Distortion sources in Loudspeaker Drivers

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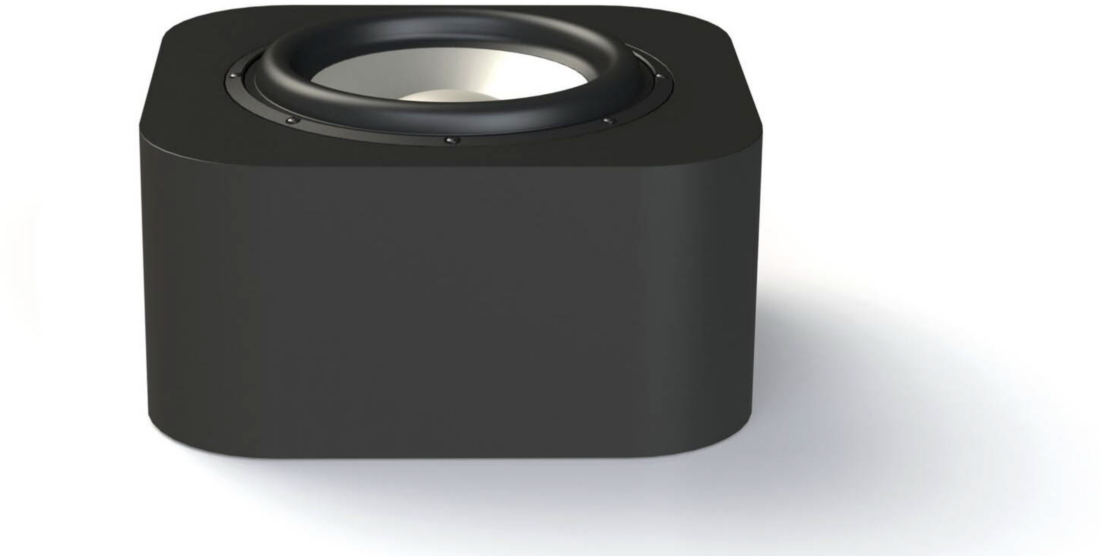

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1 Introduction

Distortion in audio systems is caused by the inability of the system to reproduce the registered sound information without errors. These errors manifest themselves in loudspeakers as an unwanted change in radiated sound waves.
Many different types of distortion exist. First of all there is the so called *Linear Distortion*, which refers to a not constant frequency response, independent of the amplitude or previous signals. This is a quite harmless kind of distortion as it can be fully compensated by linear filters.
More problematic is the *Non-Linear Distortion*, which is a non-linear function of the frequency, the momentary value of the signal, the excitation by previous signals or any combination thereof. Many different kinds of distortion are distinguished in literature of which the most well known is the *Harmonic Distortion* (HD), which is due to the creation by the system of higher harmonics of an original single harmonic sine-wave input signal with frequencies $f_{\mathrm{d},n}$ equal to an integer number $n = 2,3,4...$ of the original signal frequency f_0, $f_{\mathrm{d},n} = nf_0$.
Another well known type of distortion is *Intermodulation Distortion* (IM) where a higher frequency is amplitude modulated by a lower frequency, causing new frequencies above and below the highest frequency at a frequency“distance” equal to the lowest frequency (mirrored side-bands).
The third kind of distortion is related to strong non-linear phenomena in amplifiers, like cross-over distortion, transient intermodulation distortion and (hard) clipping, just to name a few.
Last but not least as an example of distortion due to previous signals the reduction of the sound signal due to heating of the actuator coil is called *Compression*.
The audibility of distortion is very much dependent on the kind of distortion. A double frequency like the second harmonic is for instance less audible than the third harmonic as the first is the same tone with only one octave difference while the third is a fully different tone with a quint difference (for instance the notes e-a), which really changes the sound. Often higher harmonics are appreciated as it gives a richer sound, comparable with the difference between a recorder and a trumpet of which the first produces a near sine wave while the other approaches a sawtooth wave with many harmonics. Non-harmonic distortion like the intermodulation and amplifier related distortion types are much more audible, ultimately creating a non-transparent sound stage where individual instruments can no longer be recognised.

Modern electronic circuits can be made extremely well controlled with high levels of negative feedback, achieving error levels in the order of -120 dB, which is equal to 0.0001% or 10^{-6}. Due to the nature of the non-linearity in electronics these low levels of distortion are sometimes still recognisable by trained experts and one might wonder how it is in loudspeakers. The bad news is that a mechanical system without any active control by measurement and feedback easily makes errors in the order of 1-100%, especially when low cost is required. The good news is that the distortion of loudspeakers mainly consist of harmonic and intermodulation distortion.

Both are caused by the same phenomena, a position dependent force factor (motor constant) and reluctance force effects. As a result good loudspeaker drivers have a distortion level around 0.1-1% at moderate sound levels and frequencies above the fundamental resonance. Below the fundamental resonance, where the excursion gets large, distortion levels range from 1-100%, which is extremely well audible as the human ear will only hear the harmonics due to the lowers sensitivity of the ear for very low frequencies.

In the following sections first the root causes of the most important non-linearities in loudspeakers are presented, followed by a section on the reason for the dramatic increase in distortion at low frequencies.

2 Position Dependent Motor Constant

A moving-coil loudspeaker has a motor constant, the level of force as function of the motor current ${}^{F}\!/_{I}$). This motor constant is determined by the magnetic flux density B at the coil $F \approx B\ell$, where ℓ equals the length of wire in the magnetic field. The name “motor constant” is in reality a wrong name as the magnetic field strength is never fully homogeneous, which means that the motor constant depends on the position of the coil in the air-gap. This effect is shown in the dashed line of the graph in Figure 1 and is caused by the fact that off the centre, the coil is not completely surrounded by the same magnitude of the magnetic flux.

In order to reduce the position dependency of the motor constant of a moving coil actuator in a loudspeaker, in practice the height h_g of the air-gap is chosen different from the height h_c of the coil. When the coil height exceeds, hangs over, the height of the gap, this configuration is called an *over-hung* loudspeaker actuator.
Its advantage is the optimal use of most of the permanent magnetic flux while also the position dependency is more evenly smoothed’out. The drawback of an over-hung actuator is the large number of coil windings that are not utilised effectively. In the situation, where the coil is the moving part, like in a loudspeaker, this means that the moving mass is larger than without an over-hung situation. It is a typical choice for loudspeakers where the cost of the magnet outweighs the value of a higher efficiency of the loudspeaker. The amount of overhang is chosen depending on the allowed non-linearity related distortion. For non- critical applications like loudspeakers for cars, “Public-address” in stadiums and amplification of instruments in pop-music, little or no overhang is applied, giving a maximum efficiency at elevated distortion levels. For high-end sound reproduction, often a large over hang is chosen to reduce distortion at a sacrifice on efficiency. This is the reason why amplifiers for high-end home equipment needs to have a relatively high output power capability. The configuration where the height of the air-gap exceeds the height of the coil is called an *under-hung* loudspeaker actuator. The benefits and drawbacks are just reversed. It makes best use of the coil with a resulting reduced mass but at a relative high cost of the permanent magnetic part. The position dependency of the motor constant

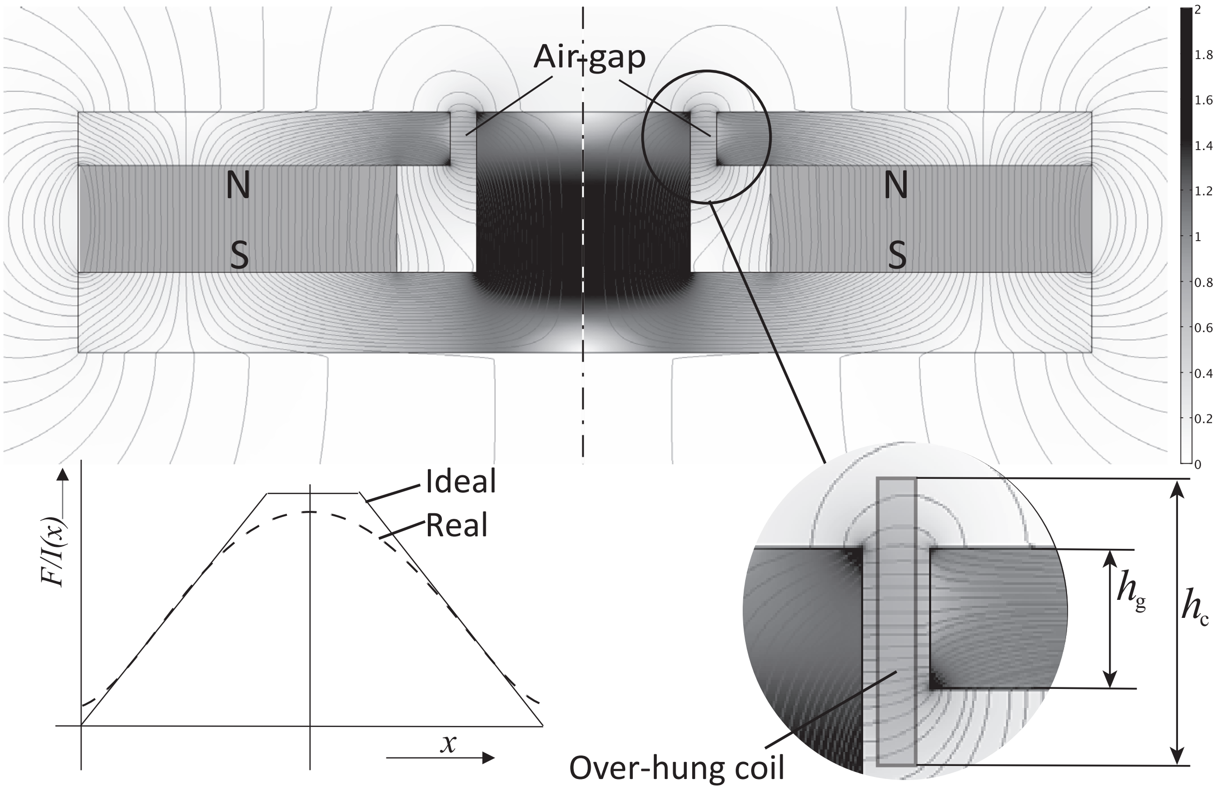

Figure 1: A Lorentz actuator has a limited stroke, determined by the dimensions of the air-gap and the coil. When the coil is only partly inserted with an effective height $h_{c,g}$ inserted in the air-gap, the motor constant (F/I) is reduced. By choosing different values for the height h_c of the coil and the height h_g of the air-gap, the motor constant can be made more constant over a certain range of x. The gradual decrease of the magnetic field (fringing flux) at the edges of the air-gap softens the transitions and creates a small force even when the coil is outside the air-gap.

is better than in the over-hung configuration, when the coil is still completely inside the air-gap, but it worsens more rapidly as soon as the coil reaches the outer range of the air-gap, due to its small size. An under-hung Lorentz actuator is chosen mainly in loudspeakers, when a long stroke is not needed and low moving mass and distortion is the primary goal. This is especially the case for mid- to high-frequency loudspeakers, the squawkers and tweeters.

One remark must be made to the often stated term “linear excursion” in data sheets. It is defined as (($h_g - h_c$) while from Figure 1 it is clear that also within this range the force is not constant at all. It is one of many examples where loudspeaker manufacturers fail to show true information, due to the combination of the need to show USP relative to the competition, while the general user has hardly any idea about the consequences. To illustrate this with real measurements Figure 2 shows force measurements of a SEAS L26RO4Y[1] subwoofer, which is specified for a linear motion range of +/- 14 mm and a force factor of 18 N/A and 500 Watt short term power handling capability, which is for 4 Ohm equal to approximately 11 A

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[1] It is important to note that the shown example is representative for most loudspeakers from many manufacturers. The chosen example was selected for its high specified force to current ratio.

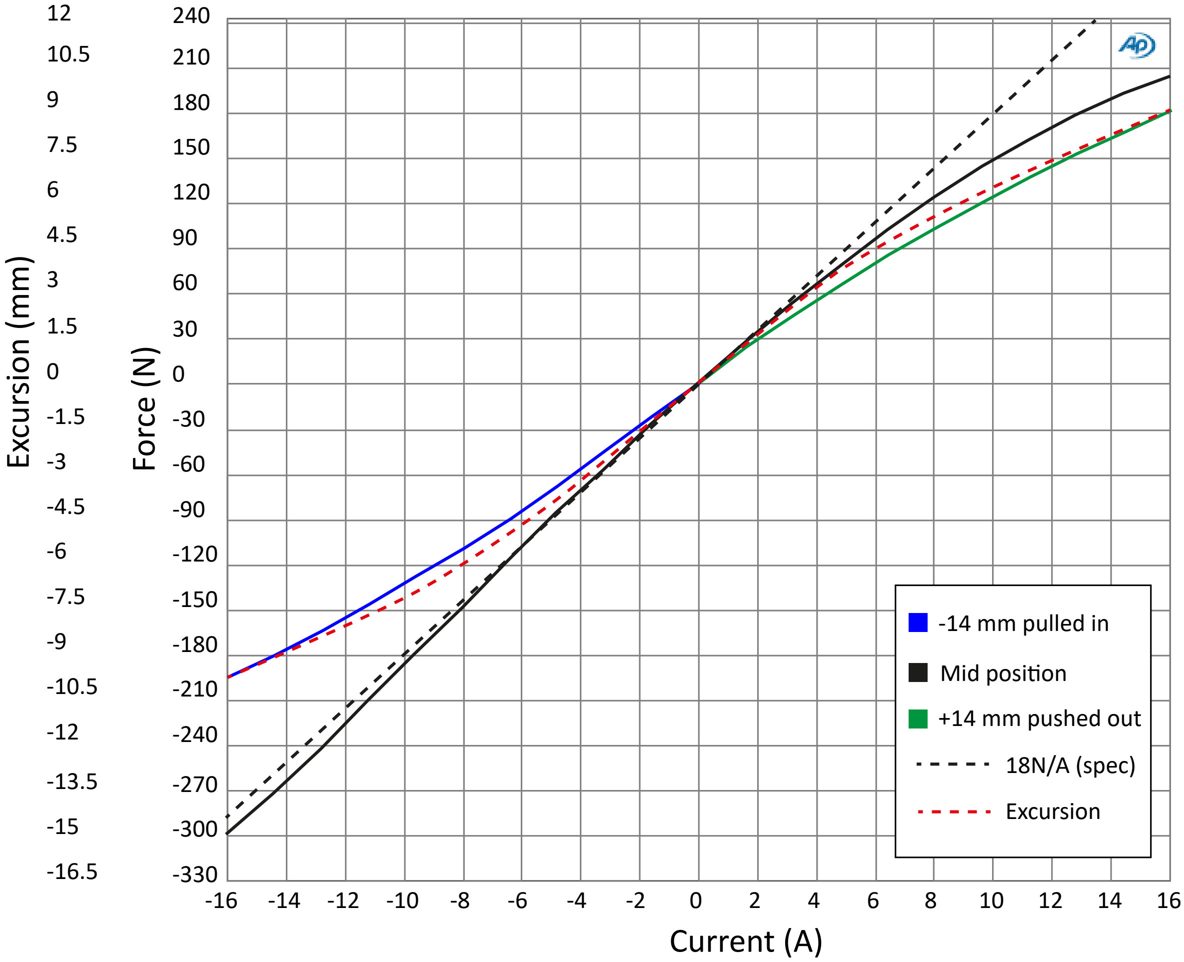

Figure 2: Force measurements on a SEAS L26RO4Y subwoofer for different current levels at different positions of the diaphragm. In the mid position the full current range is measured wile at the outer positions only the current direction is taken that corresponds to the excursion. Finally the calculated excursion is shown based on these measurements. The non-linearity of the force-to-current and force-to excursion relations is clear, even though the actuator is measured within its so called “linear range”.

RMS or 16 A peak. It clearly shows that the specification is met at the mid position for limited current levels but with a positive current the measured force starts to deviate notably towards approximately 30% at +16 A. With a negative current the deviation is far less. This asymmetry is a typical sign of 3$^{\text{rd}}$ harmonic distortion and it is fully caused by the reluctance force as will be described in the next section.
When considering that below the first eigenfrequency $f_0 = \omega_0/2\pi$ the amplitude of the diaphragm is proportional to the force divided by the stiffness of the enclosure and suspension, the force at a positive current should be measured at a positive excursion, while the negative force should be measured at a negative excursion. This is shown with the green and blue line at the maximum “linear” range of ±14 mm, resulting in an even larger deviation, although the asymmetry is less.
The next consideration is that higher harmonics in the position are increased with

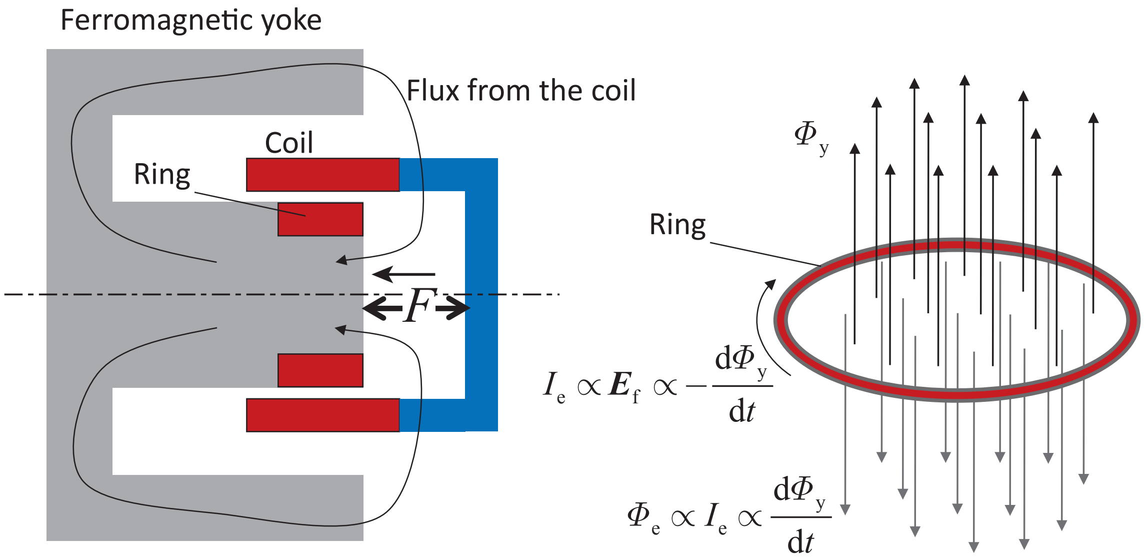

Figure 3: The reluctance force in a moving coil actuator is a force that acts independent of the permanent magnet flux. It is caused by the attraction of the iron part by the magnetic field of the current in the coil and it is always directed to the position with the least reluctance (unidirectional arrow). For high frequencies this force can be reduced by a conductive ring, which counteracts the change of the magnetic flux in the iron part, as shown at the right.

the frequency squared, due to the proportionality of sound pressure with acceleration. If one calculates the position for a sinusoidal force function and performs a Fourier analysis of the resulting deviation from a perfect sine these higher harmonics have to be multiplied with a factor 4 for the second harmonic, 9 for the third harmonic etc. This all explains the large distortion levels of electrodynamic loudspeakers at very low frequencies.

3 Reluctance Force

While ideally the Lorentz force is bidirectional, symmetric proportional to the current, the ferromagnetic structure to guide the magnetic field to the coil causes a second unidirectional force, the *Reluctance Force*, which is very non-linear, with a squared relation to the current. Figure 3 shows the induced flux by the current in the coil with an actuator where the coil is located slightly outside the optimal position in the middle of the air-gap. The permanent magnets are not shown, because the reluctance force is only determined by the ferromagnetic part.
It is clear that the the flux created by the current in the coil is at best guided through ferromagnetic material (minimal reluctance = minimal magnetic resistance) when the coil is located completely inside the ferromagnetic part. The reluctance force drives the moving part in the direction of a maximum in the magnetic flux, which is a minimum in reluctance. This means that the reluctance force on the coil is always

directed towards the ferromagnetic part.
One way of reducing this reluctance force would be to extend the ferromagnetic part to the right to beyond the magnets but that would require the coil holder to be longer and the moving mass would be larger.

3.1 Eddy-Current ring

Generally a conductive copper ring is applied to reduce the distortion by the reluctance force and decrease the self inductance, which otherwise would lower the output at higher frequencies. Eddy currents in this ring counteract the changing magnetic field in the iron yoke as shown in Figure 3. The effectiveness of this method is based on the reduction of the variability of the flux from the coil by the magnetism from the induced current in the ring. This effect is similar to the induced current in the secondary winding of a transformer by the current in the primary winding and can be explained as follows. The change of the flux $\mathit{\Phi}_\mathrm{y}$ inside the ring, by the current in the coil, induces an inner Electric field $\boldsymbol{E}_\mathrm{f}$ over the ring according to Faraday's law. This electric field causes the electrons to move, because the ring is closed, resulting in a current I_e in the ring in the direction of the electric field. This current is called an *eddy-current*, because it behaves like circular running currents inside a conductive material, like the "eddy" currents or swirl flow in a fast flowing river. In its turn, this induced eddy-current in the ring causes a magnetic field $\mathit{\Phi}_\mathrm{e}$ according to Ampère's law in the opposite direction of the magnetic flux of the coil. This means that the change of the magnetic flux of the coil inside the ring is suppressed.

Unfortunately the eddy-current ring has a severe limitation as it only compensates the magnetic flux that passes the ring, which is often not more than 50%. Furthermore the effect is frequency dependent, because the total flux inside the ring equals the integral of the change of the flux over time. The change of flux as generated by a given current level I_c in the actuator coil increases with frequency ($\mathrm{d}\Phi_\mathrm{y}/\mathrm{d}t \propto \mathrm{d}I_\mathrm{c}/\mathrm{d}t \propto I_\mathrm{c}\omega$), which means that the reducing effect of the ring on the flux, and correspondingly also on the reluctance force, is only effective at higher frequencies, while it is negligible at low frequencies, below $\approx$ 100 Hz. Even though this method is frequently applied in loudspeakers, it is in practice rather useless when applying the loudspeaker in a subwoofer for the frequency range below 100 Hz.

Next to the reduction of the reluctance force, also the self-inductance of the motor coil is changed. The self-inductance is defined to be equal to the ratio between the generated flux inside the coil times the number of windings of the coil divided by the current ($L = n\Phi_\mathrm{c}/I_\mathrm{c}$). In this relation Φ_c equals the total flux of the coil, where Φ_y equals the part of Φ_c the runs inside the eddy-current ring. As a consequence of the reduction of Φ_y by the eddy-current ring, also Φ_c and correspondingly the selfinductance is reduced. Ideally the eddy-current ring would fully cancel the selfinductance, however in practice this is not the case due to the limited coupling where Φ_y equals $\approx$ 50% of Φ_c. This causes the self inductance to act as a "fractional-

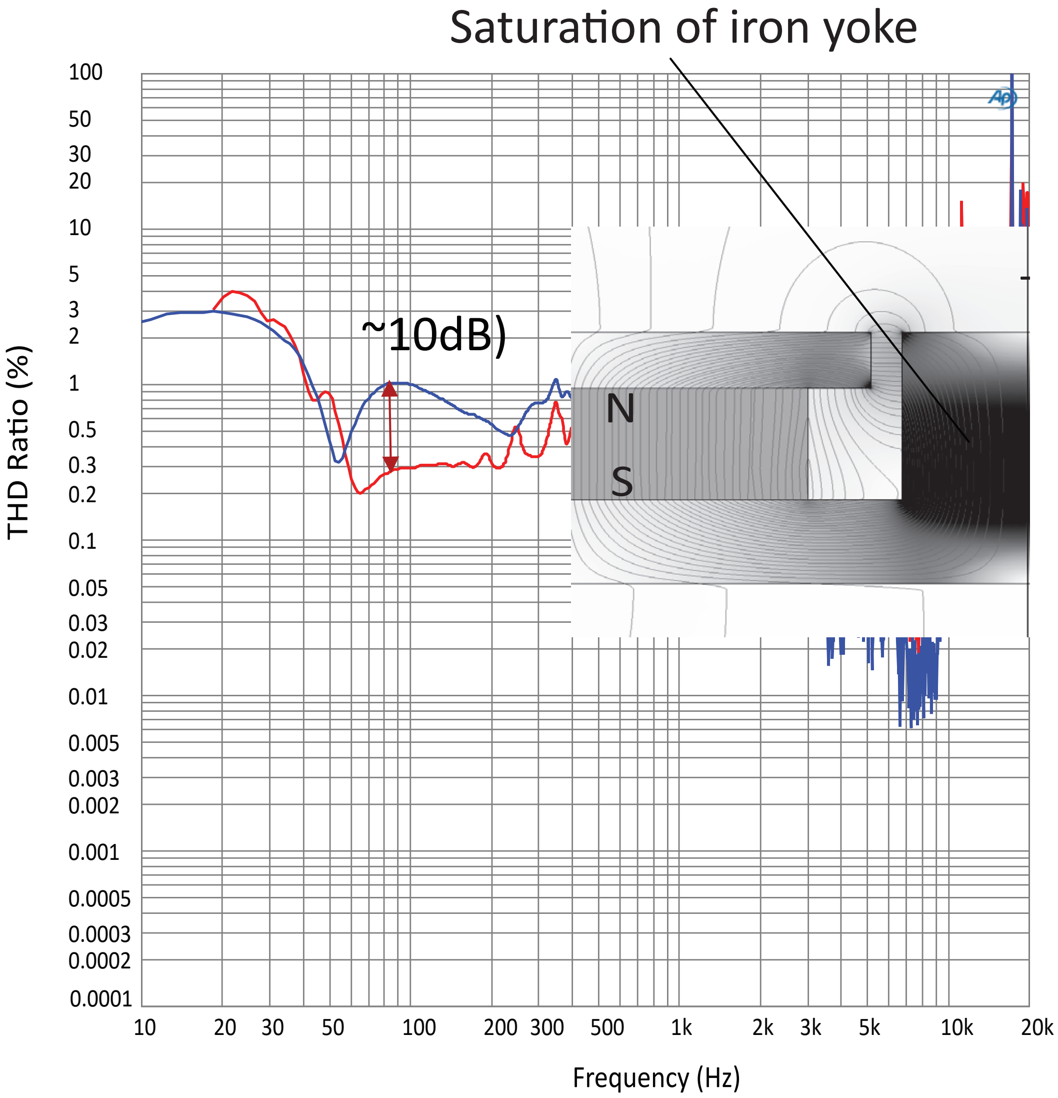

Figure 4: Non-linear current dependent self induction effects cause approximately 10 dB additional distortion when feeding the loudspeaker driver from a voltage source amplifier. Using a current source amplifier solves most of the problems due to self inductance effects.

order", also called *semi-inductance* with half the effect as a normal self-inductance. Although the eddy-current ring helps in reducing distortion by reluctance forces, the still dominant remaining part of the self inductance keeps influencing the current in the moving-coil in a not fully linear way, due to saturation effects in the ferromagnetic yoke, resulting even in a higher distortion level. In figure 4 it is shown that driving the loudspeaker with a current source amplifier this problem of the non-linear selfinductance is effectively cancelled, however unfortunately it does not cancel the effect of the reluctance force on the distortion, which means that the eddy current ring(s) still remain useful at higher frequencies when iron yokes are applied.

3.2 Ironless Stator

For the most critical applications where the linear performance is far more important than the cost of permanent magnet material, one might decide to entirely leave the ferromagnetic part away. Figure 5 shows such a configuration, where the magnets are connected to the stator by means of non-ferromagnetic material like aluminium or plastic. A second ring of magnets has been added to compensate for the higher reluctance (magnetic resistance) of the magnetic system due to the lack of ferromagnetic material. The increase of the reluctance for the permanent magnet flux at the outside is in the same order of magnitude as the reluctance of the air gap with the coil, because the longer path length of the returning flux is approximately compensated by the larger cross-section of all space around the stator. Next to the larger amount of permanent magnet material also the presence of strong magnetic fields outside the actuator is a drawback of this concept as it can create parasitic forces to other ferromagnetic parts in the surrounding, like bolts and screws.
For audio this solution has almost never been applied for cost reasons and for Low-Frequency sound systems it is hardly relevant as there the position dependent force effects are the most significant.

4 Other Sources of Distortion

Next to the physical causes of distortion in the actuator, the following phenomena all cause significant deviations from the ideal, especially in the case when the loudspeaker is used in a subwoofers, where it is forced to high excursion levels:

1. Amplifier source related.

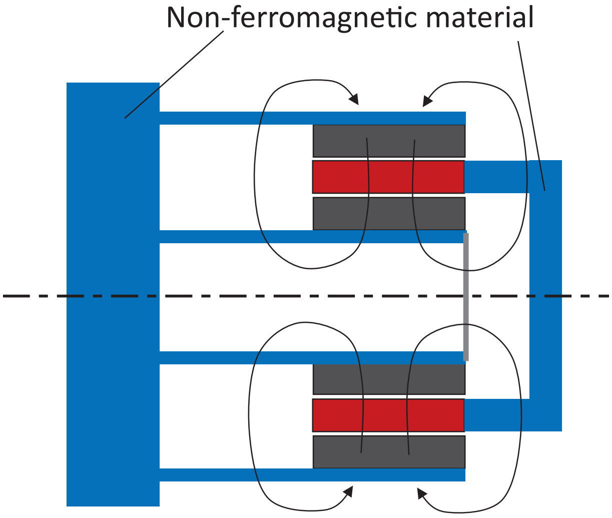

Figure 5: Lorentz actuator without a ferromagnetic part to cancel the reluctance force. The return path of the permanent magnet flux goes only through air.

   - With a standard audio amplifier the current in the coil is determined by the self-inductance and the resistance. The self-inductance is position dependent and high power heats up the coil of the actuator. A higher temperature means a higher resistance, which decreases the current and the force, a phenomenon which is called *compression*.

2. Non-linear stiffness.
   - High excursion levels will drive the surround in its stretching mode where its force rises exponentially.
   - Compression and expansion of the air in the enclosure is non-linear ($p \propto 1/x$), which is strongest with large loudspeakers in small enclosures

3. Non-linear deformation and reaction forces.
   - High forces can distort the diaphragm in a very non-linear way, both statically, called *buckling* and dynamically, called *breakup*.
   - Equally high reaction forces on the stationary part of the actuator will excite audible vibrations of the enclosure and the loudspeaker frame.

Each of these phenomena has to be addressed when designing loudspeakers in general but especially with subwoofers the phenomena are strong and cause significant flaws. The first item is related to the amplifier, while the second group of two items is related to the forces acting on the moving diaphragm as a stiff piston. The third group of two items relates to the dynamics of the system and the last item is related to the environment. Active feedback as described in another white paper deals with the first two groups, while careful design should reduce the third group.

While the other items will be further elaborated in other papers, the dynamics will be shortly given attention to.

4.1 Buckling and Breakup

Figure 6 shows a measured snapshot of an elastic diaphragm from Polypropylene under a high excursion at different frequencies. It nicely illustrates the effect of diaphragm deformation. First of all at any frequency a mechanical structure will always deform elastically when a force is exerted to it. With static forces this implies that the deformation at some distance from the point where the force is exerted will be less, when the structure is mounted on a stationary surface. Dynamic, time varying forces will give the deformation later when the sensing is at a distance from where the force is exerted due to the inertia of the mass. At elevated frequencies this elastic-inertial effect will cause an acoustic wave in the material, similar to the acoustic wave of sound in air. Although this soundwave effect in the diaphragm is mainly linear it creates a diffuse and unpredictable sound effect in the air as certain areas of the diaphragm create a positive pressure while others create a negative

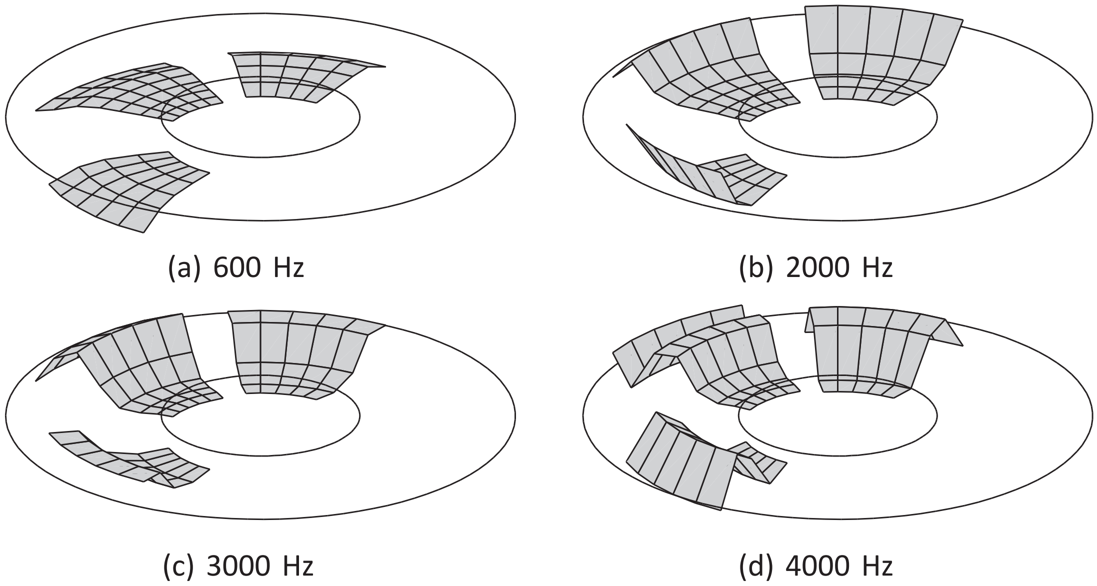
(a) 600 Hz
(b) 2000 Hz
(c) 3000 Hz
(d) 4000 Hz

Figure 6: An elastic diaphragm will deform under a driving force in its centre. At low frequencies the outer part will stay behind the movement of the inner part while at high excursion levels the outer part will even reverse its direction and move inwards, when the centre moves outwards. At higher frequencies more complex patterns will occur.
(source: Ruud Hoogenboom TuDelft)

pressure. It may help to increase the off axis radiation of a loudspeaker by having the air move on top of the expanding wave, but this is the part of the magic of some manufacturers that I would like to avoid in this paper.
On top of this soundwave there is another dynamic phenomenon which is directly related. It is called *breakup* and represents a resonating eigenmode where the mass of the diaphragm with its elasticity determines the eigenfrequency. The breakup phenomenon is shown in Figure 7 for the first eigenmode of an aluminium conical diaphragm. The effect of diaphragm breakup is a clearly observable change in the frequency response often looking like a combination of a valley (zeros) followed by a steep rise and a peak (poles). Above the eigenfrequency the centre part still moves while the outer part has “decoupled”, meaning that it cannot follow the motion of the centre part anymore. In some loudspeaker designs this effect is strived for by introducing ring protrusions. It decreases the radiating surface for higher frequencies, thereby improving the spatial spread of the sound.
For low frequency reproduction this is however not useful and a driver design should be made such that breakup phenomena do not occur in the frequency band of interest. This demands the use of stiff lightweight materials like carbon-fibre reinforced plastics, possibly in a sandwich structure, which all are rather cost intensive. When the frequency spectrum can be limited to subwoofer use below 100 Hz a thick (0.2-0.4 mm) aluminium conical-shaped diaphragm is sufficient.

Even with such a stiff diaphragm it is important to address the situation where the

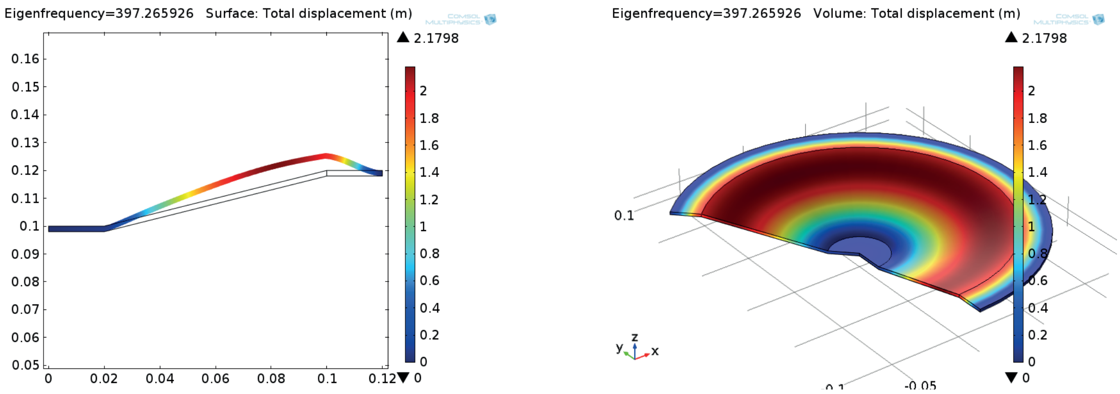

Figure 7: An elastic diaphragm will resonate with its mass in different eigenmodes. This modelled picture shows in 2-D and 3-D the first eigenmode of a straight conical-shaped diaphragm with a rotation symmetric mode shape, which bends the straight surface at an eigenfrequency of ≈ 400 Hz.
(source: Robert Valk TuDelft)

diaphragm is excited at frequencies below the first breakup eigenmode, so quasi-static, while the diaphragm is supported by a rubber surround. This matches the situation in Figure 6:a, where the force on the surround will pull the diaphragm down at the outer edge when the centre is pushed up and vice versa. At low excursion levels the edge will still follow the inner part with only a slight decrease in excursion due to the elasticity of the diaphragm material. At a certain excursion level, however, the outer edge will experience sufficient force to break down elastically and reverse its motion. This “buckling” effect is a highly non-linear phenomenon and worst-case it can be so fast that it causes audible snaps.
Buckling and breakup phenomena pose designers of loudspeakers for a real optimisation dilemma. For low frequencies a larger diaphragm is needed but this increases the risk of buckling and breakup, necessitating a thicker, stiffer material for the diaphragm, which is heavier, thereby reducing the gained efficiency by the larger diaphragm. In fact combining many small loudspeakers would be a better solution but then the costprice becomes an issue, although an even number will solve also another problem as will be shown in the next section. But even when the conical diaphragm itself is made sufficiently stiff to avoid buckling, the flexible rubber surround itself proves to be a non-linear deforming device with a relatively large surface at the outer edge of the diaphragm. In Figure 8 an explanation of this phenomenon is given in a graphical sense for a convex (bulging) surround where an upward movement will first make the surround also move upward, adding to the positive pressure, but at a certain position the surround stretches, the upward movement reverses and the positive pressure is reduced. With a concave (hollow) surround the effect is just opposite and the sign inversion is observed with a downward movement.

This effect is extremely non-linear. It is an even power function (squared etc.) because it gives an error on the sound pressure that is unidirectional downwards. With even order power a minus sign is converted into a plus sign, while plus remains

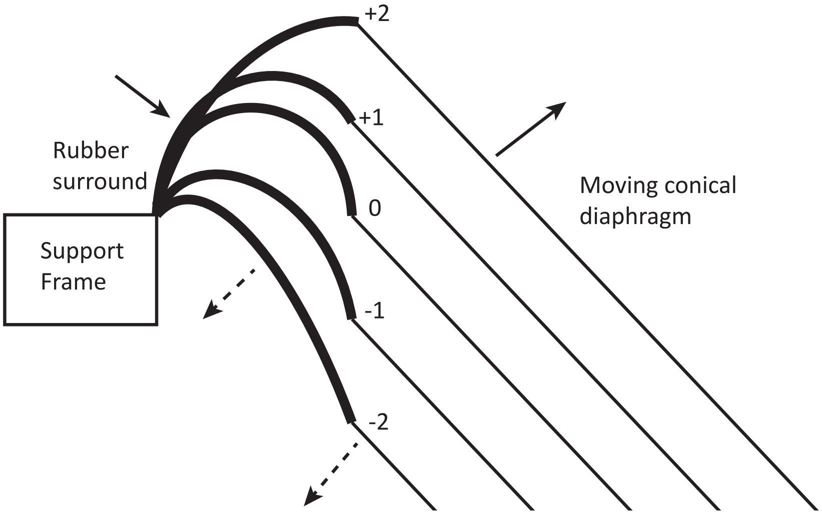

Figure 8: A convex surround will only be stretched in a downward movement while until the moment of full stretch it contributes to the same pressure change as the diaphragm (dashed arrows). In the upward direction first the surround will also move upward but near full stretch it will reverse its direction to downward.

plus. Until approximately half the attainable stroke the resulting 2nd, 4th, etc. order harmonics are not observed yet but above that range it quickly shows up.
There is no easy cure to this problem. A larger surround will become either heavy or too compliant, which will cause the same effect by the negative pressure inside the enclosure when moving upwards. Also a pure elastic surround that just stretches like a balloon will suffer from the pressure inside the enclosure. The best way would be to have no surround at all and make the diaphragm move with a very small gap between the diaphragm and the supporting frame, guided by a second spider membrane below the surface. This is frequently done at the inside when a *phase plug* is used but at the outside the gap is quickly so large that hissing sounds will be heard by escaping air or by rubbing contact between a not perfectly aligned diaphragm and the support frame. Fortunately half the moving range is only 6 dB below the maximum range and musical signals only very seldom reach the maximum peak level and a bit more distortion is then quite acceptable.

4.2 Reaction Forces

Any actuator will exert two opposite forces, following Newton's laws. One force is exerted to the mover and the equal but opposite reaction force is exerted to the stator. In the case of a loudspeaker driver, the mover is the diaphragm and the stator is the supporting frame, which is rigidly mounted to an enclosure. Fortunately with a low frequency loudspeaker a large part of the force on the diaphragm is used to overcome the stiffness of the air and the surround which leads this force towards the enclosure where it cancels part of the reaction force. The remaining force, which is used for acceleration of the diaphragm and for generating the sound pressure in the air, will however also generate a remaining reaction force, which is exerted on the enclosure

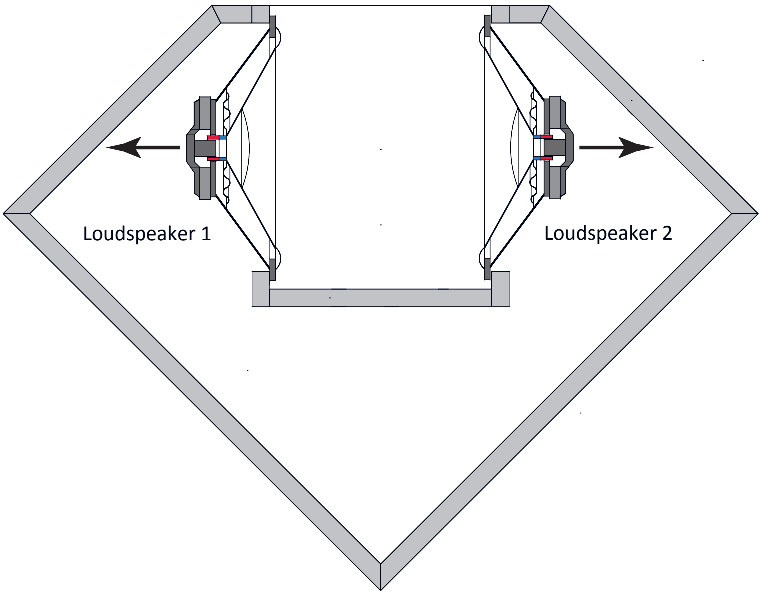

Figure 9: The reaction forces of two loudspeakers in opposite directions with the same audio signal will cancel each other out.

and can be transferred unwillingly to other places, like the floor and the neighbours. The floor will act like an unwanted diaphragm, creating sound with rattle. It will excite cupboards with glasses and no one will be happy with the tinkling sound and an angry neighbour. The problem can however be solved completely when two loudspeaker drivers are combined in the same enclosure mounted opposite to each other, either outwards, like on both ends of a pipe, or inwards like with the design shown in Figure 9. For this reason this concept is used in two other white papers.

5 Low Frequency Distortion

When measuring the distortion of loudspeakers, generally figures of around 0.1-1% are shown over the mid and high frequency audio band with a steep increase to levels of even sometimes 100% towards very low frequencies.
Two factors are responsible for this phenomenon.

- High stiffness of loudspeaker cone suspension including enclosure.
- Large cone excursions.

When observing such measurements, the increase seems to have a direct relation with the low-end resonance frequency f_0, often in the vicinity of 45 Hz. This coincidence is not illogical as below that frequency the dynamic properties change dramatically as was explained in Section 4 of the paper on “Low Frequency Sound Generation by Loudspeaker Drivers”. While at higher frequencies the radiated sound is proportional to the force of the actuator, at frequencies below f_0 the actuator force will work against the stiffness of the loudspeaker, including enclosure, with a proportional position excursion. While the sound radiation is proportional to the acceleration, this frequency range shows a +2 slope, which means that a factor two higher frequency will be radiated at an amplitude which is a factor four higher. The second item refers to the fact that for a constant sound pressure the amplitude of the cone excursion should increase towards low frequencies in ratio to the frequency squared, due to the found proportional relation between sound pressure and acceleration. A sufficient sound level at low frequencies requires in practice excursion amplitudes of several millimeter.

A simple approximating example illustrates how these two effects impact the distortion in a quite dramatic way.
Assume a system with a 200 mm diameter subwoofer in a 15 litre enclosure with $f_0 = 45$ Hz, which should produce a frequency of 20 Hz at 90 dB. This requires a large excursion of 10 mm and due to the limitation of the linear motion range of the loudspeaker motor the force will deviate 10%. The high stiffness of the small enclosure will require large currents for this excursion level, which cause significant reluctance forces, also in the order of 10% for this example. Both effects combined will cause a second harmonic distortion in the force in the order of 15% and a third harmonic distortion in the order of 5%.

Due to the fact that the second harmonic of $2 \cdot 20 = 40$ Hz is on the +2 slope of the frequency response, the sound pressure of this distortion will be a factor $2^2 = 4$ higher relative to the sound pressure by the first harmonic at 20 Hz. This means that the relative second harmonic distortion becomes $4 \cdot 15 = 60\%$. The third harmonic at $3 \cdot 20 = 60$ Hz will “only” get an increase of $(4.5/2)^2 = 5$, due to $f_0 = 45$ Hz, above which the frequency response is flat, giving a relative distortion of $5 \cdot 5 = 25\%$.

It is clear that such levels of distortion can only be solved by active control.