The Effect of Faraday Ring (Shorting Ring) Usage on Voice Coil Impedance and Its Benefits

Draft Version

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August 2, 2005

Last Revised: August 7, 2005

Revision History:

August 2, 2005 - Initial Draft Version

August 4, 2005 - Added more explanation on the coupling ratio and leakage inductance, corrected a typo in equation (21), and also some grammar and spelling corrections.

August 7, 2005 - At one place, value of leakage inductance was typed in as 0.59mH instead of 0.059mH.

August 13, 2005 - Some grammar corrections and better language usage at parts of the document and also added equations (20a) and (20b).

Introduction:

Some loudspeaker drivers are designed with a ring made from a nonferrous and high conductivity material that is placed in to the motor assembly with an orientation that it is coaxial with the voice coil. These rings are commonly called as *Faraday rings*, or *short-circuit rings*, or *shorting rings*. The name *Faraday ring* comes from the Faraday law in physics, which explains how the ring works in a speaker motor. *Short-circuit ring* or *shorting ring* names refer to the fact that these rings are single turn windings that are short circuited. But not only they are short circuited windings, they also short circuit the changing magnetic flux that passes inside them. The short-circuit and shorting ring name may also be referring to this aspect of them as well, which is actually a consequence of them being electrically short circuited windings. In any case, we will use the term *shorting ring* to refer to them here on.

In this document the effect of these shorting rings on voice coil impedance will be investigated by using simplified approximated models of the loudspeaker driver motor parts. A few examples with calculations of the voice coil impedance will also be given. Because these examples will be based on highly approximated and simplified models, they will be only for illustrative purposes to convey the idea of how they work, obviously not adequate for any real design work, which requires far more accurate modeling.

In practice, the exact placement, shape and the number of these shorting rings in a motor assembly vary from design to design. Some of them are on the base of the pole piece, some cover the pole piece as a sleeve, some are wide and cover the inner surface of the magnet, some are two rings that sandwich a T shaped pole piece from above and below, etc. A shorting ring which is a coaxial sleeve with its radius equal to inner radius of the voice coil and with a length that covers at least the over all excursion range of the voice coil, has the most effect on the impedance of the voice coil than other ring configurations that are used. Because of this and since this document is on the effect of shorting ring on voice coil impedance, the shorting ring investigated here will be of this kind. Understanding the working of such case of a shorting ring, will also lead to understanding the workings of the other configurations, because the basic physic principles that explain their working are all the same.

Diamagnetic, Paramagnetic, Ferromagnetic, Non-ferromagnetic Materials and Permeability:

Based on their inherent properties, different materials react differently when they are subjected to an externally created magnetic field. Some materials when subjected to an external magnetic field, generate a magnetic field of their own which is in opposite direction to the applied field, which results in a decrease of the net magnetic field. Such materials are called diamagnetic. Some other materials generate a field that is in the same direction of the applied field, these are called paramagnetic. There is a third group of materials that are called ferromagnetic, which fall into the paramagnetic group by definition, i.e. they generate a magnetic field of their own when an external magnetic field is applied to them which increases the net magnetic field. But the way they do this is unique and the net field increase they provide are very high. They do this by aligning the highly magnetic dipoles found in them with the externally applied magnetic field direction. Iron, Nickel, Cobalt and most alloys that contain these elements are ferromagnetic. Any material that is not ferromagnetic is called a non-ferromagnetic material, regardless whether it is diamagnetic or paramagnetic.

Permeability, which is denoted by the letter μ, is a measure of the amount of increase (or decrease) in magnetic field that a material provides when subjected to externally created magnetic field. Diamagnetic materials have negative, paramagnetic materials have positive permeability constants. Ferromagnetic materials have high positive permeability numbers, but their permeability is not constant, it depends on the strength of the field they are subjected to. Vacuum has a defined constant permeability number. Relative permeability is defined as the ratio of the permeability of a material to the permeability of vacuum. Air has a relative permeability which is practically 1, meaning air’s permeability is same as vacuum. A relative permeability of 1 denotes that the existence of the material in the magnetic field neither increases nor decreases the field. In other words the existence or non-existence of the material with a relative permeability of 1 doesn’t have any effect on the externally created magnetic field; that is if externally generated magnetic is constant, not changing. The effect of changing magnetic fields are more interesting than static magnetic fields which we’ll come to those later.

Most materials have a relative permeability close to 1. Copper and Aluminum both have relative permeability numbers that are practically 1. Since air's relative permeability is also 1, this means if air is replaced with copper or aluminum in a magnetic circuit that has only constant static magnetic field, there will be no change experienced. We mentioned copper and aluminum here, because they are the most commonly used shorting ring materials.

Permanent Magnets, Solenoids, Magnetic Field, Magnetic Flux:

Magnetic fields are generated either by permanent magnets, or by electric current. Permanent magnets are ferromagnetic materials whose magnetic dipoles are highly aligned and have high resistance to reorientation and realignment of these dipoles in them. Permanent magnets are used to provide static constant magnetic fields in electric motors, speaker drivers, etc.

Electric current is another way to generate magnetic field. As a current flows through a wire, it generates a magnetic field around it. This is defined by Amperes' Law in physics, and we won't go into the details of it here. The most used wire form that is used in magnetic circuits is a solenoid. A solenoid is made by tightly winding a wire over a cylinder shaped former. The nice thing about them is, when a current passes in the solenoid's wire, it creates a magnetic field that is constant inside the center of the solenoid and is zero outside the center of it. The magnetic field generated by a solenoid looks like a magnetic field generated by a bar magnet. The longer the solenoid, the bigger of a volume inside of it through the center has constant field strength (and a zero field region outside of it through its center). Voice coil of a speaker driver is also a solenoid, but its length is not very big with respect to its radius.

Magnetic field is usually denoted by the capital letter B and it has a unit of Tesla, or T in short. 1 Tesla is 10,000 Gauss, which is another commonly used magnetic field unit.

Magnetic Flux is defined as the amount of magnetic field strength that falls into an area. For instance the magnetic flux inside a solenoid's center, which has a constant field of B, is equal to $\pi r^2 B$ where r is radius of the solenoid. In other words the flux is equal to the cross section area of the solenoid times the magnetic field in there. The symbol Φ is used conventionally for magnetic flux. The unit for magnetic flux is Weber, or Wb in short.

Magnetic Field Force on Currents:

A magnetic field generates a force on a moving charged particle proportional to the perpendicular component of the magnetic field to the velocity direction of the moving charge. The direction of the generated force is found by the "right hand rule" which can be found in any physics text that deals with electromagnetism. Assuming the magnetic field B is already perpendicular to the velocity direction of the charged particle with a charge of q and speed v, the amount of force applied on the charge is:

$$F = q\ v\ B \qquad (1)$$

Since a current is made up of moving charged particles, by the same mechanism, a force gets applied to a wire of length l, which carries a current of i, under a magnetic field of B that is perpendicular to the wire; which has the amount defined by:

$$F = B\ l\ i \qquad (2)$$

This force is what causes a loudspeaker's voice coil to move, which in turn moves the cone that is attached to the voice coil. We will get back to in this in the following sections after we give a description of the parts of a speaker's motor assembly.

Faraday's Law and Induced Electromotive Force (EMF):

An aspect of electromagnetism, which is called Faraday's Law, is essential to understanding the effects of shorting rings in speaker drivers; hence the Faraday Ring term is used for them. The Faraday's Law states that, when a magnetic flux changes, it generates an electromotive force on the material that the flux passes through. Electromotive force (EMF) is nothing but the good old voltage quantity. If the material that an induced EMF is generated is a conductive material, and its ends are connected, it results in a current that flows in it. This is called the induced current. The direction of the induced current is also important. The direction of the induced current is always such that, the induced current generates a magnetic flux that opposes the magnetic flux that originally caused the induced the current. (Remember from previous sections that when a current flows, it always generates a magnetic field of its own). In other words the induced current always tries to cancel the magnetic flux that induced it. This aspect of the induced currents is called the Lenz's Law. The following expression defines both the Faraday and Lenz's Laws:

$$V_{emf} = - d\Phi/dt \qquad (3)$$

It says that the induced EMF is equal to the rate of change of the magnetic flux, which is the Faraday's Law, and the minus sing in there says that the induced current as a result of V_{emf} will always oppose the flux that induced it: the Lenz's law.

If the changing flux is going through inside a solenoid, because solenoid is made up of many turns, the net V_{emf} on the ends of the solenoid's wire will be equal to :

$$V_{emf} = - N\, d\Phi/dt \qquad (4)$$

where N is the number of windings that is on the solenoid, $d\Phi/dt$ is the rate of change of the flux.

An induced EMF can also be generated if the flux is constant but the wire is moving in it. This can be explained by extending the wire's ends to outside of the flux area. Then, since when the wire moves, the amount of magnetic field area that is enclosed by the wire and its extensions changes, the flux that the wire and its extensions enclose changes. This causes an EMF to be induced on the wire. Another way of explaining this is by taking into consideration that when the wire moves, the charged particles that are inside the wire are also moving with the wire. As written above in (1), a force is generated on a charged particle that moves in a magnetic field. This force pushes the positive charged particles to one end of the wire, and negative charged particles to the other end of the wire, resulting an EMF being generated between the ends of the wire.

Whichever way it is explained, the resultant formula that describes this aspect of electromagnetism is:

$$V_{emf} = B\, l\, v \qquad (5)$$

where B is the magnetic field perpendicular to the wire, which is of length l, and moves with a velocity v which is also perpendicular to the magnetic field and to the length of the wire.

Inductance and Induced EMF

Inductance is a direct result of Faraday's law of induced EMF. As we know by now, when a current flows in a wire, it creates its own magnetic field. If the current is an alternating current, it means the magnetic field it is generating is also alternating, i.e changing in time. This means there is a changing flux being generated by the wire. This changing flux generates an induced EMF on the wire, which by Lenz's Law tries to create an induced current that opposes the flux that induced it. Which means in this case, the self induced EMF will always have an opposite polarity to the voltage that started the current on the wire. In an ideal solenoid[1] we can see how this is playing. The magnetic field inside an ideal solenoid is:

$$B = \mu\, i\, N / h \qquad (6)$$

where μ is the permeability of the core of the solenoid, i is the current flowing in the solenoid, N is the total number of turns of the solenoid and h is the height of the it. If the solenoid has a radius r, then the flux in it is:

$$\Phi = \pi\, r^2\, \mu\, i\, N / h \qquad (7)$$

Then the induced EMF on it is (since only i is changing with time):

$$V_{emf} = -N\, d\Phi/dt = -\pi\, r^2\, \mu\, (N^2 / h)\, d\, i/dt \qquad (8)$$

Here recall the definition of inductance, which is

$$V = L\, di/dt \qquad (9)$$

Which also means the inductance of an ideal solenoid is:

$$L = \pi\, r^2\, \mu\, (N^2 / h) \qquad (10)$$

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[1] This is only true for an ideal solenoid, it doesn't give accurate results for real solenoids, but for our purposes in this document it is good enough. This document isn't trying to accurately calculate results, it is only trying to explain "the how", not "the how and how much".

Recall also that the unit of inductance is Henry, in short H.

Here the purpose of generating the expression of an ideal solenoid was to illustrate that the inductance of it, is directly related to how much flux change it can generated by itself. This point will be very important when we explain the changing of the voice coil impedance by the existence of a shorting ring.

Parts of a Common Loudspeaker Motor Assembly:

An overview of the parts of a motor assembly is given in Fig1 and Fig2. These figures illustrate a very plain motor assembly with a straight pole piece and no shorting rings. Parts such as spider, cone, voice coil former, basket etc are excluded from these figures, because such parts are not relevant to our discussion[2].

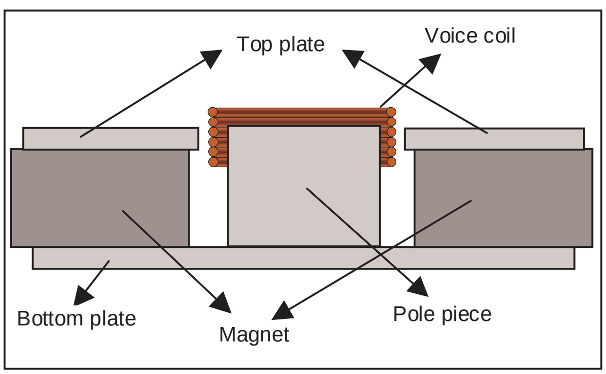

Fig 1: Cross section of a motor assembly

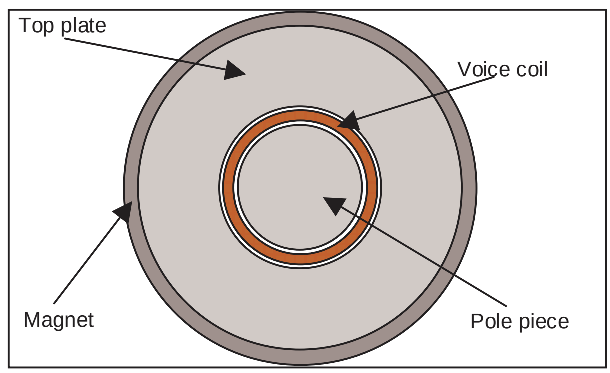

Fig 2: Top view of a motor assembly

The magnet has a disc shape and is usually made of ceramic. It supplies the static magnetic field required for the operation of the speaker. Top plate, bottom plate and pole piece are made of high permeability steel which is a ferromagnetic material. The voice coil is a short solenoid, which is made up of tightly wound wire in the shape of a

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[2] Excluding voice coil formers that are made from conductive materials such as aluminum. Such formers also have similar effects like shorting rings because of the eddy currents induced on them. We will not go into details of the effect of such formers to the voice coil impedance. These conductive formers are very thin, and are slit vertically to cut off electromagnetically induced current paths, but still some eddy currents gets induced on them which flow around their local paths. These eddy currents on such formers also considerably reduce the Q_{ms} of a driver, because the energy dissipated by the heat generated because of the internal resistance of the former to the eddy currents on them dampen the mechanical movement of the driver. Note that shorting rings are stationarily attached to the motor assembly, they don’t move with the voice coil like the voice coil former, so they don’t have any effect on Q_{ms}.

cylinder. The wire used in the voice coil is usually made of high conductivity material such as copper or aluminum, sometimes even silver. Since voice coil wire material has a relative permeability equal to 1, its mere existence doesn't interfere with the static magnetic field generated by the magnet as long as that field doesn't change, or no current flows from the voice coil, or voice coil doesn't move.

The Air Gap, Magnetic Field in the Gap, and How the Voice Coil Moves:

Fig 3 and Fig 4 depict how the magnet supplies its static field into the air gap where the voice coil is suspended by the surround (which is not shown). The blue lines show the virtual magnetic field lines inside the driver motor assembly, which are supplied by the magnet.

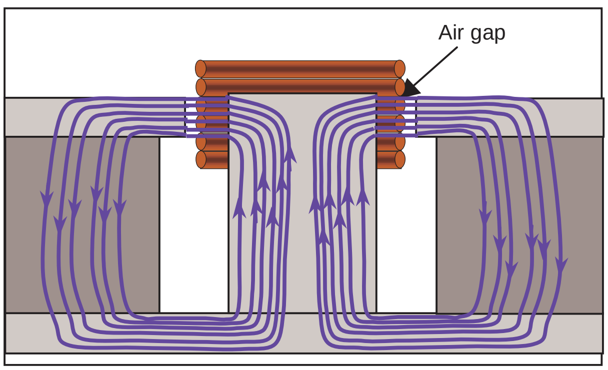

Fig 3: Static Magnetic fields in cross section view

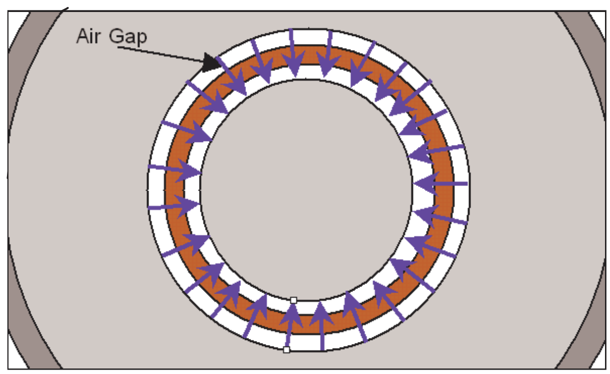

Fig 4: Top view of a motor assembly

The figures also show the air gap. The thickness of the air gap ideally would be equal to the thickness of the top plate. As can be seen from the figures, the magnetic field inside the air gap is always perpendicular to the voice coil wires, which means it will be also be perpendicular to the current flowing through the voice coil. If the magnetic field strength inside the air gap is constant with a value of B, the force that is generated on the voice coil when a current i flows in it is (using equation (2)):

$$F = B\, l\, i = B\, 2\pi r H_g\, (N/H_c)\, i \qquad (11)$$

where r is the radius of the voice coil, H_g is the height of the air gap, N is the total number of windings on the voice coil and H_c is the height of the voice coil. $H_g(N/H_c)$ gives the number of windings inside the air gap. Since a single winding's length is equal to $2\pi r$, $2\pi rHg(N/H_c)$ is the total length of the wire that is in the air gap, which is subjected to the *B* field. And hence the voice coil is accelerated back and forth as the current flowing through it changes its direction with the music signal applied to it by the amplifier. This is how the loudspeaker turns electric signals into sound waves. The voice coil is accelerated in proportion to the current, which also accelerates the cone of the speaker, which in turn accelerates the air that is around the cone causing a pressure change in air (resulting in sound waves being radiated from the cone) that is proportional to the current flowing inside the voice coil.

One thing to notice here is that, as long as the amount of excursion that the voice coil experiences in one direction doesn't go beyond $(H_c – H_g)/2$, which is called X_{max}, there will always be an equal number of windings inside the air gap, even though the voice coil moves. So this means the force applied to the voice coil for a given amount of current passing through the voice coil is independent of the position of the voice coil as long as the voice coil position doesn't go beyond X_{max} in either direction.

The figures 3 and 4 draw an idealistic case, where the magnetic field only occurs inside the air gap, and no field occurs outside of the air gap. We will assume this idealistic case in our investigation of the shorting rings effects. We will also assume that the static magnetic field strength inside the air gap, which is supplied by the magnet, is constant through out the air gap and equal to *B*. In reality both of these assumptions are not correct. There are always some "fringe" fields that exist on the outsides of the air gap, and the strength of the field inside air gap changes depending on the exact location inside the air gap. It especially changes on the direction parallel to the pole piece axis, i.e. the direction that the voice coil moves back and forth. These are sources of distortion in a loudspeaker, because the force applied to the voice coil becomes dependent to the voice coil's position inside the gap. Investigation of this distortion falls outside of the scope of this document.

A Word on Induced EMF and Q_e:

In the previous sections, it was said that when a wire moves inside a magnetic field that is perpendicular both to the wire and the movement of the wire, an induced EMF force gets generated on its ends, i.e. a voltage source occurs on the ends of the wire, which was expressed by equation (5) above. The part of the voice coil which is inside the air gap is also subjected to a magnetic field of B that is perpendicular to the voice coil wire along its length. So, when the voice coil moves, whose direction will always be perpendicular to the magnetic field and the windings of itself, an induced EMF gets generated at the ends of the voice coil leads. We can easily find its value by using (5):

$$V_{emf} = B\,l\,v = B\,2\pi r H_g\,(N/H_c)\,v \qquad (12)$$

Note here that the V_{emf} is dependent a) on the field strength, which is supposed to be constant in an ideal motor no matter what, b) the length of wire that is subjected to this field and c) the velocity of the wire. The only variable in the equation of V_{emf} is the velocity of the voice coil as long as voice coil doesn't move more than X_{max}. The reason to bring this up is, sometimes the effect of the shorting rings are tried to be explained by connecting their functioning to this induced EMF of the voice coil generated by the movement of the voice coil. When we give the explanation of how the shorting rings react with the rest of the motor below, it will become clear that shorting rings can only have an indirect effect on the V_{emf} generated by the movement of the voice coil.

Because of the Lenz's Law mentioned earlier, the polarity of the movement generated V_{emf} is always opposite to the voltage that created the current that moved the voice coil. Without going into the details of voltage/displacement equations of a driver, this works like a damper on the voice coil movement. It is this mechanism that provides the electrical damping, i.e. Qe of the driver parameter.

Voice Coil Inductance And The Detrimental Effects that are Associated With It:

As depicted in Fig1, voice coil is a solenoid that has partially iron and partially air core. In a crude approximation the part that is immersed into the pole piece can be considered as iron cored, and the remaining part as air core. With such a crude approximation, we can calculate the inductance of the voice coil by assuming it is made up of two solenoid inductors in series, one is air cored, the other iron cored. In reality it is more complex, since the windings in the air core part and windings in the iron core part will mutually affect each other. But as mentioned earlier, the aim of this document is to give a good explanation of the how, not to give ways to calculate accurate results. As long as the approximation made works to explain the how, the crudeness of it is not much important for the focus of this document.

We know the air's relative permeability, which is practicallly1. We don't exactly know the pole piece iron's relative permeability, and because it is a ferromagnetic material. Such materials don't have a constant permeability number which was mentioned earlier. The permeability of the iron pole piece is dependent on the amount of magnetic field applied on it. In a speaker motor, there is always the static magnetic field applied to the pole piece sourced by the magnet. So we need to look at what is called the B-H curve of the material that the pole piece is made from to find the permeability of it in a particulur motor. In such a B-H curves, *H* corresponds to the amount of externally applied magnetic field but divided by permeability of vacuum (μ_0), and *B* corresponds to the net magnetic field generated by the material. *B* in those curves is the sum of externally applied field that is equal to $\mu_0 H$ and the magnetic field generated by the alignment of the magnetic dipoles in the ferromagnetic material that is exposed to the externally generated magnetic field. The slope of the B-H curve at a given point gives the absolute permeability of the material at that magnetic field.

Fig5a displays an imaginary B-H which at least in shape resembles real world B-H curves of commonly used soft iron materials that the pole pieces are made from. In Fig5a, a green tangent line is drawn on the blue B-H curve and it is tangent to the curve where B is equal to 0.8T. Assuming the pole piece has a 0.8T magnetic field on it as a result of the magnet, the slope of the green line gives the permeability value of the pole piece in such a particular driver. In Fig5b shows the permeability (μ) vs net magnetic field (B) curve that is obtained from Fig5a. The permeability values in Fig5b is equal to the slope of the curve in Fig5a. Fig5b better illustrates that the permeability of such a material is dependent on the magnetic field strength.

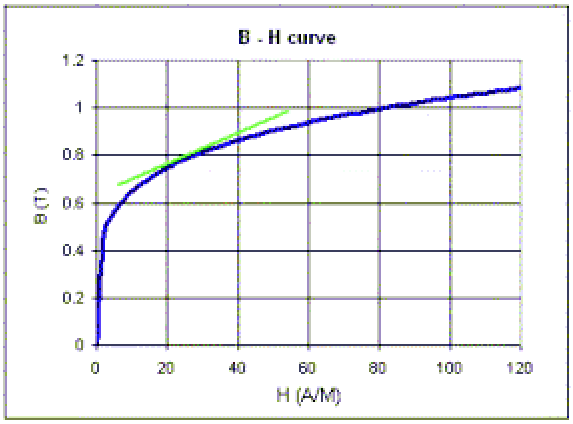

Fig 5a: An imaginary sample B-H curve

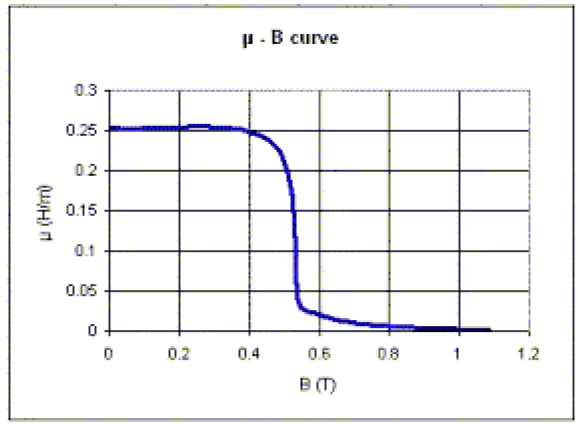

Fig 5b: Permeability (μ) – B curve

Using the permeability value that corresponds to 0.8T, which is our assumed magnetic field strength on the pole piece caused by the magnet, we can come up with the inductance value of the part of the voice coil that has pole piece as its core. But here comes the problems with the voice coil inductance. As current flows from the voice coil, being a solenoid with an inductance, it creates a magnetic field of its own. This field generated by the voice coil is added to the field that was generated by the magnet and delivered to the pole piece. In other words, the H value of the pole piece is now changed by the amount of magnetic field generated by the voice coil current. It means the B value of the pole piece will also change accordingly. But this really means a serious problem. When the B of the pole piece, i.e the net magnetic field on the pole piece changes, so does the B of the air gap, since the magnetic field in the air gap is carried there by the pole piece. This means the magnetic field strength inside the air gap that was supposed to be constant no matter what, is actually being modulated by the voice coil current. Depending on the direction of the voice coil current, the magnetic field on the pole piece and therefore on the rest of the magnetic circuit of the motor including the air gap, will either be increased or decreased. This all means the speaker will distort.

The modulation of the magnetic field on the pole piece, also modulates the inductance value of the voice coil. This is because the permeability value of the pole piece changes with changing B, as seen on Fig5b. When there was no current flowing in the voice coil, the only external magnetic field on the pole piece was coming from the magnet, and the net field on the pole piece was 0.8T. Then, we can call the point on the curve of Fig5b that has the value B=0.8T as the operating point. But as current flows in the voice coil, causing the B value to change, the operating point on the curve moves away from B=0.8T point. If the current generates a field that is in the same direction as the field of the magnet, the operating point moves to right on the curve, otherwise it moves to left. Since this means the changing of the permeability of the core of the windings that cover the pole piece, the value of the voice coil inductance becomes modulated by the voice coil current itself, again a source of distortion. The impedance of the voice coil is supposed to be a stable linear transfer function, not a changing nonlinear one. But this demonstrates that the voice coil impedance transfer function is not linear, because the voice coil inductance is not linear.

There is another aspect of the B-H curve, which is not displayed on Fig 5a that causes distortion. It is not displayed in Fig 5a, but ferromagnetic materials have hysterisis which means the B-H curve follows a different path while H value is increasing vs while the H value is decreasing. For the same reason explained in the previous paragraph this also is a source of distortion.

One remedy to the voice coil impedance distortions is to try to take the operating point on the μ -H curve where μ is constant over a wide range. There are two such regions on the μ -H curve, one is to the right which converges to full saturation of the pole piece, the other is close to the origin point. Both of these regions have straight lines parallel to the horizontal axis. Taking the operating point close to the origin is not a good choice, because it means less magnetic field strength on the air gap, which also means the driver will be less sensitive. The obvious choice would be to try to push the operating point as far to right as possible. But this requires a more powerful magnet, and the rest of the magnetic circuit such as the top and bottom plates should be able to carry the necessary flux to the pole piece to make it go up there. It appears that achieving this comes with a price tag, which requires expensive very high permeability metals and high power magnets to be used in the motor assembly. As we will see below, another solution is the use of the shorting rings to reduce these nonlinearity aspects of the voice coil inductance.

There is another nonlinearity problem with the voice coil inductance. So far we have assumed the voice coil wasn’t moving at all, when we talked about its inductance.

But obviously it moves as it generates sound waves. As the voice coil moves forward , i.e away from the bottom plate, the number of windings that have an air core increases and the number of windings that have an iron core decreases. As it moves backwards, the reverse happens. This means the voice coil's inductance will increase when its displacement is at negative excursion range, and will decrease when its displacement is at positive excursion range. This also results in distortion, because the voice coil inductance is supposed to be independent of the displacement of the voice coil, but in reality is changing with it. An elongated pole piece, or using an underhung, i.e. a voice coil whose height is less than air gap height, reduces this problem but they are not full remedies. For instance even if the pole piece is elongated, the top portion of the voice coil will still not be exactly symmetrical to the bottom portion in terms of magnetic materials around it. The bottom portion has the pole piece and then the bottom plate, but the top part only has the elongated pole piece and a top plate which is very close to the center of the voice coil, not to the end of it like the bottom plate. The same goes for the underhung motor configuration. Besides, with elongated pole piece and underhung configurations, it is likely that that there will be more mass of iron at the pole piece that is not close to full saturation. For instance, the B field on the elongated parts of the pole piece will be less than what it is at the parts of the pole piece that is close to the air gap where it meets with the top plate. This means inductance value modulation by voice coil current will be worse with such configurations. These motor configurations may be reducing the inductance modulation by excursion, but at the expense of increasing the inductance modulation by voice coil current. They also increase the average inductance value of the voice coil simply by making more of the windings to have iron core; which means the ratio of the reactance of the voice coil to the resistance of the voice coil increases. This exacerbates the inductance modulation problems, caused by both displacement and voice coil current flux, because the higher the ratio of the reactance of voice coil to the resistance of the voice coil, the more the inductance part of the voice coil have a say on the resultant current that flows in the coil, which eventually makes the speaker driver to produce sound waves.

Finally, the Shorting Ring Goes in to the Motor Assembly:

After laying down the required base material for the understanding of the workings of shorting ring, it is time to look at what do they do in a motor assembly. As explained in the introduction section, we will only look at a shorting ring configuration where a single ring as the shape of a sleeve that goes over the pole piece is used. For the sake of simplicity we will assume that the height of the shorting ring will be equal to the height of voice coil, and we will assume the voice coil is blocked from movement and is at its rest position, even though a current passes through it. Which means in this section we will ignore the voice coil inductance modulation by voice coil position. In practice usually, such a shorting is made with enough of a height such that the voice coil windings will always cover it, which makes it effective through out the whole excursion range of the voice coil, as can be seen in Fig 6. But assuming the height of the shorting ring equal to the height of the voice coil here will help us with simplifying some math.

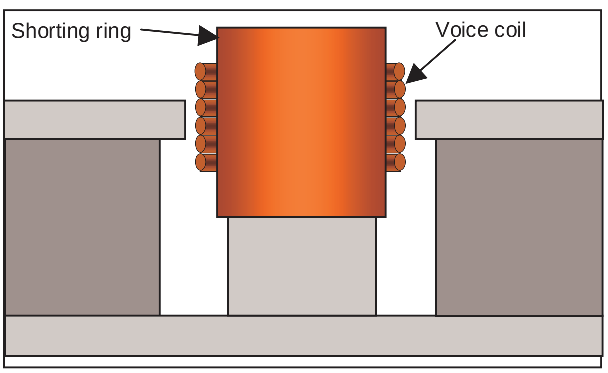

Fig 6: Shorting ring sleeve added to the motor

One way to look at the shorting ring is to think that the voice coil is a primary winding of a transformer, and the shorting ring is the secondary winding with a single turn and is short circuited. Familiarity from transformers tells us that if we short circuit the secondary winding of a transformer a high current will flow through the primary winding, which appears to the voltage supply that drives the primary winding as if the impedance of the primary winding has been reduced. The effect of the shorting ring on the voice coil impedance works exactly like this, and below we start showing it using the physics rules we had included in the earlier sections.

Lets assume that the air and iron pole piece core of the voice coil has an effective average permeability of μ_a. Then using equation (10) we can approximate the inductance of the voice coil to:

$$L_{vc} = \pi r^2 \mu_a (N^2 / H_c) \qquad (13)$$

where N is the number of windings of the voice coil and H_c is the voice coil height. This will be the inductance of the voice coil when there is no shorting ring[3].

Assuming the radius of the shorting ring is equal to the radius of the voice coil, the inductance of the shorting ring, L_{sr} ,will be same but with N = 1:

$$L_{sr} = (\pi r^2 \mu_a) / H_c \qquad (14)$$

L_{sr} is the inductance of the shorting ring when the voice coil is open circuited.

By Amperes' Law, when an alternating current flows in the voice coil, it will try to generate an alternating magnetic flux inside the coil, which will be seen by the shorting ring immediately since they are sharing the same internal volume. By Faraday's Law, this causes an induced EMF to appear on the shorting ring which causes an induced current to flow inside the shorting ring. Lenz's Law indicates that the current inside the shorting ring will be in opposite direction to the current inside the voice coil, because the induced current will always try to generate a magnetic flux of its own that will cancel the flux that caused the induction of it. The magnitude of the induced current on the shorting ring is dependent on the inductance of the shorting ring and the internal resistance of it in the direction of the induced current flow. In short, because the shorting ring cancels some of the flux otherwise would have been created by the voice coil, its existence decreases the

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[3] Here we are assuming that there was enough clearance in the air gap for the shorting ring to fit without reducing the radius of the pole piece. In reality because of the desire to achieve high sensitivity, a driver with a shorting ring in its air gap will have a lower diameter pole piece than same driver without the shorting ring, exactly by the thickness of the shorting ring used. In such a case the removal of some ferromagnetic material in order to fit the shorting ring will cause some reduction in the effective average permeability of the voice coil, and therefore cause a reduction in the voice coil inductance, but such a reduction effect will be very small compared to the inductance reduction that the shorting ring provides by the induced current on it. Besides, some configurations doesn't require any removal of ferromagnetic material and still the voice coil inductance dramatically decreases with the addition of the shorting ring(s), such as adding shorting rings to above and below a T shaped pole piece.

impedance of the voice. In order to see this relation more closely we need to take into consideration the internal resistances of the voice coil and the shorting ring first.

The internal resistance of the voice coil is a known quantity and is provided by the manufacturer as part of the driver's parameters. It can also be easily measured by an Ohmmeter that uses a DC current or voltage source[4]. We will call the internal resistance of the voice coil as R_e and call the internal resistance of the shorting ring to induced currents as R_{sr}.

The total alternating[5] magnetic field inside the voice coil at any given time will be the net sum of the magnetic fields generated by voice coil and shorting ring, called B_{vc} and B_{sr} respectively, so total magnetic field becomes:

$$B_T = B_{vc} - B_{sr} \qquad (15)$$

In (15) B_{sr} is subtracted from B_{vc} because the magnetic field generated by the shorting ring will always be in opposite direction to the magnetic field generated by the voice coil. Since the cross section area of voice coil and shorting ring is equal, which we'll call as A, the net alternating flux is:

$$\Phi_T = A\,(B_{vc} - B_{sr}) \qquad (16)$$

Then by using equation (6) and noting that the shorting ring is a single winding:

$$\Phi_T = A\,(((\mu_a\, i_{vc}\, N) / H_c) - ((\mu_a\, i_{sr}) / H_c)) \qquad (17)$$

where i_{vc} *and* i_{sr} are the currents of voice coil and shorting ring respectively. Then the rate of change of net alternating flux is:

$$d\Phi_T/dt = (A\,\mu_a/ H_c)\,((N\, di_{vc}/dt) - di_{sr}/dt) \qquad (18)$$

Now let's look at the electrical equation on the voice coil side:

$$V_{in} = i_{vc}\, R_e + V_{vcemf} \qquad (17)$$

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[4] A shorting ring doesn't have any effect on the voice coil, when the current flowing inside the voice coil is DC, because a DC current doesn't cause a changing magnetic flux, which means no current gets induced on the shorting ring.

[5] Note the usage of "alternating" magnetic field. Otherwise the total magnetic field should include the magnetic field supplied by the magnet, but that is a DC (static) magnetic field.

where V_{in} is the voltage applied to the voice coil and V_{vcemf} is the induced EMF on the voice coil caused by the changing net alternating flux inside the voice coil. By using (8) and (17) we can rewrite (18) as :

$$V_{in} = i_{vc} R_e + (N A \mu_a / H_c) ((N\, di_{vc}/dt) - di_{sr}/dt) \qquad (18)$$

Now let's look at the shorting ring side:

$$i_{sr} R_{sr} = V_{sremf} \qquad (19)$$

where V_{sremf} is the induced EMF on the shorting caused by the changing net alternating flux. Using (8) and (17) again, we rewrite (19) as:

$$i_{sr} R_{sr} = (A \mu_a / H_c) ((N\, di_{vc}/dt) - di_{sr}/dt) \qquad (19)$$

Now we have two linear differential equations (18) and (19) with two unknowns i_{vc} and i_{sr}. By replacing the value of i_{sr} from (18) into (19) and then using phasor method we come up with the impedance of the voice coil circuit which is equal to V_{in}/ i_{vc} which will be called as Z. Below we'll give the real and imaginary parts of Z and not the amplitude and phase expressions of it, simply because they are too long:

$$Real(Z(\omega)) = R_e + ((\mu_a^2 A^2 N^2 H_c^2 R_{sr} \omega^2) / (R_{sr}^2 H_c^4 + \mu_a^2 A^2 H_c^2 \omega^2)) \qquad (20)$$

$$Img(Z(\omega)) = \omega ((\mu_a A N^2 / H_c) - ((\mu_a^3 A^3 N^2 H_c \omega^2)/(R_{sr}^2 H_c^4 + \mu_a^2 A^2 H_c^2 \omega^2))) \qquad (21)$$

where ω is the angular frequency.

One interesting case would be to see the values of (20) and (21) when R_{sr} is zero, meaning shorting ring doesn't have any internal resistance. In such a case, $Real(Z(\omega))$ becomes R_e and $Img(Z(\omega))$ becomes zero, which means the voice coil impedance seen by the voltage source is pure resistance with a value of R_e. If we could come up with a zero resistance shorting ring, we would have been able to eliminate the voice coil inductance and make it pure resistive.

Another case to look at is when R_{sr} is infinite, meaning the shorting is open circuit, no current flows through it. In such a case $Real(Z(\omega))$ becomes R_e and $Img(Z(\omega))$ becomes zero $\omega ((\mu_a A N^2 / H_c)$ which is same as ωL_{vc}. This tells that when the internal resistance of the shorting ring is infinite, it won't have any effect on the voice coil impedance, which was an expected result, but provides a double check to the way we arrived at the voice coil impedance *Z*.

By using equations (13) and (14) , we can rewrite (20) and (21) as:

$$Real(Z(\omega)) = R_e + ((L_{vc}\, L_{sr}\, R_{sr}\, \omega^2) / (R_{sr}^2 + L_{sr}^2\, \omega^2)) \qquad (20a)$$

$$Img(Z(\omega)) = \omega\, (L_{vc} - ((\, L_{vc}\, L_{sr}^2\, \omega^2)/(R_{sr}^2 + L_{sr}^2\, \omega^2))) \qquad (21a)$$

Especially (21a) helps with seeing the reduction effect of the shorting ring on the effective inductance of the voice coil. We can also see from (21a) that as frequency goes to infinity, imaginary component of voice coil impedance goes to zero, regardless of the values of L_{vc}, L_{sr} or R_{sr}. As frequency decreases, R_{sr} becomes the limiting factor at the reduction of the imaginary part of the voice coil impedance. This means for the shorting ring to be effective in the lower frequencies, it needs to have a very low internal resistance.

Equations (20,20a) and (20,20b) are for an ideal case where the shorting ring is assumed to be fully coupled to the magnetic flux generated by the voice coil. In reality it misses some of the flux generated by the voice coil. We will look into this aspect more in the following sections where we will looking at some SPICE models to simulate the effect of shorting ring on voice coil impedance.

Internal Resistance of a Shorting Ring

In the previous section we have found out that the internal resistance of a shorting ring is critical to its effect on the voice coil impedance. So it is a good time to look at the resistance of a shorting ring to have a better idea what to expect from it.

The induced currents on the shorting ring flow inside them by making circles that are coaxial to the ring itself. This means the cross section area that these currents see is equal to $w_{sr}\, H_{sr}$, where w_{sr} is the thickness of the shorting ring, and H_{sr} is the height of the shorting ring. The total length of the induced currents travel is approximately equal to the mean of the outside circumference of the ring and the inside circumference, which is

$2\,\pi\,(r_{sr} - w_{sr}/2)$, where r_{sr} is the distance from the center of the ring to the outside of it. With this on hand, we can calculate the internal resistance of the shorting ring as:

$$R_{sr} = \rho_{sr}\,(2\,\pi\,(r_{sr} - w_{sr}/2))\,/\,(w_{sr}\,H_{sr}) \qquad (22)$$

where ρ_{sr} is the resistivity constant of the material that the shorting ring is made from[6]. Copper's resistivity constant is $0.017\text{x}10^{-6}$, aluminum's $0.0282\text{x}10^{-6}$, Iron's $0.1\text{x}10^{-6}$, and Stainless Steel's $0.72\ \text{x}10^{-6}$ ohm meters to give some perspective.

Using (22) we can calculate a somewhat typical shorting ring's internal resistance which is assumed to be 1mm thick, 2cm high and with a 2cm radius, which comes out to be 0.1mΩ.

A SPICE Example on the Effect of Shorting Ring to Impedance:

As mentioned above, the voice coil and shorting ring couple makes a transformer whose second winding is a single turn and is short circuited. A SPICE model[7] of this is drawn in Fig 7. The part that contains R_{e0} and L_{vc0} represents a voice coil without a shorting ring near it, and the part below that represents the same voice coil with a shorting ring. The internal resistance of the voice coil is chosen as 6 ohms, which a common figure for conventional drivers. For the inductance of the voice coil when there is no shorting ring around it, a value of 1mH is chosen. We assumed that the voice coil had 100 windings on it. Recall that we assumed the shorting ring's height and radius is equal to the voice coil's; then equations (13) and (14) tell us that the inductance of the shorting ring will be $1/N^2$ of the voice coil's inductance. For this reason the inductance of the shorting ring is assigned to the value of $1\text{x}10^{-4}$mH. We assumed a copper shorting ring with the shape given in the earlier section, which he had calculated the internal resistance of it to be 0.1m ohms, the value of which is used in the SPICE circuit model. Note the "*K Lvc1 Lsr 0.97*" SPICE directive that is used in the circuit. This links the two inductors, Lvc1 and Lsr, turning them into a transformer. The figure 0.97 is the coupling ratio between the two inductors. The highest value it can take is 1, which is for a perfect

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[6] This simple model of the internal resistance of the shorting ring ignores the "skin effect"; for a more thorough model see reference no 6.

[7] SwCAD III which is freely available from www.linear.com is used for the SPICE simulations

coupling. We used a 0.97 since we assumed the shorting ring is same size as the voice coil, which means they will be highly coupled.

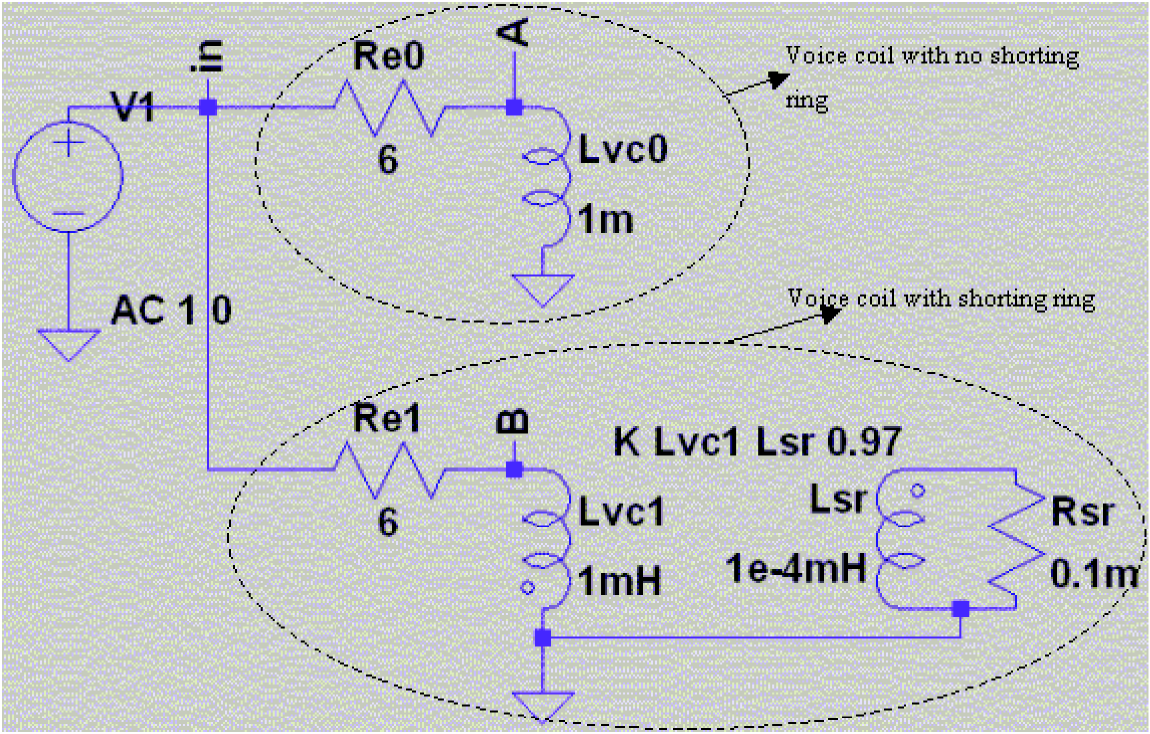

Fig 7: SPICE model for comparison the effect of shorting ring on voice coil impedance

Fig 8. below shows the simulation result of this circuit. The curve of V(in)/I(Re0), which is green, is the impedance of the voice coil without the shorting ring. It shows an expected impedance of a resistor in series with an inductor. The curve of V(in)/I(Re1), which is blue, shows the impedance of the voice coil when the shorting ring is added. The addition of the shorting ring effectively slows down the rise of the voice coil impedance. This can also be explained as the shorting ring reducing the inductance of the voice coil. But the effect of reduction of the voice coil inductance is frequency dependent. It would be more accurate to define the effect of the shorting as the changing of the voice coil impedance, rather than just reducing the inductance of it. The blue impedance curve is typically seen on drivers that use a long copper cap or a sleeve on the pole piece, which gives a good coupling ratio to the voice coil inductance, resulting in a very resistive impedance rather than an inductive one.

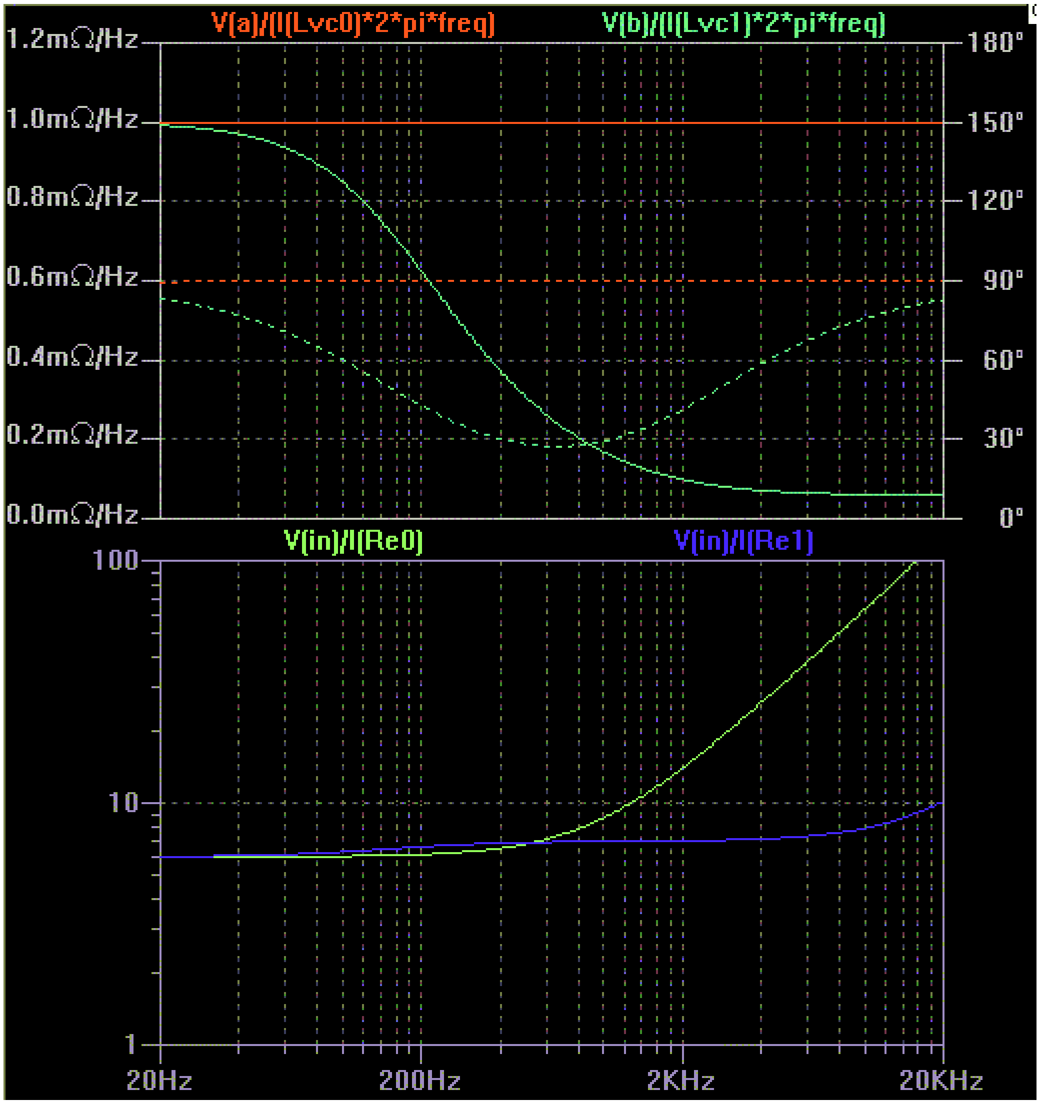

Fig 8: Simulation results of the circuit in Fig7

In Fig8, the red curve of V(a)/(I(Lvc0*2*pi*freq) gives an effective inductance value across the voice coil terminals when there is no shorting ring, and the curve of V(b)/(I(Lvc1*2*pi*freq) shows the same when the shorting ring is used. These are a visual representation of how the shorting ring lowers the voice coil inductance, turning it into a device which has an impedance which is frequency dependent. The value of the red curve stays at 1mH and its phase is always 90 degrees, which is expected from a pure inductor. On the other hand the phase of the light blue curve varies with frequency and its value decreases. When the phase is not 90 degrees, it means there is a resistive real component in the impedance that consumes energy; inductors or capacitors don't consume energy. The energy consumed in Rsr (the shorting ring's resistance) adds the real component to the impedance seen at Lvc1's terminals. For this reason it can also be said that the shorting ring turns the voice coil inductor into a lossy inductor.

Note also that , the V(b)/(I(Lvc1)*2*pi*freq) curve shows that the inductance lowering effect of the shorting ring initially increases but then settles down. In our sample case, at 20Khz the effective voice coil inductance value is converging to 0.059mH and its phase converges to 90 degrees. This can also be seen in the blue V(in)/I(Re1) curve as a late coming impedance rise. If we review equation (21), the effective inductance value should be converging to zero as frequency converges to infinity. So, where is this convergence to 0.059mH is coming from? The answer is the 0.97 coupling ratio value of Lvc1 and Lsr that we used in the SPICE model. A coupling ratio less than 1 is indicating that not all turns are perfectly coupled between the primary and secondary windings. The turns that are not coupled show themselves as what is called a "leakage inductance" in the transformer. This 0.059mH is the leakage inductance of the voice coil when the voice coil and the shorting ring is considered to be forming a transformer. The leakage inductance at the voice coil side is equal to: L_{vc} $(1-k^2)$ = 1.0mH $(1- 0.97^2)$ = 0.059mH, where k is the coupling ratio.

A few examples of such real driver curves can be found at www.typhany.com website under Scan-Speak product line, such as the mid-woofer 18W/8542 or the midrange driver 13M/8636. Both of these drivers use a copper cap on the pole piece, which is termed as SD motor version by Scan-Speak, and their impedance curve shape in general looks similar to the blue impedance curve of our simulation result. In comparison, the drivers that use Scan-Speak's patented SD-1 motors, display a higher rate of impedance rise, which can be seen in the mid-woofer 18W/8545's impedance curve. This is because SD-1 motors leave the part of the pole piece that corresponds to the air gap without any shorting ring, but they have shorting rings above and below the air gap section of the pole piece. This means the part of the voice coil windings that are in the air gap, are not coupled to the shorting rings very well. If the coupling ratio parameter of the K SPICE directive in our circuit model is decreased to account for this fact, the simulation result then gives an impedance curve shape like the drivers with SD-1 motor. This also explains why shorting rings that are placed at the base of the pole piece have less effect on the voice coil impedance, and their impedance curve rise is not much different than a regular driver without any shorting ring. When the shorting ring is at the base of the pole piece, it misses some of the flux that the voice coil generates, which is the same thing as saying that voice coil and the shorting ring coupling is lower than ideal. The smaller the coupling ratio, the less effect shorting ring has on the impedance.

The internal resistance of the shorting ring is also an important factor. As we have mentioned earlier, if it could be made to be zero, it would totally eliminate the voice coil inductance and make its impedance seem like a pure resistor of value R_e. The higher the shorting ring resistance, the less effective it becomes.

Induced Eddy Currents On the Pole Piece, What do They do?

Up until now, we ignored any induced currents that will run inside the pole piece, which makes up most of the core of the voice coil. So up to here, our assumption was that the pole piece was a non-conductive material with a very high internal resistance which didn't allow any current to be induced in it. Pole piece being made from high permeability steel, of course this assumption is not correct. In this section we will try to find the effects of induced currents on the pole piece. The induced currents on the pole piece by changing magnetic flux caused by the changing voice coil current are called Eddy currents, because the pole piece wasn't made to carry induced currents on it, and it is not shaped to allow the maximum induced current to flow on it. Induced currents that occur on parts that weren't supposed to carry induced currents are usually called Eddy currents. Because most often the shape of such parts aren't made to give the optimum flow of induced currents in their shortest flow direction, the induced currents on them usually run in local circular paths, which resemble eddy whirls on a stream of running water. Other than the differences that give them their particular name, the way these eddy currents are generated and the way they react back to the electromagnetic system is nothing different than the induced currents on the secondary winding of a transformer, or a short circuit ring in a loudspeaker driver motor. Eddy currents also occur on other conductive parts of the motor such as the top plate, bottom plate, even to some degree on the parts of the basket of the driver that are closer to the voice coil, if the basket is made from a conductive material, and also the special case of a conductive voice coil former which is already shortly mentioned on footnote 2. We'll only focus on the pole piece here, because it sees the most of the flux change caused by the voice coil, i.e. it is highly coupled to the voice coil.

In order to see the effect of eddy currents on the pole piece to the voice coil impedance, we could model it as a series of concentric virtual rings of equal thickness but increasing their radius from zero to pole piece's radius. The virtual rings that are close to the outer edge of the pole piece will enclose must of the flux change by their cross section area, but the virtual rings that are towards the center of the ring will enclose smaller of the flux change proportional to their cross section area. At the same time the ring that are towards the center will have less internal resistance, while the rings at the outside will have higher resistance, as indicated by the equation (22). Such a model would require taking into consideration of the resistances and cross section areas of each ring and find their aggregate sum effect on the voice coil inductance, which would be a more complex job than what we are after. Once again, we are not after accuracy here, we are after simple enough approximate models that will be adequate to display how they work.[8] So here we will take a very crude model as an approximation of the pole piece's eddy current's effect. We will assume an equivalent ring with thickness $r_{vc}/2$, and outer diameter of ¾ r_{vc} (where r_{vc} is the voice coil radius) and a height of H_{pole} . We will assume that the induced currents on this equivalent ring will have the same effect of the induced currents on the pole piece of with a radius r_{vc} and height H_{pole}.

By using equation (22) and assuming the resistivity of the pole piece material is $0.3x10^{-6}$, for a voice coil radius of 2cm and pole piece height of 3 cm, our assumed equivalent pole piece ring will have an internal resistance of :

$R_{pole} = 0.06 m\Omega$

By using equation (14) and taking the average radius of the ring to be (¾ r_{vc} – ¼ r_{vc}), the inductance of this equivalent assumed pole piece ring will be:

$$L_{pole} = (\pi\, r_{vc}^2\, \mu_a) / (4\, H_{pole}) \qquad (23)$$

Then the ratio of L_{pole} to L_{vc} becomes, using (23) and (13):

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[8] The crude approximation model we are using here totally ignores the "skin effect", for a more accurate modeling of the eddy currents on pole piece see the reference no 6.

$$L_{pole}/L_{vc} = H_c / (4\, H_{pole}\, N^2) \qquad (24)$$

SPICE Example Comparing the Individual Effects of Pole Piece Eddy Currents And Shorting Ring:

Here we will use the same voice coil model we used in the earlier SPICE model, but will also look at the effect of eddy currents on the pole piece. Using (24) and the same earlier example of a voice coil with inductance of 1mH and height 2cm, the equivalent inductance of a pole piece with 3cm height becomes:

$$L_{pole} = 0.16\text{x}10^{-4}\text{mH}$$

We had already calculated the equivalent internal resistance of such a pole piece as $R_{pole} = 0.06\text{m}\Omega$ in the previous section. With these at hand we arrive at a circuit model which is displayed in Fig 9.

The circuit in Fig 9 is made up of three parts. The upper part corresponds to a voice coil with no shorting ring and no eddy currents on its core. The middle part corresponds to the same voice coil but the eddy currents on the pole piece is taken into account by the secondary winding and its resistor, which represents the eddy currents on pole piece. The lower part corresponds to the same voice coil with no eddy currents on the pole piece but a shorting ring is added, which is the secondary winding in there. This way, we can compare the individual effects of eddy currents and shorting ring on the voice coil impedance. Note that the coupling coefficient of the pole piece to the voice coil is selected as 0.8. This is made in order to account for the fact that the pole piece doesn’t cover all of voice coil’s windings at rest position, therefore it is somewhat less coupled to the voice coil than a shorting ring that goes full length of the voice coil.

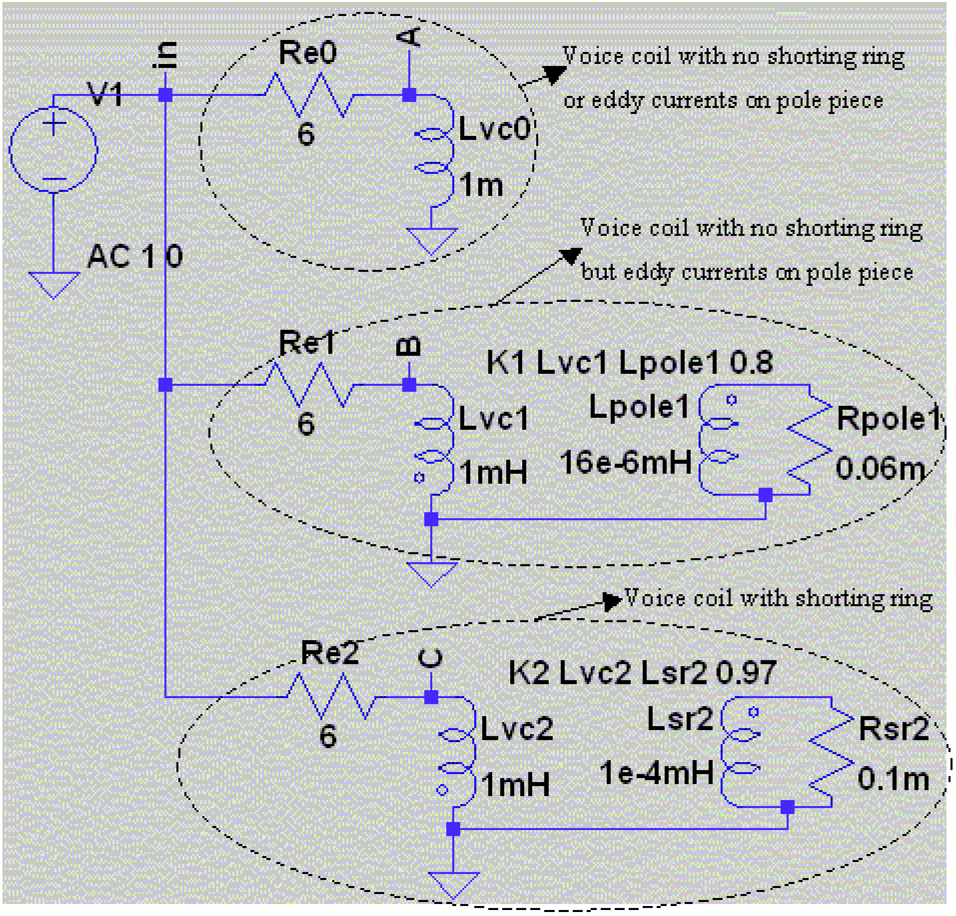

Fig 9: SPICE model for comparison individual effects of shorting ring and eddy currents on voice coil impedance

Fig 10 below shows the results of the simulation of the circuit in Fig 9. Here again the green curve of V(in)/I(Re0) is the impedance of the voice coil with no shorting ring and no eddy currents on pole piece. It is again the standard rising curve of a resistor in series with an inductor. The blue curve of V(in)/I(Re1) belongs to the case where the eddy currents on pole piece are taken into account. Note that the eddy currents slows down the rise of the impedance curve. Such a curve is very typical of any loudspeaker driver that use conductive material such as iron as part of their magnetic circuit. Unavoidably, eddy currents gets induced on these iron parts as a reaction to the magnetic flux change caused by the voice coil currents. So all conventionally built loudspeaker drivers exhibit this phenomena of an impedance that diverges from a simple resistor plus inductor.

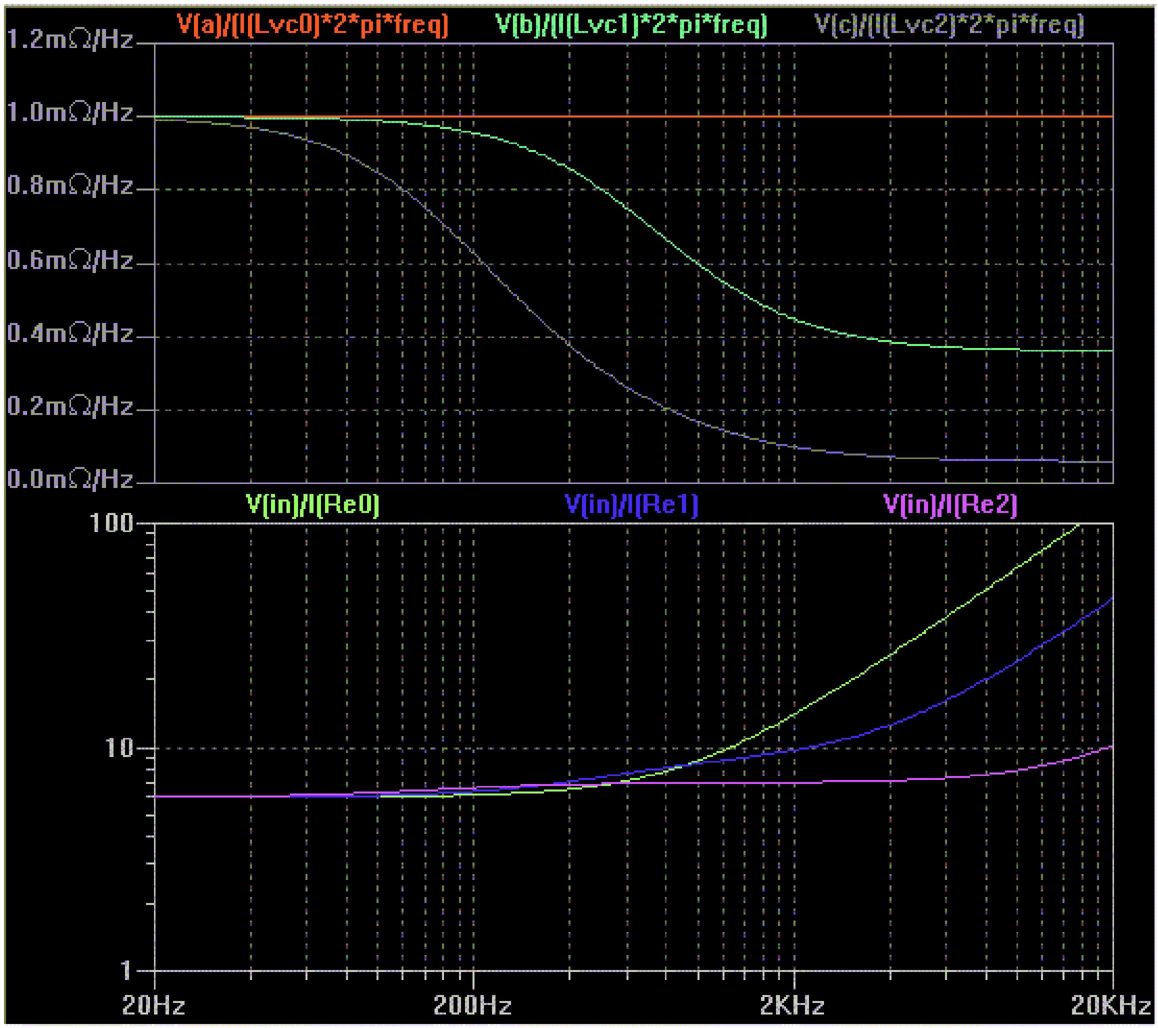

Fig 10: Simulation result of the circuit in Fig 9.

The pink curve of V(in)/I(Re2) belongs to the case where there are no eddy currents on the pole piece but a shorting ring is added. It can be seen that a shorting ring usually have more effect on the voice coil impedance than the eddy currents on the pole piece. The important thing here is that both the eddy currents on the pole piece and the currents on the short circuit ring have the same effect, because they work under the same laws of physics. The difference with eddy currents is that, they are not easily predictable (unless you make very crude approximate models like we did, which is not adequate to be used in real world designs), and they have asymmetry between the top of the pole piece and the bottom of the pole piece, and also between the top plate and the bottom plate. The asymmetry is caused by the existence of the air gap, which doesn't exist on the bottom plate[9]. So instead of requesting the pole piece and other ferromagnetic parts of the motor to do a double job of both channeling the magnetic flux of magnet into the air gap and reducing the modulation and inductance of the voice coil by allowing eddy currents to flow on them, it would be a better idea to put in a shorting ring to do the latter and leave the iron parts to do the former, which is their sole job. We'll look into this in the next section.

SPICE Example Which Both Shorting Ring and Eddy Currents Exist

In order to see what happens when both the effect of shorting ring and eddy currents on the pole piece are taken into account, we add a new part to the circuit of Fig 9, which couples all the three coils with each other: the voice coil, pole piece and the shorting ring. The resultant circuit is shown in Fig 11. The top three parts of the circuit of Fig 11 are identical to Fig 9's, the last bottom part is for investigating the case where both the shorting ring and eddy currents on pole piece exist. The SPICE directives K30, K31 and K32 couple Lvc3, Lpole3 and Lsr3 to each other with the same coupling ratios used when the pole and shorting ring existed individually. An arbitrary value of 0.9 is selected for the coupling of the shorting ring and the pole piece. This coupling between the two depends very much on both the shapes of the pole piece and shorting ring, as well as the placement of the shorting ring on the pole piece.

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[9] The US patent US5357587 gives a good description of the problem of asymmetric eddy current flow on top and bottom parts of the loudspeaker driver motor.

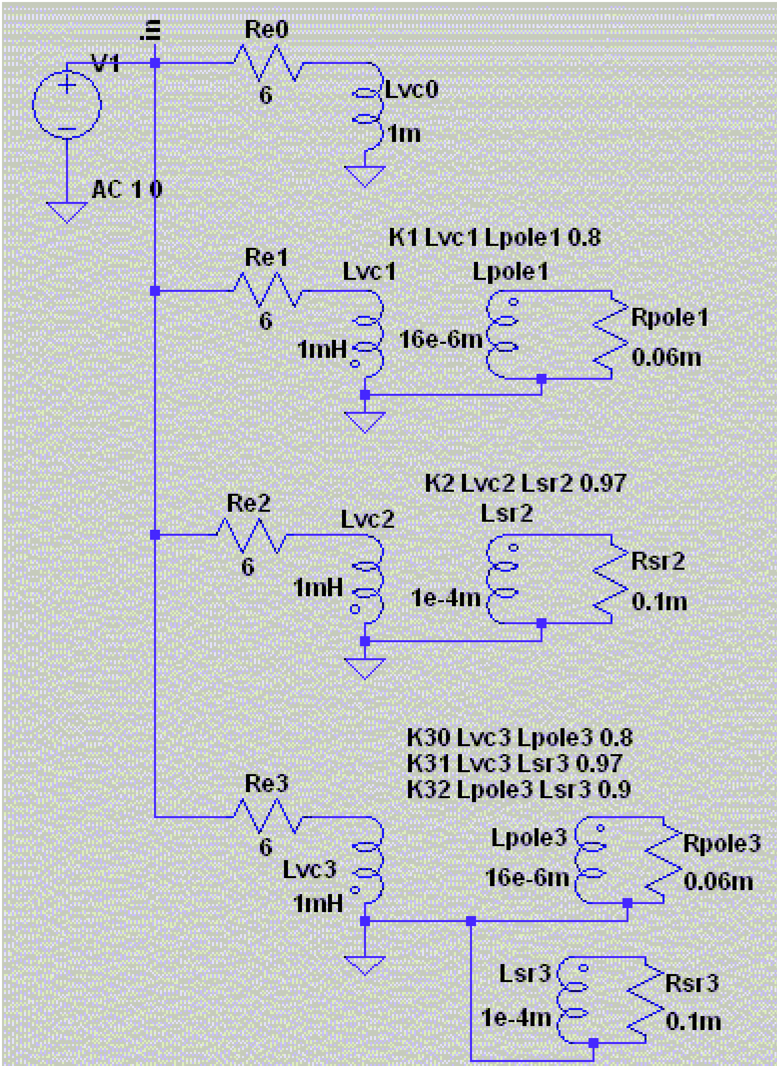

Fig 11: Circuit model where the case of both shorting ring and eddy currents on pole piece existing with the voice coil added to the model of Fig 9.

Fig 12 shows the simulation result of the circuit of Fig 11. The green, blue and pink curves correspond to the same impedance curves of Fig 10.. The red curve belongs to the case where both the eddy currents on the pole piece and shorting ring are taken into account. As can be seen, the curve is close to the pink curve where there was only shorting ring without the effect of eddy currents on the pole piece, but there are some differences nevertheless.

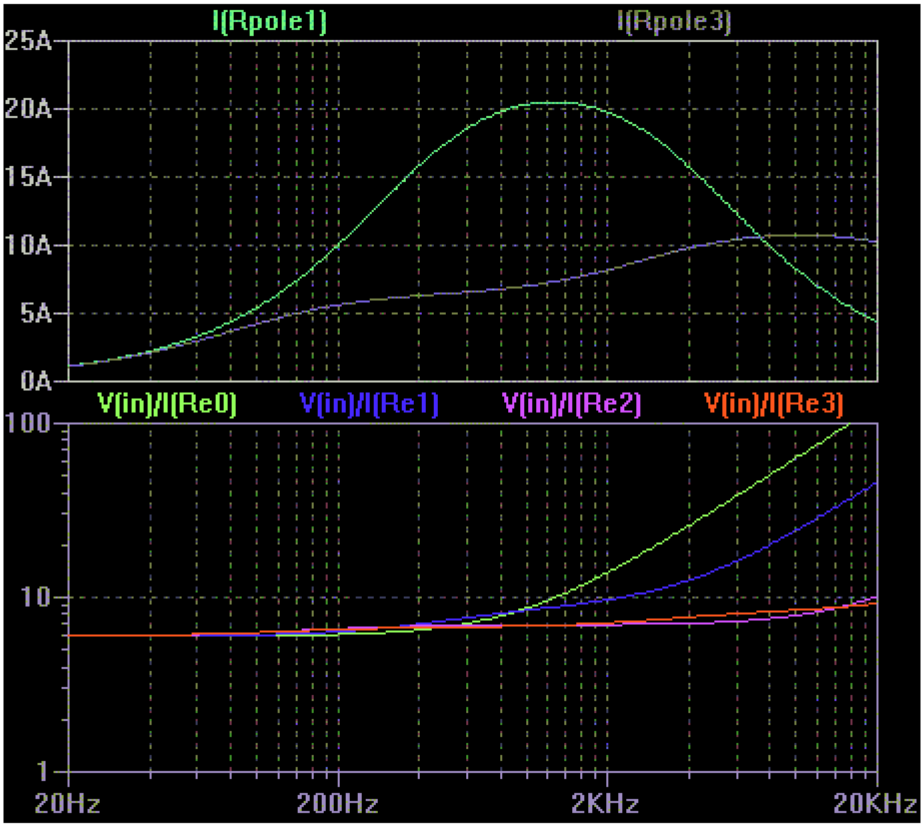

Fig 12: Simulation result of the circuit of Fig 11 .

A more interesting result can be seen by looking at the magnitude of the eddy currents flowing on the pole piece. The curve of I(Rpole1), which is on the upper pane of Fig 12, corresponds to the eddy current amount on the pole piece when there is no shorting ring. The curve I(Rpole3) which is on the same pane, is the amount of eddy current flowing on the pole piece when there is a shorting ring highly coupled to it. As can be seen, for the most part of the frequency range, the eddy current is reduced because of the existence of the shorting ring. This is expected since the shorting ring has a higher inductance than the pole piece and better coupled to the voice coil, which results in it reacting better to the change of flux than the pole piece. And as a result most of the induced current flows on the shorting ring rather than the pole piece. But as frequency increases, because the internal resistance of the pole piece is lower than the shorting ring, the eddy currents on the pole piece starts to increase back again.

There is also the “skin effect” phenomena that would reduce the available cross section area of the current, which would make the internal resistance of both the pole piece and the shorting ring to increase. Such detailed analysis is beyond the scope of this document, for additional information on this and more accurate modeling of the eddy currents reference 6 recommended.

The Benefits of Usage of Shorting Rings:

Under the light of the information represented above, we can now comfortably look at what benefits that comes with the usage of shorting rings. The most immediate and apparent one is the reduction of the impedance rise with increasing frequency. This means the sensitivity of the driver as frequency increases will be increased with the usage of a shorting ring. This is commonly stated as the shorting ring extending the high frequency roll off of the driver.

Second benefit comes from the fact that shorting ring reduces the effective inductance value of the voice coil at a given frequency. In an earlier section we had discussed the causes of the nonlinearity of the voice coil inductance and its detrimental effects. One way to look at this is, by reducing the effective value of voice coil inductance, these detrimental effects will also be reduced, including the nonlinearity caused by the operation on the nonlinear part of the B-H curve, or the hysterisis of the B-H curve. Then we had mentioned there was also the nonlinearity problem of voice coil inductance being dependent on the position of the voice coil. A shorting ring will be a remedy to this by simply the fact that it will reduce the inductance of the voice coil. Even if it still gets modulated with position of the voice coil, this change in modulation will have less effect because the average value of voice coil inductance is reduced but the resistance of the voice coil remains the same. With the average value of the voice coil reduces, resistance of the voice coil has more say on the impedance, and the changes that the inductance part goes through have less effect on the voltage to current relation. And with careful positioning of multiple shorting rings, not only the voice coil inductance value can be reduced, but also the modulation of it by excursion. We will not go into detail of this here, but a case of it can be found at B&W’s “Development of the 700

Series” white paper, available at http://www.bwspeakers.com/downloadFile/technicalFeature/700SeriesWhitepaper.pdf

Since we were focused on the effect of shorting ring to the voice coil impedance, so far we have only slightly touched to the effect on the reduction of the modulation of the air gap flux by the usage of shorting ring. Considering the information presented so far, it is obvious that the shorting ring effect on the voice coil impedance is a result of the way it reduces the amount of flux modulation the voice coil current would cause if shorting ring didn’t exist. This lies at the core of how it reduces the rise of the impedance of the voice coil. Since the magnetic flux change caused by voice coil current is transmitted into the flux inside the air gap by the high permeability iron pole piece; the voice coil current also modulates the flux inside the air gap, which is supposed to be constant for the linear operation of the driver. By reducing the magnetic flux change caused by the voice coil, the modulation of the air gap flux will also be automatically reduced. Since this is what the shorting rings do, they will also be reducing the modulation of the air gap magnetic flux by the voice coil current. It means shorting ring will not only reduce the nonlinearities associated with the voice coil inductance, it will also be reducing the nonlinearities caused by the modulation of the air gap field.

And as a last note, lets go back to the induced EMF caused by the movement of the voice coil and Q_e. In an earlier section we gave the equation of the induced EMF of a driver caused by the movement of the voice coil in (12). We had said there that the shorting rings don’t have any direct relationship to this. Now we are better equipped to comment on it. Since the only things that determine the motion caused induced EMF are the magnetic field inside the gap, the length of coil inside the gap and end the velocity of the voice coil, let us see what can the existence of a shorting ring do to it. The velocity in that equation is the variable causing the EMF, so we are not interested in it. Since shorting ring doesn’t have any effect on the physical shape of the voice coil, the length of voice coil inside the air gap is not affected by a shorting ring’s existence. But since shorting ring reduces the modulation of the magnetic field inside the air gap, it means it will make the motion induced EMF more linear. This also means it will make the Q_e, which is a result of the induced EMF by the motion of the voice coil, independent from the magnitude of voice coil current. If the voice coil current modulates the field in the gap, Q_e will also be modulated by the voice coil current.

In short, the shorting rings are good to have, as long as their shape and position is well thought out and placed on the motor. The only problem they bring is they generally reduce the sensitivity of the driver, because either they cause to widen the air gap if they are placed in there, or they cause the shape of the pole piece to be made such that a it won't be able to channel the maximum amount of flux to the air gap.

Closing Remarks

The goal of this document was to give an insight on the workings of a shorting ring on a loudspeaker driver and also to take a peek at some of the nonlinearities of the loudspeaker drivers that are addressed by the usage of shorting rings. It was the author's impression that there is a lack of readily available and easy to understand documentation on the subject of shorting rings, especially available to the average DIY speaker builders and designers. There are a few short attempts of explanation available on the Internet, but they either don't do a very good job of explaining or contain misleading information that causes confusion on the readers' minds. This document is written with the hope of filling this void.

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