A Novel Broadband High Sensitivity Current Probe Design and Analysis for Conducted Emission Testing

Sha Miao¹, Teng Wanxiu¹, Song Gang¹, Mu Xiaotong², Shang Baoying³, Song Jilei⁴, Lv Dongxiang⁵

¹ CRRC Changchun Railway vehicles CO, LTD, No.435 Qingyin Road, Changchun, China.
² Bei Hang University, No.37 Xueyuan Road, Haidian distrcit, Beijing, China.
³ Shenzhen beihang testing co. LTD, No.1, Xuefu road, shenzhen, China.
⁴ BeiHang engineering technology center (Shenzhen) CO. LTD, No.2, Yunxing road, Nanshan district, Shenzhen, China.
⁵ Foshan Shunde Hangce electromagnetic compatibility technology CO. LTD, No.12, West road, Shunde district, Foshan, China.
ledisun@163.com

Abstract. Current probe is one of the most important measurement equipments in electromagnetic compatibility (EMC) for electromagnetic conducted emission testing. The measurement sensitivity of the current probe can directly affect the testing results. A novel broadband high sensitivity current probe is designed and analyzed by combining calculation method of equivalent circuit and high frequency electromagnetic field. The Fe based microcrystalline is used for the magnetic core of the novel current probe. The structure dimension is determined according to simulations and analyses. The novel current probe is compared with the commercial current probes by practical testing. The testing results show that the sensitivity indexes of the novel current probe surpass that of the commercial ones nearly 10 dB from 20 Hz to 10 kHz. Besides, the transfer impedance indexes of the novel current probe could attain the performance of commercial probes from 10 kHz to 500 MHz.

1. Introduction
Conducted emission testing is one of the core contents in electromagnetic compatibility (EMC) testing. The conducted emission testing is divided into two types. One is conducted interference voltage testing. The other is conducted interference current testing. The conducted interference current is tested by the current probe and auxiliary instruments. The current probe is clipped to the mains of equipment under test (EUT). The electromagnetic signals generated from the mains are detected by the current probe according to Faraday's law of electromagnetic induction. The electromagnetic signals transmitted to the receiver are recorded. The conducted interference current of the mains under test is obtained by calculating the recorded results [1].

The conducted emission testing used the current probe is a convenient method, which has a low requirement for the testing environment. So the current probe used in the conducted emission testing has been paid more and more attentions. So far, the researched of the current probe mainly concentrate...
in calibration precision [2-3]. The influences of the performance indexes of current probe [4-5], mainly consisted of new EMC test methods, uncertainty of measurement in EMC test and so on [6-7].

In recent years, some researchers proposed a new conducted interference voltage testing method used current probe without line impedance stability network (LISN) [8]. The new method expands the application range of the current probe. The current probe is used more widely in EMC testing.

So far, there are no literature records of researches on measurement sensitivity of novel currents. A novel broadband high sensitivity current probe is proposed in this paper. The transfer impedance of the novel current probe is dramatically improved in a low frequency band from 20 Hz to 10 kHz. Besides, the transmission performance of the novel current probe is satisfied to the testing requirement from 10 kHz to 500 MHz. The novel current probe is suitable for different standard testing from 20 Hz to 500 MHz.

2. Modelling analysis and design

The current probe is used to detect electromagnetic conducted emission of the mains under test in this paper. According to the working principle of the current probe, the working process can be equivalent to a mutual inductance coupled circuit. The circuit principle diagram is shown in figure 1.

![Figure 1. The equivalent circuit of the current probe working process is established based on a transformer model.](image)

In figure 1, the mains under test are equivalent to the primary coil, the current probe is equivalent to the secondary coil. Lp is the self-inductance of the primary coil. Ls is the self-inductance of the secondary coil. LM is the mutual inductance of the circuit. Ip is the current in the mains under test. Is is the induced current of the secondary coil. Rs is the self-impedance of the current probe. R0 is the load impedance of the circuit. RM is the loss impedance of the magnetic core. C is the distributed capacitance of secondary coil. V0 is the terminal voltage of the load. The values of RM and C change with the increase of the operating frequency of the circuit. The self-impedance of primary coil is far less than the mutual inductance of the circuit which could be neglected in the calculation. According to the definition of the current probe transfer impedance, the calculation equation of current probe transfer impedance is

\[
Z_i = V_i/I_p
\]  

(1)

When the operating frequency of the circuit is less than kilohertz, the values of the loss impedance and the distributed capacitance of the magnetic core are very small that can be neglected in calculation. The primary coil is equivalent to a current source. According to Kirchhoff’s Current Law, the equivalent circuit calculation equation is

\[
j\omega L_{m} I_p = j\omega (L_{s} + L_{m}) I_s + I_s R_0
\]  

(2)

Substitute equation (2) is into equation (1),

\[
Z_i = \omega \cdot L_{m} / \sqrt{1 + [\omega (L_{s} + L_{m})/R_0]^2}
\]  

(3)

where, \(\omega\) is the angular frequency of the circuit. When \(\omega \leq R_0/(L_S + L_M)\), as well as the operating frequency \(f \leq R_0/2\pi(L_S + L_M)\), equation (3) is transformed to
It is analyzed from equation (4) that when the current probe works in a low frequency band, the value of the transfer impedance $Z_t$ linearly increases with the operating frequency. It can be seen from equation (3) that when $\omega >> R_0/(L_S+L_M)$, as well as the frequency $f >> R_0/2\pi (L_S+L_M)$, the transfer impedance calculation equation is transformed to

$$Z_t = (R_0 \cdot L_M)/(L_s + L_M)$$

(5)

It is analyzed from equation (5) that the transfer impedance is related to the values of mutual inductance, secondary self-inductance and load impedance. RM and C increase with the increasing operating frequency. At this time, according to Kirchhoff’s Current Law, the transfer impedance of current probe calculation equation is

$$j\omega L_M = I_s \left[j\omega (L_n + L_M) + Z\right]$$

(6)

where, $Z$ is the loss impedance of the secondary coil, which is calculated by

$$Z = 1/(1/R_s + 1/(R_0 + R_n) + j\omega C)$$

(7)

According to equations (1) and (6), the transfer impedance $Z_t$ calculation equation is transformed to

$$Z_t = (j\omega L_M \cdot (Z + j\omega (L_n + L_M))) \cdot (Z \cdot R_n/(R_0 + R_n))$$

(8)

According to equations (1) and (7), the transfer impedance $Z_t$ calculation equation is transformed to

$$Z_t = \frac{(j\omega L_M \cdot R_0)\left(\frac{(R_0 + R_n + R_M)}{R_s \cdot (R_0 + R_n)} + j\omega C\right)}{(R_0 + R_n)\left[\frac{1}{R_s \cdot (R_0 + R_n)} + \frac{1}{R_0 \cdot (R_0 + R_n)} + j\omega C\right]}$$

(9)

where, $R_0$ is 50Ω. Rs is far less than $R_0$, and $L_s$ is far less than $L_M$. Therefore, $R_s$ and $L_s$ can be neglected in the calculation. So, equation (9) is transformed to

$$Z_t = \frac{j\omega L_M \cdot (R_0 + R_n)}{R_s \cdot (R_0 + R_n) + j\omega C}$$

(10)

When the operating frequency $f$ increases to megahertz, $(R_0 + R_M)/(R_M - R_0) + j\omega C > 1$. At the same time, $Z_t$ linearly decreases with the increase of the frequency. Otherwise, $R_M$ and $C$ increase rapidly with the increase of the frequency. This situation leads $Z_t$ to present nonlinear changes with the increase of the frequency. In this case, $Z_t$ cannot be calculated by equivalent circuit method directly. It is indicated that the transfer impedance of current probe need to be calculated by electromagnetic field numerical calculation method in radio frequency (RF) band.

In terms of equations (4), (5) and (8), it is analyzed that the transfer impedance is mainly depended on $L_M$ from hertz to megahertz. According to the mutual inductance generation principle of the circuit, $L_M$ can be represented by

$$L_M = KL_s$$

(11)

where, $K$ is the coupling coefficient, $L_P$ is the self-inductance of the primary coil, $L_s$ is the self-inductance of the secondary coil. $L_P$ is far less than $L_s$ which can be neglected. When the mutual inductance coupled circuit works from hertz to megahertz, the leakage flux of the magnetic core is tiny. $K$ is approximately equal to one. The self-inductance of the secondary coil should be improved in order to improve the mutual inductance of the circuit. The self-inductance of the secondary coil is related to the materials and the structure of the current probe. The calculation equation of the inductance of the magnetic core is

$$L = (k\mu_0 N^2 S)/l$$

(12)

where, $\mu_0$ is vacuum permeability with the value of $4\pi \times 10^{-7}$, $\mu_s$ is the relative permeability of the magnetic core, $N$ is the number of windings around the magnetic core, $S$ is the cross sectional area of the magnetic core, $L$ is the length of the magnetic core, $k$ is the magnetic core coefficient which depends on the ratio of the radius and the length of the magnetic core. In equation (12), the self-inductance $L_s$ of the secondary coil is mainly related to the magnetic core and the structure of the current probe. In order to improve the transfer impedance of the current probe from hertz to megahertz,
In addition to modify the structure of the current probe, it is necessary to select the material with high magnetic permittivity for the magnetic core. According to the above analyses, there are four kinds of materials are selected, which are Fe based amorphous alloy, cobalt based amorphous alloy, Mn-Zn ferrite, and Fe based microcrystalline alloy respectively. The characteristics parameters of the four materials are given in Table 1.

### Table 1. The characteristics parameters of the four materials for the magnetic core of the current probe.

|                      | Permeability         | Saturation flux density (T) | Coercivity (A/m) | Magnetic moment ratio | Magnetic core loss (kw/m³) | Curie temperature (°C) | Saturation magnetostrictive constant (e-6) | Resistivity (Ω*m) | Density (mg/m³) |
|----------------------|----------------------|----------------------------|------------------|-----------------------|---------------------------|------------------------|--------------------------------------------|------------------|---------------|
|                      | 50 Hz                |                            |                  |                       |                           |                        |                                            |                  |               |
| Fe based microcrystalline alloy | >20000               |                            | 1.3              | 0.6                   | 350                       | 570                    | 2.3                                        | 1.1e-6           | 7.4           |
| Mn-Zn ferrite        | 2000                 |                            | 8                | 0.23                  | 1200                      | 150                    | 0                                         | 0.2              | 4.85          |
| Cobalt based amorphous alloy | >50000               |                            | 0.32             | 0.5                   | 300                       | 180                    | 1.3e-6                                     | 1.3e-6           | 7.7           |
| Fe based amorphous alloy | >15000               |                            | 5                | 0.65                  | 2200                      | 415                    | 1.4e-6                                     | 1.4e-6           | 7.18          |

a The D.C. Magnetic properties in the maximum magnetic field of 800 A/m.
b The measurement environment is $B_m=0.2$ T at 199 kHz.

It can be seen from Table 1 that the characteristics of the traditional Mn-Zn ferrite material like the parameters of permeability, core loss, and saturation of magnetic are far lower than those of the microcrystalline and amorphous alloy materials. The various characteristic parameters of the microcrystalline and amorphous alloy materials are comprehensive considered. Besides, in order to take into account the actual requirements of the current probe, the Fe based microcrystalline alloy material is selected as the magnetic core for the current probe.

According to the analyses of the equivalent circuit of current probe, when the current probe is working from megahertz to gigahertz, the distribution parameter effect of the equivalent circuit is obvious, and the transfer impedance of the probe is nonlinear. At this time, the equations derived from the equivalent circuit cannot accurately calculate the transfer impedance of the current probe. Therefore, the transfer impedances of current probe are calculated by electromagnetic field numerical calculation method in RF band [9]. In this paper, different simulation tools based on different calculation methods are used to simulate the transmission characteristics of the current probe in RF band. The simulation results of different tools are comprehensive analyzed and optimized.
Figure 2. The comprehensive simulation and calculation transmission coefficients of the current probe.

The optimization results of the transmission characteristics of the current probe from 20 Hz to 500 MHz are obtained by using the above mentioned equivalent circuit calculation method combined with the electromagnetic field numerical simulation and calculation, which are shown in figure 2. It can be seen from figure 2 that the transmission coefficients of the current probe obtained by simulation and optimization are in accord with the characteristic curve of the typical current probe in operating frequency band in CISPR-16-1-2. It is indicated that the designed current probe is in line with the actual requirement, and which can be applied to the electromagnetic compatibility test.

3. Experimental verification

According to the standard ISO11452-4 of international organization for standardization (ISO) [10], the measurement method for the transfer impedance of current probe is shown in figure 3. Figure 3 (a) shows the self-calibration of the measurement system. Figure 3 (b) shows the measurement configuration for the transfer impedance of current probe.

![VNA calibration and measurement diagram](image)

(a) Calibration  (b) Measurement

Figure 3. The measurement method for the transfer impedance of current probe based on ISO11452-4.

It can be seen from figure 3 (a) that the measurement system must be self-calibrated before the transfer impedance measurement. The vector network analysis is used to calibrate the calibration fixture and the load. The voltage standing wave ratio of the measurement system must be less than 1.2. The measurement system is satisfied to the measurement precision. The measurement process is shown in figure 3 (b), the measurement system is used to test the transmission coefficient (S21) of the current probe.

The transfer impedance of the current probe is calculated by
The measurement results are compared with the simulation and calculation results. The comparison curves are shown in figure 4. It is observed from figure 4 that the transmission coefficients variation trend of the measurement results is almost conformed to the simulation and calculation results. The maximum error is less than 6 dB in the whole frequency band. Therefore, the actual performance of the novel current basically has reached to the design objective.

4. Conclusion
In this paper, the equivalent circuit model is used to calculate and analyze the transmission characteristics of the current probe. In accordance with the analyses, the use of Fe based microcrystalline alloy material as the magnetic core of the current probe is proposed. Multiple simulation and calculation methods are comprehensive used to simulate and analyze the transmission characteristics of the current probe in the RF band. The structure dimension of the current probe is determined by simulated and calculated. The novel current probe is fabricated and whose transfer impedance is compared with the commercial current probes’ in the operating frequency band. The comparison results verify that the sensitivity of the novel current probe is higher than that of the commercial ones by 10 dB average from 20 Hz to 1 MHz. The sensitivity of the novel current probe can achieve the performance of the commercial probe in the RF band from 10 kHz to 500 MHz. Therefore, the novel current probe is completely suitable for practical electromagnetic compatibility testing.

Acknowledgments
The paper is supported by South Wisdom Valley Innovative Research Team Program.

References
[1] Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods 2006 Part 12: Radio Disturbance and Immunity Measuring Apparatus—Ancillary Equipment—Conducted Disturbances (IEC Standard CISPR16-1-2)
[2] Road Vehicles—Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy 2005 Part 4: Bulk Current Injection (BCI) (ISO Standard ISO11452-4)
[3] Operating Manual, Current Probe, Calibration Fixtures, Fischer Custom Communications, Inc, 2009 (Torrance, CA, USA)
[4] MIL-STD-461G Requirements and Measurement of electromagnetic emission and susceptibility
for military equipment and subsystems 2015 *Washington, D. C: United States Department of Defense*, chapter 12 p 33-38

[5] Costa, F, et al. 1997 *IEEE Transactions on Industrial Electronics* vol 44 p 502-511

[6] Yao, L, Weiyu M, and Canyi Y 2014 *IEEE Electromagnetic Compatibility Magazine* vol 23 p 51-55

[7] Sekiguchi, Hidenori, Tsuyoshi F 2014 *IEEE Transactions on Electromagnetic Compatibility* vol 56 p 871-877

[8] Sen, O, et al 2015 *IEEE Electromagnetic Compatibility Magazine* vol 4 p 58-65

[9] Li, K, Kye Y S, Rathnayaka M, Sooriya B 2016 *IEEE Transactions on Electromagnetic Compatibility* vol 58 p 776-783

[10] Hanigovszki, Norbert, et al 2006 *IEEE transactions on power electronics* vol 21 p 273-281