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Comparison of Toroid and E-I Magnetic Core in Modern Common Mode Choke

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Abstract. In contemporary power electronic systems, common-mode chokes are crucial parts for suppressing electromagnetic interference (EMI). High-permeability magnetic material is always desired by engineers to achieve higher inductance and better noise suppression. This article compared the inductance, impedance, and frequency response of two commonly used magnetic core structures: E-I cores and toroidal cores. Experimental results show that toroidal cores offer higher inductance at low frequencies, but their performance degrades significantly above 100 kHz due to core loss and magnetic saturation. On the other hand, the small natural air gap between the E and I elements reduces effective permeability, helping to minimize high-frequency losses and allowing the E-I core to maintain more stable characteristics across a wider frequency range. In order to address the trade-offs between permeability, inductance, and stability, the article also compares two ferrite materials (R10K and R15K) and discusses how material selection influences performance, providing useful guidance for modern common-mode choke design.

Keywords: Common mode choke, EMI, Permeability, Air gap

1. Introduction

In the research area of electromagnetic compatibility (EMC), the continuous pursuit of higher functionality, improved performance, and reduced production costs has become a dominant trend in the development of modern electrical and electronic systems. However, these advancements are often accompanied by a side effect: an inevitable increase in the level of electromagnetic interference (EMI) that such systems generate. As devices become more compact and operate at higher switching frequencies, the emission spectrum of unwanted noise tends to broaden, posing significant challenges for EMC design. To address these challenges, electromagnetic interference filters have been widely adopted, and among their critical components, the common-mode choke stands out as a fundamental building block. This component plays a decisive role in suppressing common-mode noise, especially in power conversion and switching applications, where power electronic devices typically produce disturbances over a wide frequency band ranging from a few kilohertz to several megahertz [1,2]. In power supply systems, electromagnetic noise can generally be divided into two categories: differential-mode noise and common-mode noise.

Differential-mode noise appears when current flows in opposite directions through the signal line and the return (ground) line. In contrast, common-mode noise propagates along all conductors

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within the cable in the same direction. To suppress the latter, common-mode choke coils are employed. When common-mode currents pass through the choke, they generate magnetic flux that accumulates inside the ferrite core, enabling the device to function effectively as an inductor and thereby attenuate the unwanted noise. For differential-mode currents, however, the magnetic flux induced in opposing directions tends to cancel out, which means the choke offers little impedance to these currents and issues such as magnetic core saturation remain minimal [3]. In this paper, the different magnetic structures will be clarified. The air gap's function in E-I core common mode choke will be explained with EMI test phenomenon.

Table 1. E core and Toroid core comparison

Core Shape	Advantages	Disadvantages
E cores	1. Winding structures can be realized with relatively low cost. 2. The generated heat can be dissipated efficiently. 3. Installation is flexible, allowing multiple mounting orientations. 4. Direct mounting onto printed circuit boards (PCBs) is supported. 5. The assembly process is straightforward and convenient.. 6. Core materials are generally inexpensive and easily available.7.Cores are inexpensive.	1. Shielding is minimal.
Toroid	1. Minimal radiated magnetic flux. 2. Does not require additional mounting accessories. 3. Core materials with low magnetic loss are available. 4. Air gaps can be introduced to adjust magnetic characteristics. 5. Rounded edges reduce the risk of wire bending stress. 6. Surface coating or painting is possible. 7. Core materials are generally cost-effective. 8. High input impedance is achievable.	1. Specialized winding equipment is required for toroidal shapes. 2. Susceptible to external stray magnetic fields. 3. Cores may experience saturation under unbalanced excitation conditions.

2. Comparison of E-I core and toroid core common mode choke

Common mode choke can have many different shapes: toroid, E cores, pot cores, etc. Each structure has its advantage and disadvantage. Shows in Table I [4].

3. Inductance vs. frequency

International Special Committee on Radio Interference is responsible for the EMC requirements with (CISPR22) defining the strictest limit on conducted emissions. These limits (conducted emissions) core described in the product standards EN55022 limits for class B digital devises, in the frequency range of 150Khz to 30Mhz [5].

Power board needs to pass the conductive emission test using Line Impedance Stabilization Network based on CISPR22. The interesting phenomenon is using E-I core as common mode choke has better performance than using toroid core common mode choke even E-I core common mode choke has lower inductance than toroid core common mode choke.

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The only variable in this experiment is common mode choke's structure, analyzing the effect for differential mode noise and common mode noise will not clarify in this paper.

$$L = \frac{\mu n^2 A_c}{\ell_m}$$

L: Inductance
μ: core permeability
n:number of turns
Ac: effective cross section area
Lm: mean magnetic path length

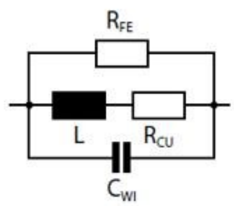
Figure 1. Inductance formula and explanation

Table 2. Detail of two different common mode choke

Core Shape	Core permeability	Turn	Ac(mm²)	Lm(mm)	Inductance(uH)
Toroid	10000	6	28	43.98	295
E-I	10000	6	60.5	32.8	270

Fig.1 indicates the inductance definition formula. We selected the toroid common mode choke with inductance 295uH and E-I core common mode choke with inductance 270uH. (Test condition is 0.1 Volts with 1 Kilohertz) To be fair, both common mode choke used the same core material and wind the same turns. The detail shows in table2.

In [2], it gives us an equivalent circuit of the common mode choke validating up to 40Mhz. The test frequency range is 1Khz to 10Mhz in this experiment. The simplified equivalent model shows in Fig 2.



R_{FE}: equivalent magnetic loss
L: Inductance
R_{CU}: copper loss
$C_{WI:}$ winding capacitance

Figure 2. Common mode choke simplified model

For the ideal common mode choke, the impedance would increase with the rising frequency. With the winding capacitance and other parasitic parameters, the relationship between impedance and frequency does not linearize. The test results show in Fig.3 and Fig.4

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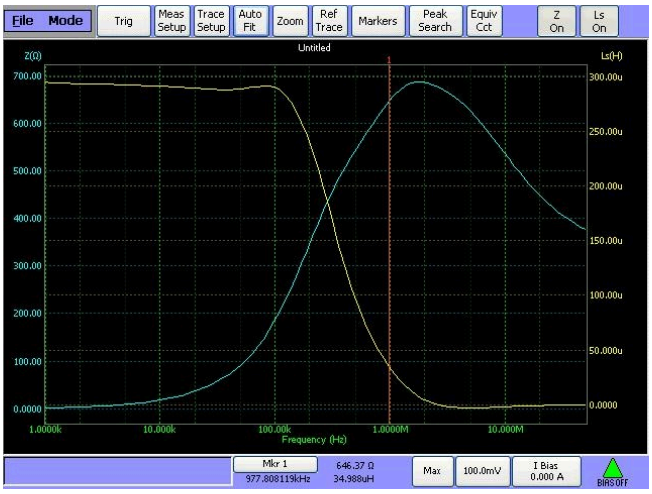

Figure 3. Toroid core frequency vs. inductance (impedance)

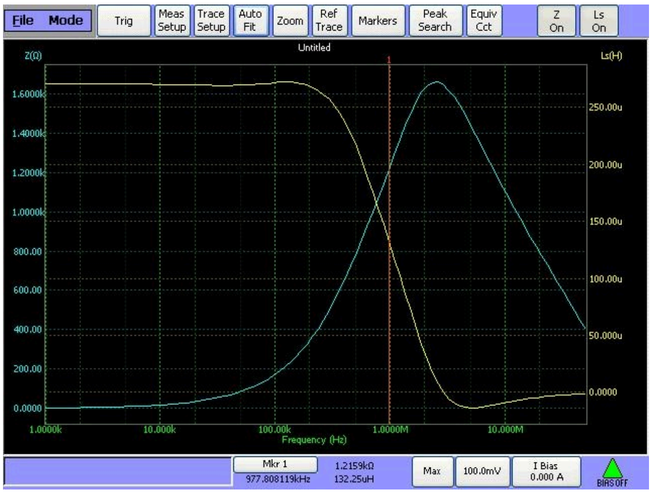

Figure 4. E-I core frequency vs. inductance (impedance)

The marking line in Fig.3 and Fig.4 measuring the inductance and impedance at 977.808Khz. At this point, toroid common mode choke's inductance is 34.988uH, E-I common mode choke's inductance is 132.25uH. To compare the two shape common mode chokes inductance clearly, we pick up some key frequency points and redraw the inductance along with frequency plot. Shows in Fig.5.

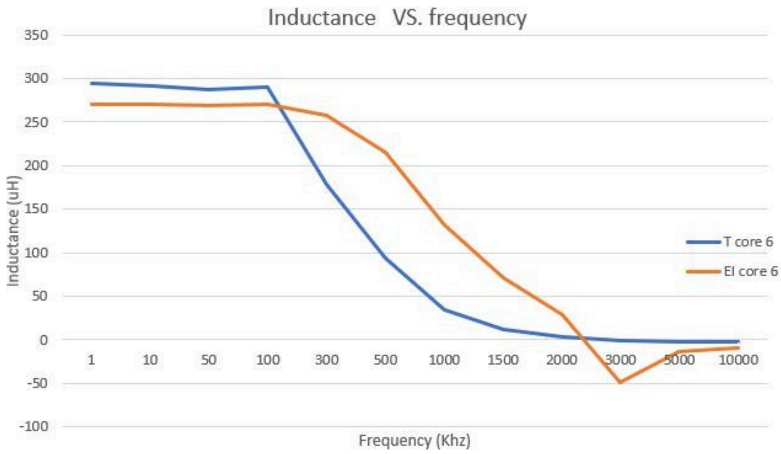

Figure 5. Comparation of Toroid and E-I common mode choke's inductance VS. frequency curve

Obviously, toroid common mode choke has a higher inductance than E-I common mode choke before 100Khz, however, toroid common mode choke's inductance drops dramatically as frequency above 100Khz.

4. Make use of the air gap

Calculate E-I common mode choke's inductance with Fig.1's formula. The inductance according to the formula should be 834.44uH.

$$L = \frac{\mu * n^2 * A_c}{l_m} = \frac{10000 * 4 * \pi * 6^2 * 6.05 * 10^{-4}}{3.28} = 834.44uH$$

After a lot of research and consulting, the reason why the E-I core's inductance much lower than calculation is there has the inartificial air gap in between E core and I core. Fig.6.

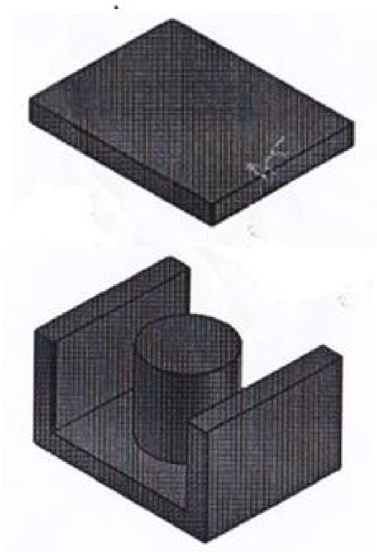

Figure 6. E-I magnetic core

The effect of an air gap is to reduce the permeability and to make the coil's characteristics less dependent upon the initial permeability of the core material. For other applicationsA gap helps prevent saturation under large AC or DC currents and allows better control of inductance, but in a common-mode choke, the flux from the two windings cancels each other. According to [6], the effective permeability formula shows in Fig.7.

$\mu_e = \dfrac{\mu}{1+\dfrac{l_g}{l_e}\mu}$	μ_e: Effective Permeability
	μ: Permeability
	l_g: air gap length
	l_e: effective magnetic circuit length

Figure 7. Effective permeability formula and explanation

This formula is valid for closed magnetic cores of any geometry, provided that the initial permeability is high and the gap is relatively small. According to manufacturer data, the air gap between an E-core and an I-core typically ranges from 5 μm to 10 μm.

Calculate the effective permeability using E-I core's parameters, see equation (1) for an example:

$$\mu e = \frac{L*lm}{0.4*\pi*Ac*n^2} = \frac{270*3.28}{0.4*\pi*0.605*6^2*0.01} = 3235.7148$$

From Fig.7's formula, the estimate air gap depth can be calculated, see equation (2) for an example:

$$Lg = \frac{\left(\frac{\mu}{\mu e}-1\right)*le}{u} = \frac{\left(\frac{10000}{3235.7148}-1\right)*3.28}{10000} = 6.8569um$$

The inartificial air gap between the test sample is about 6.8569um. Due to this air gap, the effect permeability becomes less sensitive to the frequency. On the other hand, toroid core makes up of ferrite without any air gap. Its permeability drops sharply as frequency above 100Khz. Fig.8 [7].

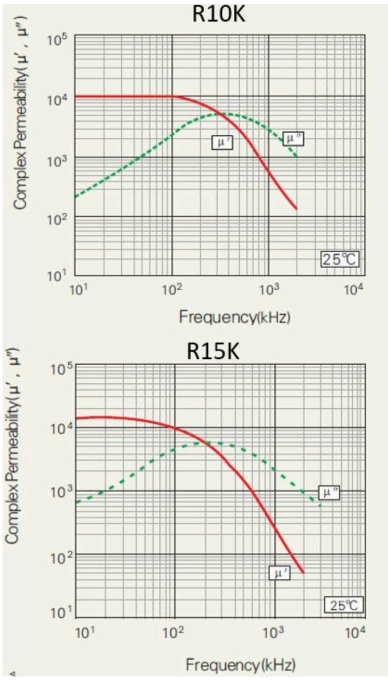

Figure 8. R10K and R15K material

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The most popular material for common mode choke is initial permeability 10000 Mn-Zn ferrite, such as R10K from DMEGC [7], T38 from EPCOS and W type from Magnetics. In most design solutions, engineer pursuits high permeability to build a high inductance common mode choke. The product's frequency response is also important. In pursuit of high permeability will result in inductance and impedance dropping early. Below plot shows the initial permeability 10000 and the initial permeability 15000 material E-I core's impedance with frequency response.

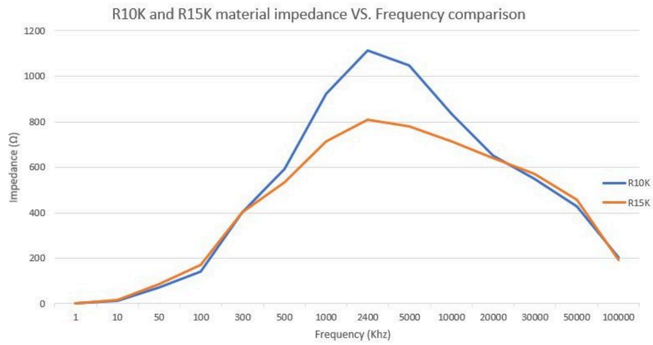

Figure 9. R10K and R15K material impedance vs. frequency

Clearly, the impedance of R10K material performs better than R15K material. The reason can be seen in Fig.8. R15K has poor frequency stability above 300Khz. Higher the permeability may not result high inductance.

Insertion loss of the common mode choke coil will be reduced when the ferrite core contact surface is polished [8]. The inartificial gap will reduce after polish, further, the air gap will reduce its height which will lead to less fringing effect and less loss.

5. Conclusion

Design a common mode choke does not need to care too much about core saturates and core loss. This makes designer chase a high permeability material to get a high inductance. After comparing the different core structure's common mode choke, the truth is, different structure can also have an influence on the common mode choke even they have the same inductance. The micron level air gap in between E core and I core makes the effective permeability smaller than initial permeability and makes E-I structure common mode choke more robustness to frequency than toroid structure common mode choke.

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