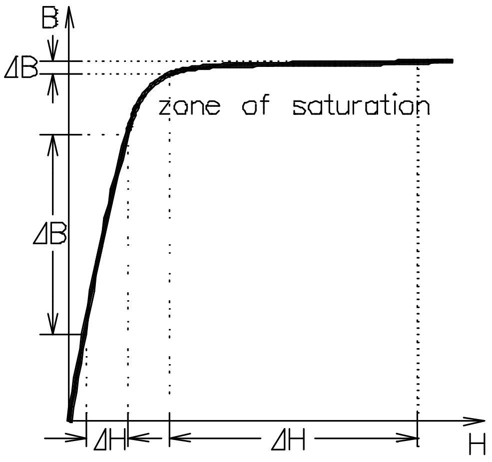

Fig. 1.3.3.
Magnetisation characteristic of steel.
When steel is being magnetised for the first time the magnetisation curve has a steep slope, i.e. μ_r is high (äB/äH is high).
Above a certain field intensity H, the slope is reduced. This means that μ_r is now reduced.

When the coil is provided with a magnetic core, the slope of the B/H -characteristic is strongly increased. The density B is proportional to the field strength H only as long as the permeability μr remains constant. At high flux density all molecular magnets will be orientated. From this point on the core can not contribute any more to the total flux, even if the field strength H is further increased.
We say the core is SATURATED.

The values of the permeabilities of magnetic material are given for flux densities far below saturation, normally around zero.

When the field strength H is increased from zero towards positive values, the density B increases until the steel is saturated (B_{sat}). When now the field strength H is reduced to zero again, the density B will not follow to zero, but a certain flux density will remain, which is called the REMANENCE B_r.

In order to fully demagnetise the steel, i.e. in order to bring the density B to zero again, a certain field strength in reverse polarity (-H) must be applied. This is called the COERCIVE FORCE H_c.

When the field strength -H is further increased (in negative direction) the opposite saturation point ($-B_{SAT}$) will be reached. If now -H is reduced towards zero, -B will also go towards zero. But when H = 0 again, B will not be zero, but will be at the negative remanence -Br. Now a positive coercive force is required, in order to bring B to zero, etc.

The graphical representation of this relationship results in a loop, which is called the HYSTERESIS CURVE.

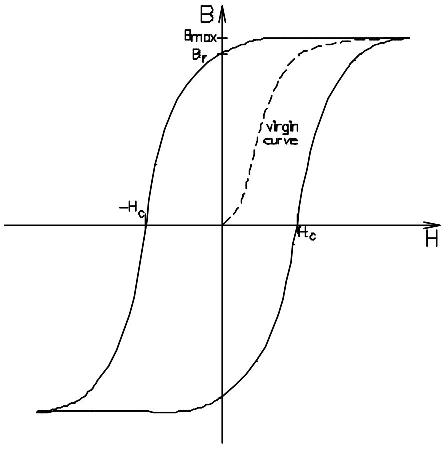

Fig. 1.3.4.

The hysteresis curve of a magnetic material (steel).

The magnetisation of the material continuously follows such states along the hysteresis curve, when AC current is causing H. This is the case in transformers, chokes, HF coils, etc. if they are provided with a core.

The reason for the remanence (e.g. of steel) is that, when the field H is removed, not all molecular magnets in the core material will return to their original (random) directions.

Hard magnetic materials, as used for permanent magnets, have a high remanence and a high coercive force. These include hard magnetic ferrites. The materials used in cores for normal coils and transformers should have the lowest possible remanence: Soft ferrites, i.e. soft magnetic materials.

Summary:
Core materials increase the flux density by the factor μr as compared with air. The permeability μr depends on the material used and on the 'working point', i.e. the point along the hysteresis selected for operation. This is usually done by selecting a core of suitable cross sectional area. Increasing the area, reduces the density for a certain intensity H.

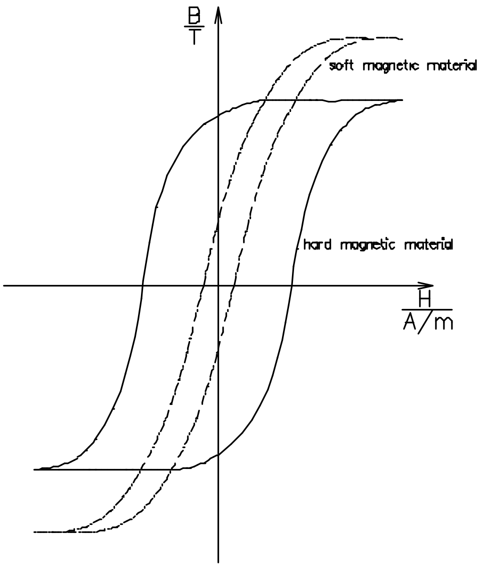

Fig. 1.3.5.
Hysteresis curves for hard and for soft magnetic materials.

1.4. The Curie Temperature

It is the property of all magnetic materials, that they loose their magnetic properties (μr becomes 1) abrupt and completely, if a certain temperature is exceeded. This temperature is a constant for the material and is called the Curie temperature.

If the temperature of the material drops below the Curie temperature again, the material will regain its permeability and will behave like a magnetic material, but any previous remanence will be lost. Therefore heating permanent magnets above the Curie temperature will demagnetize them.

The Curie temperature of different magnetic materials lay between 100°C and 1000°C. Alloys and ferrites with well specified Curie temperature within this range are available.

The Curie temperature of core materials and permanent magnets have to be well above the maximum operation temperature of the very application, to ensure that the core does not loose its magnetic properties during operation.

On the other hand the Curie temperature of a material can be used for temperature sensing:

If a magnetic alloy with a certain Curie temperature is used in conjunction with permanent magnet, then the alloy will be attracted by the permanent magnet, as long as the temperature of the alloy is below the Curie temperature. This force can be used to operate a switch. This switch will be open, if the temperature of the alloy exceeds the Curie temperature. This principle is used e.g. in thermo-static solder irons.

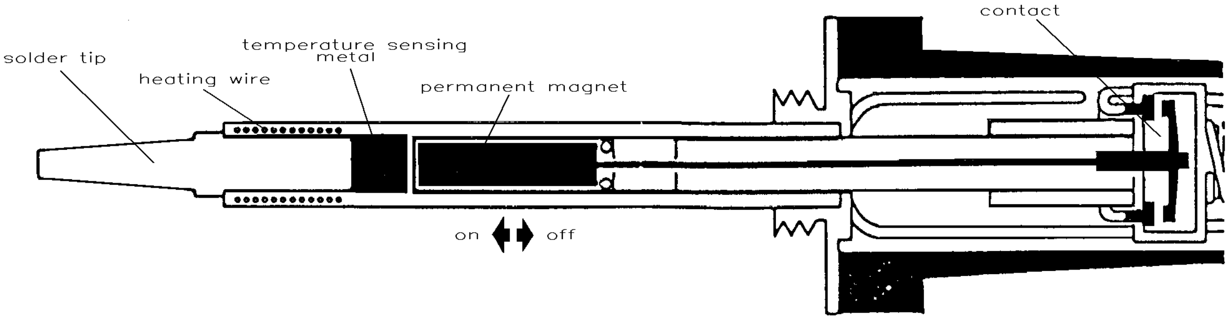

Fig. 1.4.1.
The principle of the thermo-static control of a solder iron, using the Curie temperature of a piece of alloy attached to the solder tip.

2. Electromagnetic Induction

The condition whereby a current produces a magnetic field, is partly reversible:
An electric voltage will be produced in a coil, when the coil is exposed to a CHANGING magnetic field.
This is called ELECTROMAGNETIC INDUCTION (or simply induction).

Within a closed circuit this voltage will cause a current.

This current produces a magnetic field, which has a direction, so as to try to maintain the original condition.

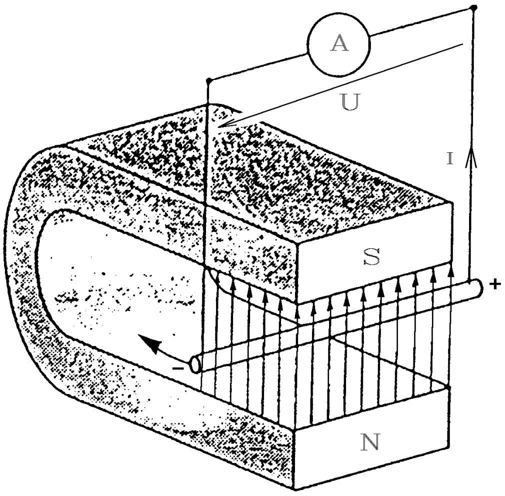

Fig. 2.1.
A voltage and a current are induced in a conductor which is moved in a magnetic field (or vice versa). The direction of the induced voltage and current is as shown and depends on the direction of the magnetic field and the direction of the movement.

When, for instance, the magnetic flux in a coil is reduced, the current induced in the coil will produce a flux, which is supporting the flux in the coil, i.e. induced voltage and current try to maintain the original field.

When, for instance, the magnetic flux in a coil is increased, the current induced in the coil will produce a flux, which tries to prevent any increase of flux in the coil.

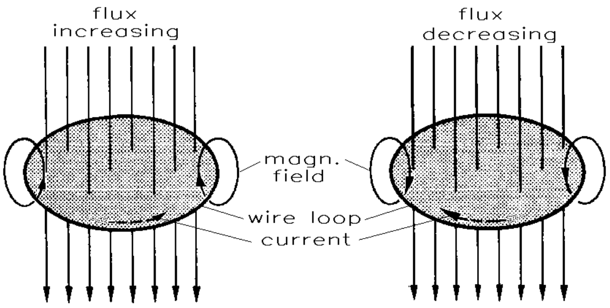

Fig. 2.2.
The current induced in a closed coil of wire is producing a magnetic field, which is always opposing the change of flux.

The magnitude of the induced voltage depends on the rate of change of the magnetic flux.

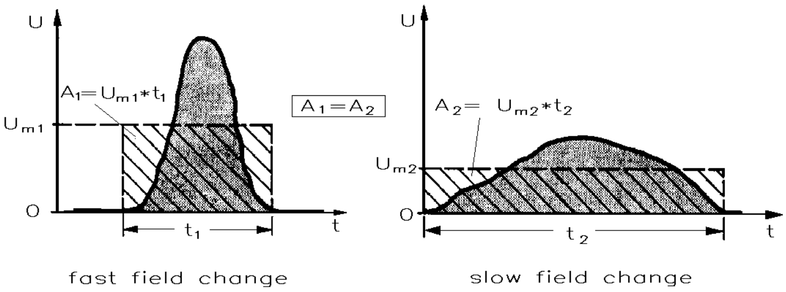

Fig. 2.3.
Experiment: The same magnet is moved over the same distance through a coil.
left: t_1 is short. The induced voltage U_{m1} has a high mean value.
right: t_2 is longer. The induced voltage U_{m2} has a lower mean value.
The area corresponding to the product of voltage and time does not depend on the speed of change.

The induced voltage increases,
- when the difference of flux increases, i.e. when df increases,
- when the speed of change increases, i.e. when the df is reduced
- when the number of turns (N) is increased.

The induced voltage in a coil can be calculated by the formula

$$U = \frac{d\Phi}{dt} * N$$

This is the basic formula for the electromagnetic induction and it can be applied to any application, where voltage is generated by the movement of a inductor in a magnetic field.

Some practical uses of induction by mechanical movement:

- generators
- pick-up,
- dynamic microphones, etc.

The integral of the induced voltage over time gives an information about the flux of the magnetic field.

The magnetic flux can thus be defined by the voltage-time integral it produces in a coil. This is done for the unit of the magnetic flux, Weber (Wb):

$$1\mathrm{Wb} = 1\mathrm{V} * \mathrm{s} / N$$

The magnetic flux of one weber will induce in a coil of 1 turn a voltage of 1V, if the flux is reduced to zero within 1 second at a constant rate.

So the magnetic flux Φ is a magnetic quantity, which is proportional to the electrical quantity of voltage. Thus also the flux density B is proportional to voltage.

Remember that the magnetic quantity of field strength H is proportional to the electric current.

The somewhat strange value of the dielectric constant µo is selected just in such a way, that the magnetic and electric units match with the MKS-system.

3. Self Induction

When a magnetic field is produced by a current through a coil, the resulting flux can be calculated from the equation

$$H = I * \frac{N}{l} \qquad \text{and} \qquad B = m_r * m_0 * H \qquad \text{and} \qquad \Phi = B * A$$

thus

$$\Phi = I * \frac{N * m_r * m_0 * A}{l}$$

The flux in a coil is proportional to the current I and depends beside this only on the physical construction of the coil. If the current is time-varying, also the flux will be time varying.

Such a time varying flux will now induce a voltage in the coil itself, which will follow just the very laws found for the electromagnetic induction in the previous chapter. This kind of induction is called

SELF INDUCTION

as a voltage is induced due to a current in the coil itself and not due to foreign magnetic field.
A coil which is operated with self induction is called an INDUCTOR.

The voltage induced by self inductance can be calculated from the law for the electromagnetic inductance, where the flux Φ is as expressed above:

$$U = \frac{d\Phi}{dt} * N \qquad \text{and} \qquad \Phi = I * \frac{N * m_r * m_0 * A}{l}$$

The self-induced voltage in an inductor therefore depends on the rate of change of the current and on the physical construction of the coil.

$$U = \frac{dI}{dt} * \frac{N^2 * m_r * m_0 * A}{l}$$

Note that the number of windings N is to be considered with its square. This is due to the fact, that the number of winding affects the produced flux and the induced voltage at the same time.

The second term in this formula, which describes the physical construction, is a constant for a coil and is given the name

INDUCTANCE L

$$L = \frac{N^2 * m_r * m_0 * A}{l}$$

The inductance depends on

- the square of the number of windings. Thus when the number of windings of a coil is doubled, its inductance is 4 time larger,

- the effective area A (cross-sectional area) of the coil,

- the core material (μ_r),

- the length of the magnetic path of the flux.
  If the coil has a core, it is the length of the magnetic path of the core. The shorter the magnetic path, the higher the inductance.

When the flux density reaches the saturation point of the core, the inductance will decrease because μ_r decreases.

This risk of reaching saturation is especially present in coils or transformers that carry DC with superimposed AC. The DC-magnetisation shifts the flux density towards saturation. The risk of saturating the core can be reduced by providing an AIR-GAP of 0.1mm...1mm. The total µ of the core is thereby reduced and with the same field strength, less flux density is reached.

If we look at the above formula for L we see that it consists of parameters of the core (μ_r, A and l) and a parameter of the winding (N).

The parameters for the core can be combined in the so-called A_L factor:

$$A_L = \frac{m_r * m_0 * A}{l}$$

As the core is normally industrially produced the manufacturer will specify the A_L value of a core.

When a coil is then produced with this core, the inductance can be calculated as:

$$L = A_L * N^2$$

The required number of windings for a given inductance is calculated as:

$$N = \sqrt{(L / A_L)}$$

4. Losses in coils

In the same way as the capacitor stores electrical energy in an electric field, the inductor stores electrical energy in a magnetic field. The ideal inductor should not consume any electrical energy, but should be able to feed all of its stored energy back to the circuit.

Practically coils will consume a part of the stored energy. The losses occur partly in the coil and partly in the core and are referred to as
COPPER LOSSES and IRON LOSSES.

Copper losses can be represented by a series resistor to the inductor. The core losses do not occur in the electric path and can therefore either be represented by a parallel or a series resistor to the inductor.

The losses have different physical reasons:

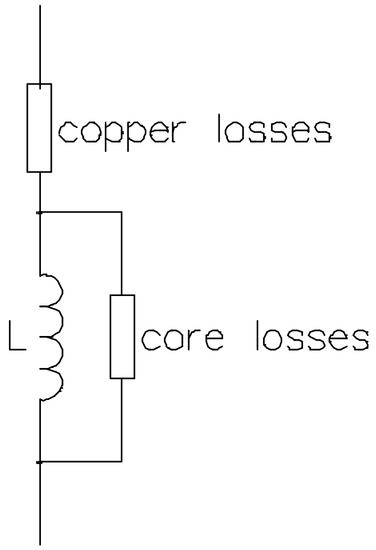

Fig. 4.1.
The losses in a coil consist of copper (coil) losses and iron (core) losses. They can be represented by resistor in series and in parallel to the inductor.

Coil Resistance:

Every coil has an ohmic resistance, the resistance of the copper wire. This resistance converts electrical energy into heat. This energy is applied to the coil, but is not stored, is therefore lost.

Skin effect:

At high frequencies the current tends to flow only on the surface of the conductor. Thus the effective c.s.a. of the coil wire is reduced and the resistance of the coil is further increased, causing more losses.

The effect is reduced by using litz wire (up to 3 MHz):
The conductor is made up of a great number of thin insulated wires.

Note: When repairing litz wound coils, every individual wire must be carefully scraped before soldering the litz wire.

Magnetizing losses:

If AC current is applied to a coil, the core material must be constantly magnetised and demagnetised. This produces "magnetic friction" within the core material, which produces heat and requires energy.

The magnetising losses depend on the shape of the hysteresis curve:
The area enclosed by the hysteresis loop is proportional to the magnetisation losses in the core material. Low remanence and in particular low coercive force are required. In order to keep the magnetizing losses as small as possible, core material with a "slim" hysteresis loop will be selected.

The losses occur with each cycle of the applied signal. So the losses will increase proportional with the frequency.

Eddy current:

In core material which is an electric conductor (e.g. iron), magnetic field changes induce currents in the core. Such currents can be high, if the resistance of the core is low. This results in heating of the core and consumes energy. These losses increase with frequency because the voltage induced in the core increases with frequency.

To avoid eddy current losses, the flow of current in the core must be prevented. There are two ways to achieve this:

- use of non-conductive core materials:
These are the so-called ferrites, which are sintered metal-oxides which are magnetic but non-conductive.

- use of laminated cores:
Instead of solid iron the cores are constructed of laminated sheets with insulated surfaces. So the voltage induced in the core will find no closed path and the flow of current is prevented.

Stray fields:

Not all magnetic field may pass through the coil only, but some may stray into the vicinity. This may induce voltages and currents in adjacent metal structures (e.g. chassis).
These losses increase with frequency.
Remedy: Constructional care.

5. Constructions of Coils

Only few coils are produced as ready-made devices which can be sold off the shelf. Most coils are produced to specifications or are self made using standard cores. The dimensioning will be done according to tables of data sheet. See chapter 3.6..

5.1. types of cores

The most important characteristics of the coil will depend on the core. Therefore the selection of a suitable core is the first and most important step when designing a coil.

The following types of cores are available:

Laminated cores:

These are constructed of standardized transformer iron sheets. Different types of sheets each with a standardized variation of sizes are available on the market.
(For a list of M-types refer to chapter 4., "Design of transformers".)

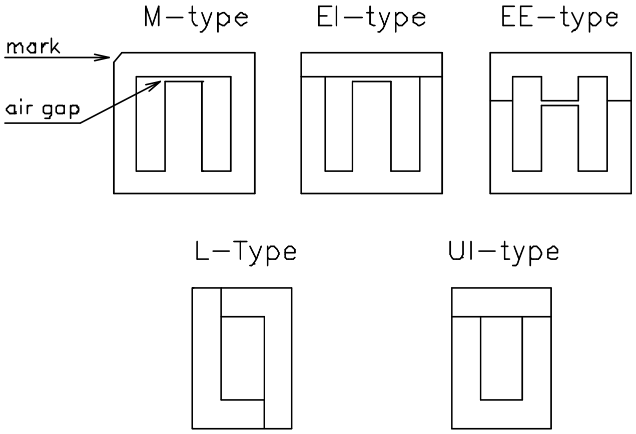

Fig. 5.1.1.
Some of the different types of laminated iron sheets available as core materials for coils and transformers

Laminated cores can be constructed with and without air gap. The transformer sheets normally have an air gap of 0.1mm to 0,5mm on the centre leg. If the sheets are assembled in such a way, that the air gaps of all sheets are on one side, the core will have an air gap. If the sheets are assembled alternating, so that the air gaps are on different sides, the core will have no effective air gap.

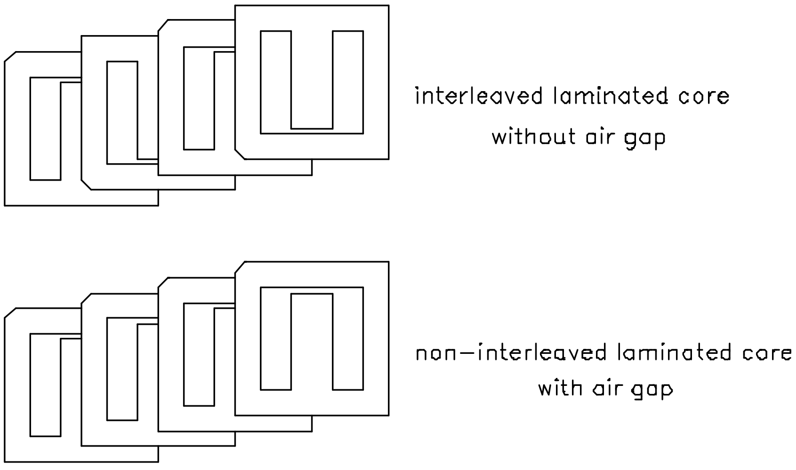

Fig. 5.1.2.

By assembling the sheets of a core with alternating direction, the air gap of the sheets will not be effective.

Ferrite Cores:

A big variety of different ferrite materials and different shapes of cores are available on the market. Ferrite cores are made of ceramic oxides, which have the advantage of very high resistivities and therefore producing low eddy current losses.

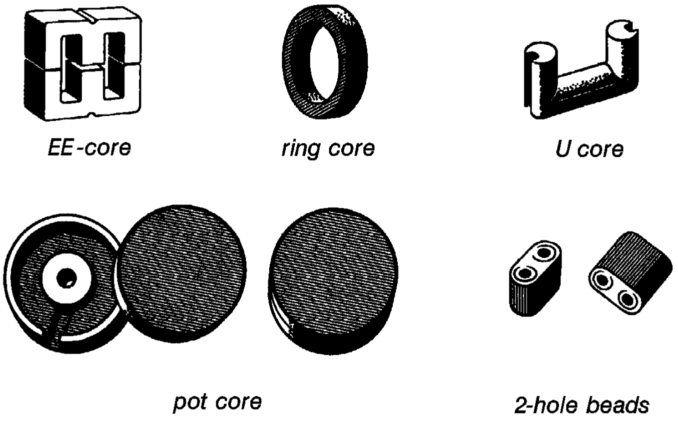

Fig. 5.1.3.
Some of the ferrite core types available on the market.

For the individual construction of coils pot cores are useful, because they provide relatively high AL values, they are easy to assemble, they can be made adjustable and they are available with and without air gap.

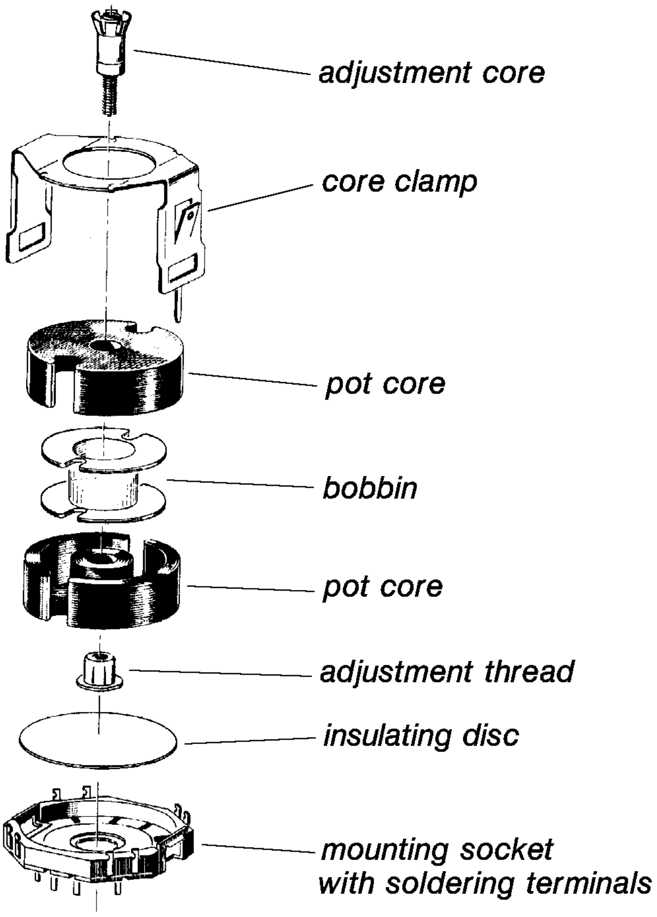

Fig. 5.1.4.
Construction of a ferrite pot core.

5.2. Selection of Cores

When selecting a core for an inductor the following parameters have to be considered:

The required inductance L:

Depending on the required inductance different types of cores can be selected:

Low inductance (µH):
No core at all (air coil), a bar core or a ferrite bead may be sufficient.

medium inductance (mH):
Ferrite cores with closed magnetic path will be preferred,
e.g. pot cores, EE-cores, U-cores, ring cores.

high inductance (100mH - H):
Here laminated iron cores will be used.

Frequency Range:

Low frequencies (10Hz - 100Hz):
Entirely laminate iron cores will be used.

Audio frequencies (20Hz - 20kHz):
Mainly laminated iron cores with very thin sheets (.3mm) are used. For low inductance values (<100mH) also pot cores can be used.

High frequencies (20kHz - 1MHz):
Varies types of ferrite cores are used depending on the applications.

Very High Frequencies (>1MHz):
Open cores (bar cores, beads) or air coils are used.

Required Q-Factor:

The required Q-factor (or allowed losses) will have an influence on the selection of the core material (iron or ferrite, types of ferrite) as well as on the size of the core. The larger the core, the lower the flux density, the lower the losses.

Generally: A high Q-factor requires a larger core.

AC-Current loading:

Depending on the current the wire will be selected. Thicker wire requires a larger window and thus a larger core. Furthermore the current influences the flux density. Therefore the larger current requires the larger c.s.a. of the core.

Generally: The larger the current, the larger the core.

DC-Current loading:

When a d.c. current flows through a coil it can produce magnetic saturation of the core. To prevent this, the core should have an air gap. The air gap will strongly reduce the μ_r (and therefore the A_L) of the core, this will require a larger core.

Generally: DC currents will require a larger core.

5.3. Construction of the Windings:

The windings of a coil will normally be made on a bobbin or shell. The bobbin will provide easy production of the winding, protection of the wires and insulation from the core. The bobbin will reduce the space available in the window of the core. The number of turns that can be applied on the bobbin will depend on the diameter of the wire (including the insulation lacquer!), the width and the height of the core and the amount of additional insulating material required.

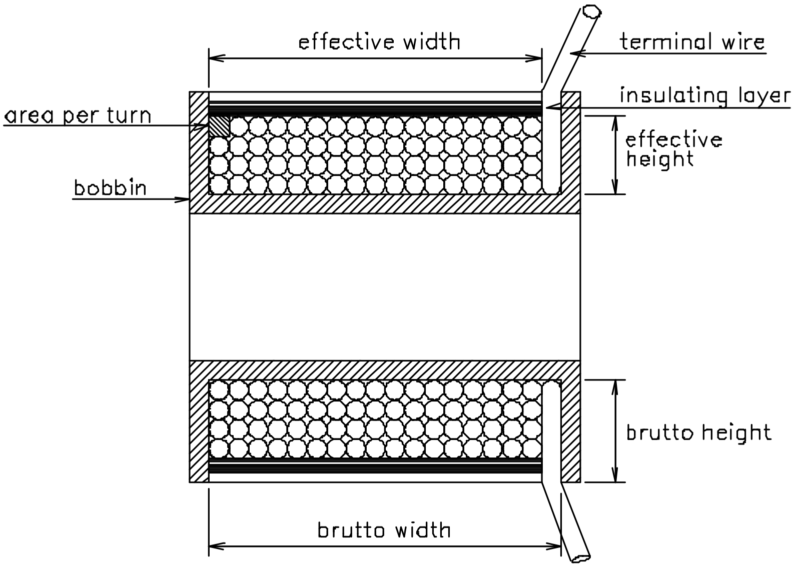

Fig. 5.3.1.
The number of turns that can be wound on a bobbin depend on the dimensions of the bobbin and the diameter of the wire, and the space required for further insulation and the terminal wires.

6. Design of Standard Inductors

When we want to make an inductor, we will normally use an industrially made core. When such cores are used information about the cores (data sheets) must be available.

For audio frequencies ferrite pot cores are suitable to cover a wide range of inductance. The inductors may be adjustable or non-adjustable. This chapter will describe the steps you have to follow when designing and building an inductor using pot cores.

Step 1: Selection of the core materials.

There are different types of ferrites available, where each material is suitable for a different frequency range. If there is a choice of different core materials, the one producing minimum core losses at the required frequency range should be selected.

The core losses will depend on the inductance of the coil. Therefore the data sheets will relate the losses (tanä) to the initial permeability (μ_i) to allow the selection of the optimum material.
(The initial permeability µi is the relative permeability of the core material for low values of H, so around the initial value of H)

Procedure:
Refer to the diagram showing tanä/μ_i as function of frequency.
Select the core material with the lowest losses at the required frequency.

Step 2: Decide about the air gap.

Pot cores are available with different air gaps.
The air gaps serves two purposes:

1. To avoid saturation of the coil if d.c. current flows through the coil.
2. To make the coil adjustable with an adjustment screw.
   The wider the air gap, the wider the adjustment range of the coil.

If any of these two criteria require an air gap, select its required width. Remember that any air gap will reduce the A_L value strongly. Cores without air gap have relatively high tolerances of the A_L value.

Step 3: Select the suitable core size.

Pot cores are available with different sizes (diameters) and different air gaps. Both will have an influence on the A_L-value and the absolute loss factor of the core.

General rule: the larger the core, the lower the core losses.

The data sheets will give the A_L value for the selected core size and air gap.

Furthermore the data sheets give a value for the effective permeability μ_e for the selected core. This can be used to calculate the effective core losses:

$$\tan d_{core} = \frac{\tan d}{m_i} * m_e$$

Step 4: Select the suitable adjustment screw.

A variety of adjustment screws are available for each type of core, each for different frequency ranges. Select a suitable screw from the data sheets. The data sheets will give the range by which the inductance of a certain coil can be varied (10% to 20%).
The A_L value of the core will be increased by this value.

The middle position of the adjustment will be at half of the adjustment range.
E.g. 16% adjustment range: middle position at 8% increase of A_L.
The effective A_L value of the core can be increased by this amount.

Example:
From step 3: A_L value 630nH,
Variation range of core: 16%
Add 8% to 630nH = 680nH. This is the effective A_L value to be considered for the design. The coil can than be adjusted by ±8% from its nominal value.

Step 5: Calculate the required number of turns.

The required number of turns can be calculated from the formula

$$N = \sqrt{(L/A_L)}$$

Remember to use the effective A_L-value from step 4 when using an adjustment screw.

Step 6: Determine the Suitable wire resistor.

The wire for the windings should be as thick as possible to minimize the coil losses. But its diameter is limited by the space available on the bobbin. The maximum diameter that can be used to fill the bobbin fully can be calculated from the formula

$$D = \sqrt{(W * H/N)}$$

With

D	diameter of the wire including its insulation
W	effective width of the bobbin
H	effective height of the bobbin
N	number of turns

The data sheets for the core materials also have nomograms to read the maximum diameter of the wire directly.

Step 7: Calculate the coil losses.

At audio frequencies the coil losses will mainly be caused by the wire resistance. The wire resistance can be calculated by the formula

$$R = \frac{N * l_N * mm}{56000 * A}\Omega$$

With
R resistance of the coil wire (copper)
N number of turns
l_N mean length of one turn (in mm!). The value can be found in the data sheets, or can be calculated as square of mean bobbin diameter divided by π/4.
A c.s.a. of the wire (in mm^2). When calculating the area from the wire diameter. Note that only the copper diameter has to be considered!

In the data sheets also the A_R-value for the bobbin is given. It can be used to calculate the resistance of the winding:

$$R = A_R * N^2$$

Note that this formula will only give correct values, if the maximum wire diameter was used and the bobbin is really fully used.

The coil losses can then be expressed as loss factor tanδ by using the relationship

$$\tan\delta_{coil} = \frac{R}{2\pi * f * L}$$

Step 8: Calculation of total losses.

The total losses consist of the core losses and the coil losses. The total losses can be found by adding up these losses:

$$\tan\delta = \tan\delta_{core} + \tan\delta_{coil}$$