Distortion, The Sound That Dare Not Speak Its Name

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Read any discussion about loudspeakers and you get the impression that distortion as a topic is eagerly avoided. If it is mentioned, it is done sotto voce, implicitly. For instance: "you can't get good bass out of a small long-stroke driver. There's no substitute for cone area when you want to move air". Doesn't sound like it is about distortion at all, does it? Let's unpick the statement a bit: there is no substitute for cone area. Of course there is: displacement. If you want to move 100 cc of air, you could move a 500 cm^2 cone by 2 mm or you can move a 200 cm^2 cone by 5 mm. At the wavelengths we're talking about, there's no difference between the two.

So if the bigger driver sounds better, it must be because it's managing that 2 mm movement much more precisely than the smaller driver is managing its 5mm. And that is a statement about distortion. If we can crack the question why a short-stroke driver is more accurate over short strokes than a long-stroke one over long strokes, it should enable us to build a long-stroke driver that's just as accurate as a long stroke one for the same acoustical output. More accurate in fact, because once you understand the problem, there's no reason why you couldn't reduce distortion even further.

This is what PURIFI set out to do.

Identifying the Problem

Loudspeaker drivers are coupled problems. They consist of a motor, a suspension and a diaphragm that interact with each other mechanically. All three parts cause distortion in different ways, and those distortion components add up in unexpected ways. A HD measurement done on a complete driver tends to show a complicated jumble of frequency and amplitude dependent distortion products. An IMD measurement shows another jumble. Figuring out what distortion component in the reproduced sound is produced by what element is remarkably hard.

Getting round this requires decoupling the problem again and trying to predict what each part will do on its own. After following the evidence with quite some rigour, PURIFI identified two significant distortion mechanisms that have gone mostly unnoticed: Force Factor Modulation (FFM) and Surround Radiation Distortion (SRD). Together they explain practically all low-frequency distortion that currently remains in otherwise well-designed drive units.

For something as notoriously complex as a loudspeaker driver, this list is startlingly short. Really? Just those two? And nobody has noticed before? Things become less mysterious when you look at the distortion signatures of FFM and SRD. They are very similar in nature and magnitude. For someone with an experimental penchant (and let's be honest, that's all of us in the speaker industry) it's easy to hypothesise one of these problems and try a fix. Only to find that distortion has barely budged. So that wasn't the problem we think and move on.

Once you know what to look out for, you'll find various products that have indeed attempted to solve one problem or the other. None of them made history: it's only when you address both that distortion plummets and sonic magic happens.

THD, IMD

When we talk about distortion, there's often a distinction made between Harmonic Distortion (HD) and Intermodulation Distortion (IMD). These aren't two different types of distortion per se, but different ways in which the same distortion mechanism can manifest itself more or less saliently. Take for instance a woofer whose BL curve droops progressively with excursion. Tested with a single 30 Hz sine wave, this will only manifest itself as a form of soft limiting. This sounds like a change in tonal quality, but little more. The effect of the suspension progressively stiffening (Kms increases) with excursion would sound more or less the same in a single sine wave test. A HD measurement is not helpful in telling you which of the two effects is happening.

By contrast, imagine what happens if you add a 1kHz tone to the bass tone. The added excursion caused by the 1kHz component itself is negligible. But now the two distortion mechanisms show very different signatures. As BL rises and falls throughout the 30 Hz cycle, so does the sensitivity of the motor. The 1 kHz tone gets amplitude modulated. You can hear the 1 kHz tone wobble. BL droop manifests itself not only as harmonic distortion, but also as intermodulation. The variable stiffness of the suspension however has no such effect. The 1 kHz tone will not be modulated by suspension stiffness. Why should it? 1 kHz is well above the resonance frequency, so there the mass of the cone completely dominates how the 1kHz component makes the cone move. The difference between the two distortion mechanisms is plainly audible on any genre of music that has both bass and midrange content. And as a distortion mechanism, the droop of the BL curve is much more audible than the progressive stiffening of the suspension.

This is rather important. One often encounters drivers where two different distortion mechanisms are precisely orchestrated to make their harmonic distortions cancel. Such drivers look great on paper but this sleight of hand actually worsens IMD.

Even though there are no standardised methods of presenting loudspeaker IMD measurements on paper, it is quite crucial to learn to think about loudspeaker nonlinearities in terms of intermodulation rather than harmonic distortion.

Force Factor Modulation (FFM)

The impact of position dependent force factor BL(x) and the position dependent suspension stiffness Kms(x) have been well publicised. These parameters aren't nearly enough to predict real life distortion performance though. They only predict distortion when excursion is large, which you only get when you play bass heavy music very loud. If the BL(x) and Kms(x) duo are to be believed, all speaker drivers ought to have the same negligible distortion under normal listening conditions. This we know is not the case.

PURIFI has extended the purely statistical concept of BL(x) into a dynamic one that includes time and voice coil current. The new mathematical model correctly predicts motor force for an arbitrary combination of applied voltage signal and movement. The model reveals that all motor distortion that can't be explained by BL(x) can be explained by something called Force Factor Modulation. FFM happens when the magnetic field created by the current in the voice coil adds itself to the magnetic field created by the permanent magnet. Ideally, the magnetic flux in the air gap is only determined by the magnet and the geometry. In practice, it varies strongly because of the current in the voice coil. The problem is exacerbated in long-stroke drivers because a larger portion of the coil is creating this unwanted magnetic field without actually producing useful drive force. This goes some way in explaining why short stroke, large diameter woofers have such a faithful following. It also tells you exactly what problem to solve to get the same sound out of a compact long stroke design.

The distortion takes the form of the signal being multiplied with a filtered version of itself, so it is predominantly second order in nature. Now, there is a common misconception that second order distortion is innocuous. This may be largely true of harmonic distortion where a second harmonic is easily masked by the fundamental, but in the case of intermodulation distortion it is patently false. Second order IMD generates difference frequencies which are below the signal frequency and don't get masked at all. They audibly clog up the bass region in a manner which becomes extremely obvious once you remove the distortion. Also, amplitude modulation of mid frequency signals by the bass is very audible as burbling.

A second important insight was that Force Factor Modulation isn't just linked to position dependent inductance and to reluctance force (=the attraction between the coil and the iron parts), but that all three phenomena are actually one and the same thing. This insight has driven the design of PURIFI's new motor which is virtually free from force factor modulation.

Additionally, the new motor allows FFM and BL(x) droop to be optimized independently. It wouldn't help much to remove FFM and then to find distortion dominated by classical BL droop, so additional refinements were made that make the static BL(x) curve extremely flat over a large excursion range. The linearity of PURIFI's motor is significantly better than what was historically possible with short-stroke designs.

With Force Factor Modulation comes a side order of Magnetic Hysteresis Distortion. If the magnetic flux in the gap varies with current, any iron in the gap will be subject to that varying flux. Magnetic hysteresis is quite different from saturation. Saturation is a fairly benign, soft-limiting type of distortion that happens at very large signal levels. Hysteresis by contrast happens at all signal levels and lends a grainy, hazy type of distortion to almost any transducer that contains iron. In terms of measurements, hysteresis distortion tends to dominate the midrange (well above resonance and below breakup) outright. Hysteresis distortion is worst in underhung drivers because of the sheer volume of iron surrounding the voice coil.

This explains the recent arrival of so-called "iron free" drivers. Such drivers do address the problem, but at enormous expense. PURIFI's motor combines the performance advantage of iron-free while retaining the economic and technical benefits of using iron to shape the magnetic circuit.

Surround Radiation Distortion

The surround is generally considered part of the suspension, and as such only its contribution to Kms(x) is noted. Its contribution to sound output is rarely noted. In modern (i.e. long-stroke) drive units the surround can easily make up 20% of the radiating surface. It would be optimistic in the extreme to expect that a piece of deforming rubber will end up radiating undistorted sound. Indeed, it does not – its distortion contribution exceeds that of the cone by orders of magnitude. Again the distortion is second order in nature and most obvious at low frequencies. But again that introduces intermodulation distortion affecting the entire frequency range of the driver. SRD is the second reason why large diameter, short stroke drivers have a leg-up. The surround simply takes up a smaller percentage of the moving area. Clearly though, that is only half a solution. The real solution lies in finding a design whose acoustical output is distortion free.

This is what PURIFI has done. Depending on the application PURIFI deploys differently shaped surrounds to neutralise SRD. The precise shape is determined by numerical optimisation, but the result is that across the full excursion range, the surround moves an amount of air that's precisely proportional to excursion.

Conclusion

It is possible to build compact long-stroke matching or bettering the audio performance of short-stroke, large-area drivers. Doing so requires addressing two very specific distortion mechanisms: Force Factor Modulation and Surround Radiation Distortion. PURIFI's drivers put these insights into practice.