Magnetic cores even more noisy: mechanical resonances

In our previous paper "The issues with noisy magnetic cores and how to solve them", we explored the different sources of noise caused by magnetic flux and some of the methods you can use to reduce this noise. However, the noise caused by magnetic flux can be exponentially increased due to mechanical resonance.

Magnetic cores can be considered as elastic bodies having natural frequencies. When the cores consist of different parts, which are coupled mechanically and by magnetic forces, we have to consider them as coupled oscillators. Therefore, a large number of natural modes exist, which interfere – creating a variety of mechanical resonant frequencies.

When the exciting signal in a component matches a resonance frequency, the "normal" noise can be amplified to a horrible volume. More dangerous in terms of application: power losses can be increased by order of magnitudes, and impedance changes drastically, affecting the functionality of the component.

How mechanical resonances are caused inside the core material

In a closed core, ie without a gap, the flux is guided exclusively within the core and the only source of noise is magnetostriction, a material property that describes a change to the material's shape or dimensions during the process of magnetisation.

Magnetostriction is the change in length is caused by induction and is normally defined as:

$$\frac{\Delta l}{l} \sim \lambda_S \left(\frac{B}{B_S} \right)^2$$

We have to be aware that B is a vector, ie length change and induction, are to be considered in the same direction and that the volume of the core remains constant. That means – in one direction the core may lengthen and in another direction shorten.

As a simplification, the induction is considered to follow a sinusoidal wave form (AC part), with a superimposed DC-Bias:

$$B = B_{DC} + B_{AC} \sin(\omega t)$$

Hence

$$\Delta l \sim B_{DC}^2 + 2 B_{DC} B_{AC} \sin(\omega t) + B_{AC}^2 \sin(2\omega t)$$

What we hear are two different frequencies, depending on the relevance of the bias:

a) $B_{DC} \rightarrow 0$: Mechanical oscillation has double frequency as the electrical excitation, or: a mechanical vibration is excited by an electrical signal with half frequency. "50Hz hum" is actually 100 Hz tone,

b) $B_{DC} >> B_{AC}$: Mechanical oscillation follows the electrical excitation.

Of course, the induction never follows a pure sinus – ie we have to consider higher harmonics of the exciting signal (current) and resulting induction.

The exciting signal creates fluctuations of density within the core, which produces compression waves and finally sound waves. When these sound waves also match the materials mechanical natural frequencies, this is the worst case scenario and it can only be described mathematically for simple shapes. For example, in a rod with free ends, the resonance frequency is described as:

$$f = \frac{n}{2l}\sqrt{\frac{E}{\rho}}$$

l = length, E = elastics (Young's) modulus, ρ = density, n = order (harmonics)

N = 1 corresponds to lengthen and shorten the bar while narrowing and broaden it, respectively (see fig. 1 left in the previous paper). N = 2 means, that one half of the rod lengthen, the other shorten, etc. This is valid for the length of bar cores, but also for other shapes with one constant "length" in one direction, for example, the height of toroids or E-cores. A toroid is considered in this case as a very broad and curved rod, and l is actually the height. Therefore, we will call these resonances transversal. Since these dimensions are well defined, the resonances are very sharp.

For a toroid, the resonance frequencies along the circumference (we will call the longitudinal resonances) are

$$f = \frac{n}{u}\sqrt{\frac{E}{\rho}}$$

u = circumference

N = 1 means again, the complete toroid increases / decreases the circumference (see fig. 1 right in the previous paper), etc. Since the circumference is distributed from inner to outer diameter, the resonance is less sharp.

Fig. 1 shows the simplest case in practice: We have toroidal cores of material with B_S ~ 1.2T with different saturation magnetostriction which, when excited, corresponds to about a 50mT AC and 700mT DC Bias. The resonance of around 18kHz is the first longitudinal resonance mode, at 110kHz the first transversal. 7ppm saturation magnetostriction is not the worst case scenario for a soft magnetic core material – but the increase in power losses, due to the DC bias, is already dramatic.

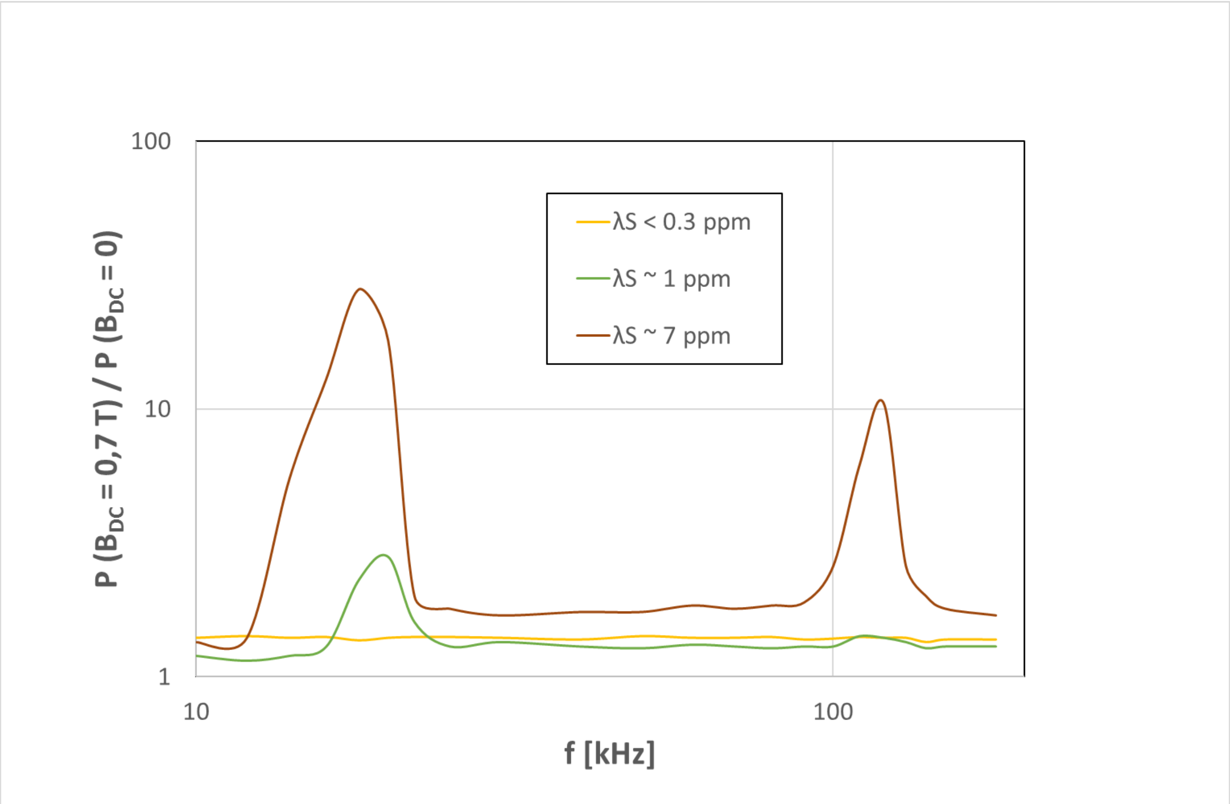

Fig.1: Toroidal cores with B_S ~ 1.2T and different magnetostriction: core losses P (at B_{AC} = 50mT) as a function of exciting frequency, displayed as the ratio between with and without DC Bias.

Fig. 2 shows a more complex picture: for a material with 7ppm magnetostriction, we compare the results with and without bias, and different operational and test conditions: power losses with significant AC amplitude, and µ" (also indicating losses) at very small amplitude. The intensity of the resonance effect is different, even the frequencies are shifted. Most eye-catching: without DC, the resonances are excited by half frequency, denoted as 1/2 L1, for example, The L1 resonance at about 50kHz is excited by an operational frequency of 25kHz – remember the 50 Hz / 100Hz hum paradoxon.

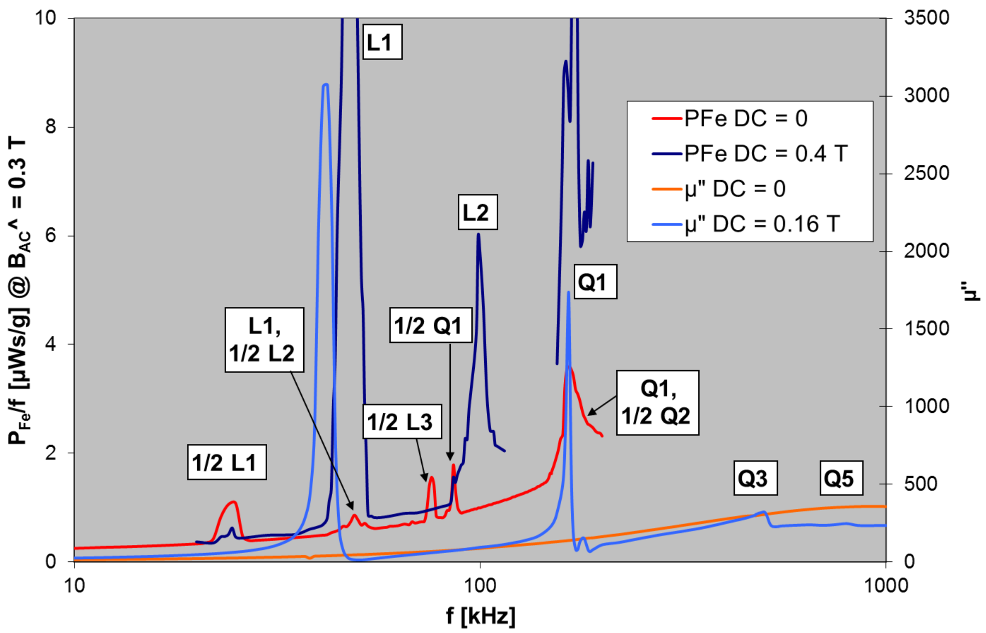

Fig.2: Toroidal core with B_S ~ 1.2T and λ_S ~ 7ppm: core losses P_{Fe} and imaginary part of permeability µ" as a function of exciting frequency, both with and without DC Bias. L indicates longitudinal, Q transversal resonance modes; the number the order.

Even if it appears to be complex – a toroid is a simple geometry. Knowing density and elastics modulus, one can calculate roughly dangerous frequencies and adjust dimensions or application parameters to avoid problems. But imagine an EFD shape, there is a really complex resonance spectrum, hard to calculate, but fortunately, the resonances are broad and less pronounced than in a simple case with well-defined geometrical structure.

The additional challenges of multi-part cores

In the next step, we consider the challenges caused by a core consisting of different parts, like a cut core. The parts attract each other when magnetized. Usually, the parts are connected by glue, potting around them, clamps or fastener straps. That means there is a mechanical force between the parts depending on the actual distance. Note that small relative movements are possible even when the parts are connected – materials are elastic, and we speak about audible displacements <1µm.

Under these circumstances, the parts have a natural frequency depending on the modulus of resilience (comparable to spring constant), and the mass. If we consider the connection between a core part and the "environment" like a spring, for example, resonance frequency depends on spring constant D and mass m as:

$$f \sim \sqrt{\frac{D}{m}}$$

If the operational frequency of the device matches this natural frequency (or higher harmonics), resonance occurs again. In the audible range, the noise levels can easily exceed the noise of the resonances from magnetostriction. Both the resonance frequencies of different parts and the amplitude of displacement, ie the noise is mainly controlled by the kind of mechanical connection (force dependent on displacement). This gives us the strategy to control it: we can change the mass (the size and mass of both parts of a cut core can be different, for example), or we may vary the mechanical construction and connection technique.