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A New Calibration Method for Current Probes

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Abstract—EMC engineers often use current probes to detect common mode currents. It is necessary to characterize the probes up to Giga Hertz frequencies. Existing calibration methods for current clamps suffer from the problem of not directly measuring the current within the current clamp. Instead they either reconstruct the current from measurements at other locations or they use assumptions regarding the geometry which allows them to use a current that is measured at a different location without applying a mathematical correction. The proposed method overcomes these disadvantages by directly measuring the current at the center of the current clamp. This paper also discusses some of the non ideal effects of current clamps.

Keywords—current clamp; current probe; calibration; transfer impedance; transfer function

I. INTRODUCTION

Current probes are used in many EMC applications, for example, to identify the sources of radiation [1] or as injection probes to emulate the coupling of fields to wires [2]. Limiting the analysis to the application as current monitoring probes, the transfer impedance Z_{trans} is the most important parameter.

$$Z_{\text{trans}} = \frac{V_{\text{clamp}}}{I_{\text{wire}}} \quad (1)$$

Here, V_{clamp} is the output voltage of the clamp loaded with 50Ω in most cases. And I_{wire} is the current that is flowing in the wire at the center of the clamp.

A simple transformer model for a current probe is only valid at low frequencies as at high frequencies, the parasitics internal to the probe require the use of a complex equivalent circuit and the probe body scatters the field that is propagating along the wire [3]. The situation is further complicated by currents on the cable that connects to the probe. Exact analytical derivation of the transfer impedance based on details of the construction is only obtainable for the simplest cases. Consequently, there is need for the characterization of the probes up to GHz frequencies via experimental methods.

The basic drawback of present calibration methods [2, 3, 4, 5] comes from the way the current within the clamp is obtained. Instead of a direct measurement, it needs to be reconstructed using data measured somewhere else. In case of [2, 4], the geometry must be adapted to each clamp by maintaining a 50Ω transmission line impedance as good as possible, in order to determine the current with low uncertainty. The method proposed in [3] uses a good combination of time

and frequency domain measurements and processing to compensate for effects introduced by a simple setup, and allows determining the full S-matrix.

The method proposed in this paper, directly measures the current at the center of the current clamp, thus eliminating the need for complex data processing while directly obtaining the transfer impedance. This way the mechanical dimensions of the test setup are not critical anymore i.e., one setup can be easily used to measure a large variety of clamps.

II. MEASUREMENT SETUP

The current clamp is placed around a wire that carries a current. The current in the wire and the output voltage of the clamp are measured. The setup is shown in Fig. 1.

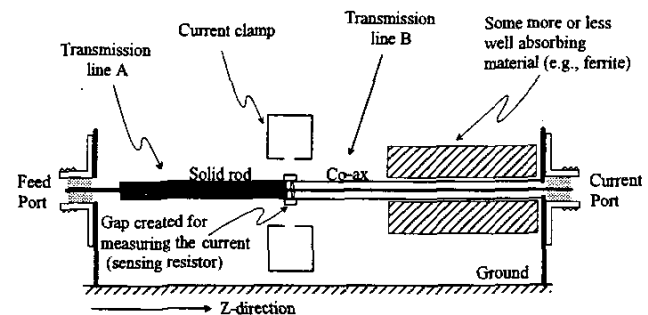


Figure 1. Calibration setup for current clamps using a series resistor to measure the current.

As shown in Figs. 1, and 2 only the inner conductor of the semi-rigid coax cable (Transmission line B) is connected to the rod of the transmission line system A. Disregarding the displacement current, the current which flows on the “center” conductor of transmission line system A must flow via the low impedance sensing resistor to reach transmission line B. The current is obtained from the voltage drop across the sensing resistor taking into account that from a current’s perspective the sensing resistor is in parallel with the terminated 50Ω impedance of the current port.

The setup comprises of the following elements as shown in Figs. 1, and 3:

- A feed port for creating the current by injecting a signal.
- A transmission line A from the feed port to the gap. The transmission line is formed by a solid rod above a ground plane. Here, the shield of a semi-rigid cable is used as the rod.

- A gap between two transmission lines (Gap). The gap allows measuring the current using a sensing resistor. The sensing resistor is formed by placing 0805 surface mount (SMT) resistors around the circumference of the gap to form a low inductance resistor, Fig. 4. Assuming a frequency independent real resistance, the current is given directly by the voltage measured at the “current port”. The value of the SMT shunt resistance should not be too low (e.g., 1 Ω maybe too low) as the mutual inductance may cause a frequency dependent measuring impedance. It should not also be too high, as the longitudinal E-field will cause a displacement current. The magnetic field of the displacement current would also be measured by the current clamp, but the displacement current would not be measured by the current sensing resistors, leading to a systematic error.
- A second transmission line (transmission line B) forms two transmission line systems: An inner one (made from a semi-rigid co-ax cable) that is used to connect the gap to the current port and an outer transmission line between the shield and the ground plane. Although not necessary for the function of the test method, the outer transmission line has the same cross section as the transmission line from the feed-port to the gap.
- A current clamp positioned above the gap.
- An absorbing structure placed on transmission line B. The purpose of the absorbing structure is to reduce the Current Standing Wave Ratio (CSWR) on the transmission lines A, B and in the gap region. As the current is measured via the current port, the absorbing elements do not have to provide a good match. They are mainly there to avoid current-nulls or large current gradients (dI/dz) that might occur at the position of the current clamp if the CSWR were to be large.
- A port to measure the current (current port).

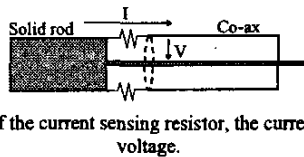


Figure 2. Detail of the current sensing resistor, the current and the detected voltage.

Two test setups have been built that differ significantly in the geometry, the sensing resistor values and the characteristic impedances. A summary of the main parameters of both test setups is given in Table 1. The sensing resistances have been determined using 4-wire-4-contact point measurements.

TABLE I. SETUP PARAMETERS

Setup parameter	“Large” setup	“Small” setup
Transmission line height / diameter	51 mm / 6.35 mm	51 mm / 2.2 mm
Transmission line impedance	185 Ohms	240 Ohms
Sensing resistor	4.8 Ohms	9.3 Ohms
Setup length	610 mm	410 mm

Fig. 3 shows a photo of the large setup. It has been constructed from a low loss 0.25 inch semi-rigid co-ax cable. The characteristic impedances of the transmission line A and the outer transmission line system of transmission line B were determined to be 185 Ω from the dimensions of the structure.

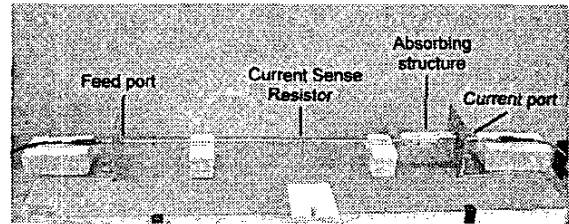


Figure 3. Photo of the large test setup. The ferrites form an absorbing structure. Having a few clamp-on ferrites provides sufficient absorption.



Figure 4. Detail of the current sensing resistor made from a circular arrangement of SMT resistors.

III. MEASUREMENT PROCEDURE

The probes are characterized in a two step process. The first step (measurement #1) determines the current within the clamp and the second step (measurement #2) determines the output voltage of the clamp. In the data analysis the ratio of the measurements is taken to determine the transfer impedance.

A. Measurement # 1: Characterization of the current

A network analyzer is connected to the “feed port” and the “current port”. The current clamp is positioned above the gap and terminated with 50 Ω . The cabling to the current clamp is in its final position. The S_{21} measurement (S_C) will determine the current in the gap, i.e., the current at the center of the clamp. The current needs to be determined as the voltage drop across the parallel connection of the sensing resistor and the 50 Ω load at the “current port”.

B. Measurement # 2: Characterization of the current clamp output voltage

In the second step, the termination is moved to the “current port” and port 2 of the network analyzer is connected to the current clamp. This S_{21} measurement (S_V) will determine the output voltage of the current clamp.

C. Data analysis

The magnitude transfer impedance Z_{trans} expressed in dB Ω is obtained from the data sets S_C and S_V and the value of the sensing resistor R_{sense} using

$$Z_{trans} = S_V - S_C + 20 \cdot \log_{10} \left(\frac{R_{sense} \cdot 50}{R_{sense} + 50} \right). \quad (2)$$

IV. PERFORMANCE

The performance of the method is analyzed in three steps. The first two steps show the self consistency of the method. Finally, the transfer impedance obtained by this method is compared to another method.

A. Transfer impedance independent of the impedance of the test setup

The widely used CISPR [4] method requires maintaining a 50 Ω transmission line impedance, forcing the user to design different test setups for different current clamps. The proposed setup overcomes this limitation, as do the methods proposed in [3, 5], although not explicitly shown.

Transfer impedance of an F-65 (Fischer Custom Communications) current clamp was measured in the “large” and the “small” test setups. The results shown in Fig. 5 indicate that the differences are less than ± 0.3 dB for frequencies within the specified operating range of 100 kHz – 1 GHz. This data supports the claim of being able to characterize the transfer impedance of the probe independent of the geometry of the test setup.

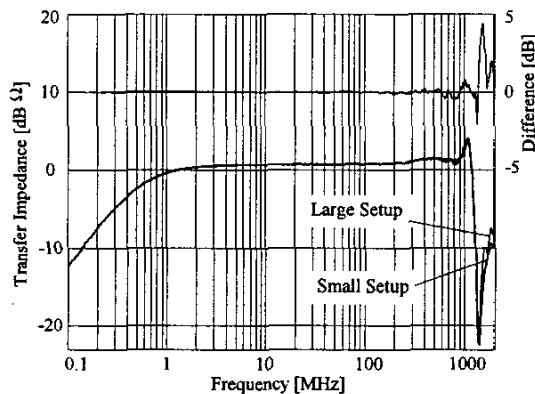


Figure 5. Comparison of the transfer function obtained in the “large” and the “small” calibration setups. The top trace indicates the difference and is referenced to the Y-axis on the right side.

B. Transfer impedance independent of the termination method

Another important property of this test setup is that no good match needs to be obtained for the wave on the outside of the transmission lines B as it encounters the metal plane at the “current port”.

A termination cannot be totally avoided for two reasons:

- If the CSWR would reach infinity, there could be a current null at the position of the clamp. This needs to be avoided as very low current values would increase the sensitivity to noise and small geometry variations would move the position of the current null.
- If the gradient of the current (di/dz) is too strong the exact position of the current clamp starts to influence the measured current and the definition of the current clamp transfer impedance weakens.

Still, the resulting requirement for termination is not strong. In practice, a few ferrites will be sufficient. They do not have to be effective absorbers at lower frequencies, as long as the distance between the current port and the sensing resistance is less than $\lambda/4$. A further enhancement is possible by placing ferrites onto transmission line A, close to the feed port. These ferrites will partially absorb energy that is reflected by the current probe’s body, thus reducing the current gradient. The resulting reduction in the available power by a few dB (Fig. 6) in the measurement system by the ferrites on the transmission line A, will not affect the uncertainty of the measurement as the difference between two measurements is taken.

The current at the center of the same F-65 current clamp was measured while the absorbing structure was varied. Setups “Ferrite 1” and “Ferrite 3” have different number of ferrites at the current port and the same number of ferrites at the feed port. Setup “Ferrite 2” is similar to “Ferrite 1” except that it has no ferrites at the feed port. As one would expect, the largest difference is seen if a ferrite is placed at the feed port (Fig. 6). Setup “Ferrite 2” has the worst standing wave ratio, as reflections between 100-1000 MHz become visible as undulations of the current magnitude.

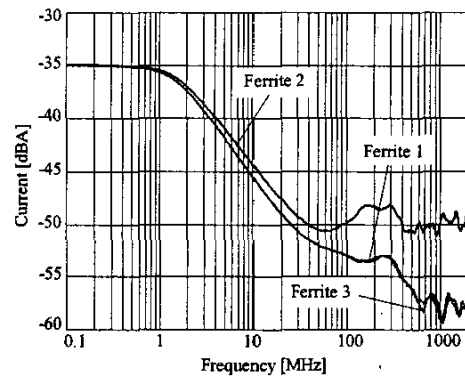


Figure 6. Current passing through the current sensing resistors relative to 1 volt source voltage of the network analyzer.

The voltage output of the current clamp was measured for these ferrite arrangements and the transfer impedances were calculated. Fig. 7 shows the transfer impedances obtained.

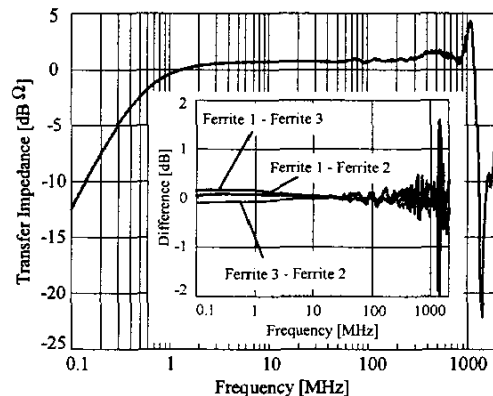


Figure 7. Comparison of the transfer function obtained using different absorbing structures at the current port and the feed port

The results support the claim of independence of the absorbing structure (Fig. 7). For improved visualization, the differences between the transfer impedances are shown in the inset of Fig. 7. The differences are minimal, less than ± 0.4 dB within the design range of the current clamp (100 kHz – 1 GHz). Larger deviations occur at resonance frequencies of the clamp, most likely due to small shifts in the resonance behavior that are enhanced by taking the difference.

C. Comparison with other methods

A method that uses a highly controlled geometry was chosen as a reference method (Fig. 8). Here, a current clamp can be calibrated by placing it around a transmission line that is well terminated at both ends. The method was selected since it can be analyzed analytically and the absence of reflections can be verified by moving the current clamp along the wire.

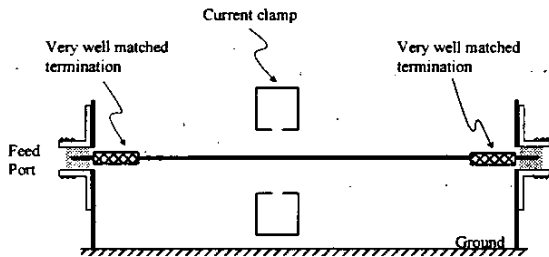


Figure 8. Calibration of a current clamp in a well-matched transmission line system.

Using an S_{11} measurement the system was matched as good as possible. The symmetric system had a 320Ω characteristic impedance, the matching structures on each side consisted of resistors having a total of 270Ω distributed over a length of about half of the height and a 50Ω coaxial termination. The current, that is needed to reference to the clamp output voltage is obtained at the far-end termination. It equals the current within the current clamp providing reflections and radiation do not play a significant role. While it is easy to check for reflections by moving the clamp along the line, it is not possible in this setup to correct for radiation. Fig. 9 shows the comparison of transfer impedances obtained in this method to the proposed method.

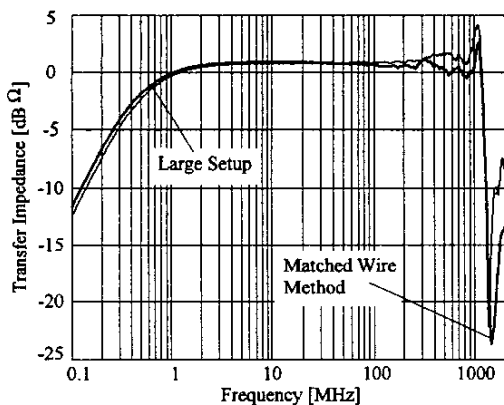


Figure 9. Comparison of the transfer functions measured in the proposed method (large setup) and the matched wire above the ground plane method.

Results for both methods indicate the difference is less than 1 dB up to about 400 MHz. Beyond this frequency, the difference is larger due to the radiation loss in the matched wire method, as its wire height above ground was 6 cm.

V. DISCUSSION

A current clamp is placed around a current carrying wire to measure the current as shown in Fig. 10.

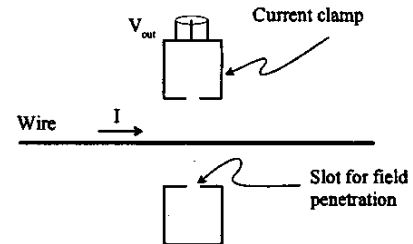


Figure 10. Basic functioning of a current probe

In the ideal model the current probe provides an output voltage proportional to the current on the wire.

The output voltage of the probe is given by

$$V_{out} = KI \quad (3)$$

Features of the ideal model are:

- The factor K is frequency independent,
- The factor K does not depend on the position of the current carrying wire within the current clamp
- The current clamp has no influence on the current
- A voltage difference between the wire and the current clamp does not cause a signal at the probe's output

However, current clamp measurements are affected by a multitude of secondary parameters. It is important to consider them if the uncertainty of the measurement is estimated or formally calculated. Significant ones are related to currents flowing on the cable that is attached to the clamp, the exact positioning of the wire through the clamp and the effect of the CSWR. Most of these influences are caused by the coupling between the wire and the current clamp's enclosure, remaining capacitive coupling to the internal wiring and an internal construction that does not provide symmetry of revolution.

A. Effect of current clamp on the current passing through the wire

The underlying assumption of most uses of current clamps is that the current that is supposed to be measured is not or little affected by attaching the current clamp. For multiple reasons, one of them the conservation of energy, there must be some effect on the current. Otherwise, no energy would be available at the output port of the current clamp.

There are three types of effects of placing a clamp around the wire:

- The clamp is a transformer, i.e., it transforms the attached load into the wire via its transform ratio.

- The capacitance to the clamp body will provide a displacement current path to the clamp and possibly to ground via the outer shield of the cable that is connected to the clamp.
- A wave that travels along the wire will be scattered by the body of the clamp.

B. Capacitive current to the shield

If there is a significant voltage between the body of the current clamp and the wire, the capacitance between them will allow part of the current to flow onto the shield of the current clamp. This influences the total current. Further, the capacitance can be broken down into two parts, C_1 , C_2 , and C_3 , C_4 as shown in Fig. 11. Assuming symmetry, the capacitance on the left is equal to that on the right of the clamp.

The current clamp measures the magnetic field. The magnetic field can penetrate into the core of the clamp via the coupling slot (a slot in Phi-direction).

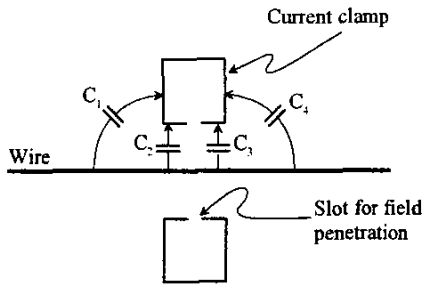


Figure 11. Capacitive coupling between the wire and the shield of the clamp.

It is a reasonable simplification that the current clamp measures the magnetic field underneath this slot and that the magnetic field has no Z-component. The currents caused by C_1 and C_2 will not be measured, while the currents through C_3 and C_4 will be measured by the current clamp.

The capacitance between the shield and the wire will reduce the current on the wire by about:

$$I_c = V / j \omega C \quad (4)$$

Where, $C = C_1 + C_2 + C_3 + C_4$

However, the measured current is only affected by half of I_c .

C. Electric field coupling to the internal wiring of the clamp

If there is a voltage difference between the wire and the shield of the clamp, most field lines will end on the shield, but some will go through the slot onto the internal structure of the current clamp (Fig. 12). This field can be understood as a (small) coupling capacitance between the wire and the output port of the clamp.

For easy understanding, the following discussion assumes an injection current clamp. But the same is true for a monitor current clamp as well. The exact coupling depends on the internal structure of the current clamp and cannot be discussed in general. Still, some general conclusions can be drawn.

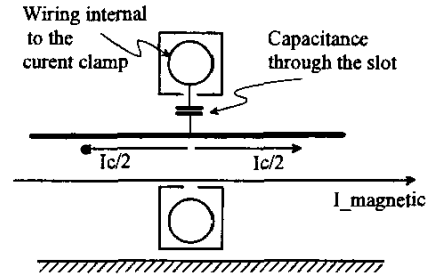


Figure 12. Coupling between the wire and the internal structure of the clamp

Capacitive coupling should cause a current on the wire. This current is symmetric with respect to the left and right of the clamp. But the current caused by the magnetic coupling flows in the same direction with respect to the left and the right of the clamp (I_{magnetic}). Due to the different signs, the magnetic and the electric current should add on one side and subtract on the other. This should lead to a slight directivity of the clamp. In other words: Any directivity of the current clamp indicates electric field coupling to the clamp's output port.

As some of the electric field between the clamp and the wire will not reach the shield of the clamp but will reach into the clamp via the slot that is needed to allow for the magnetic field coupling, the coupling equation (3) is modified to

$$V_{\text{out}} = K_1(f) I + K_2(f) V. \quad (5)$$

$K_1(f)$ is the function that describes the contribution of the current (via the magnetic field) and $K_2(f)$ is the function that describes the contribution of the voltage difference between the wire and the current clamp (via electric field coupling).

D. Current Standing Wave Ratio (CSWR)

At first it will be shown that the CSWR limits the ability to define a unique Z_{trans} . Let us imagine the case of two transmission lines having distinct characteristic impedances joined shortly after the current clamp as shown in Fig. 13.

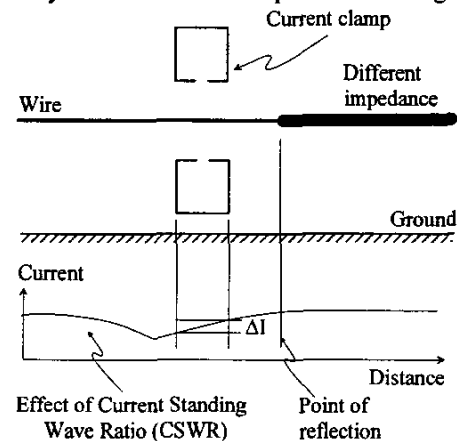


Figure 13. Effect of CSWR on the current through a current clamp. The CSWR will cause a current difference ΔI between the left and the right side of the current clamp.

For the assumptions of 3 GHz frequency and a CSWR of 1:3, the distribution of the current along the line can be obtained, Fig. 14, ignoring the scattering by the clamp's body.

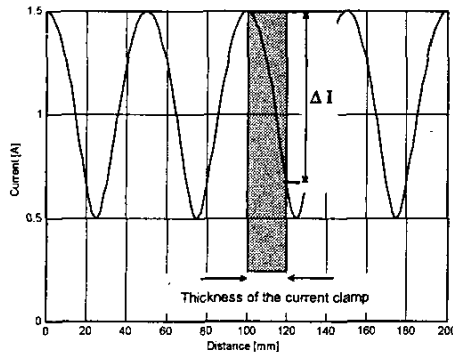


Figure 14. Effect of CSWR on the current along the thickness of a current clamp for the parameters shown above.

The current varies by more than 1:2 throughout the 20 mm width of the current clamp. Typically, when using the transfer impedance one does not specify in detail at which spot of the wire the current is measured. But as shown in Fig. 14 this question is of relevance. One could define it as the average of the current to the left and to the right, or as the current exactly underneath the current sensing slot. As further factors contribute to the reading, such as non perfect TEM structure of the fields, possible higher order modes on the current clamp body, tilting of the current clamp etc. it is arguable that no further detailing of the analysis will provide an improved Z_{trans} as long as the dimensions of the current clamp are not significantly reduced.

In this case the clamp had a width of 0.2λ which led to an additional uncertainty of ± 3 dB. For practical applications we need to accept that if the width of the current clamp is not narrow relative to the wavelength, then the CSWR will introduce an additional uncertainty that may reach many dB.

E. Off-center positioning of the probe

If the current clamp just measures the magnetic field using Ampere's law, the position of the wire within the clamp should not be relevant. There are some reasons why deviations may be observed:

- The capacitance between the clamp and the wire has its minimum if the wire is in the center of the clamp. Increased capacitance by off-center positions will lead to a larger capacitive current to the clamp.
- The current clamps are not built 100% perfect bodies of revolution. The proximity of the wire to some internal structures might change the coupling.

Throughout the previous sections describing the proposed calibration method, we assumed that the wire passes through the center of the current clamp and that the current clamp is not tilted. While this is generally achieved during calibration, it is not the case in most measurements. The open nature of the proposed setup allows obtaining an insight into these effects, such that the user could take them into an uncertainty calculation. Off-centered wire placement of the probes varied

the transfer impedance in the range of ± 0.6 dB up to 1 GHz and larger values above 1 GHz for the F-65 current clamp.

In theory, the current clamp should not influence the fields and from Ampere's law, it should not matter where the current passes through the current clamp. But as additional currents are introduced on the clamp's body their magnetic fields will couple to the internal structure of the clamp influencing the reading. Further analysis of this coupling is beyond the scope of this article. However, it can be summarized that the transfer impedance can be determined within about ± 1 dB up to 1 GHz and with larger certainty up to a few GHz.

VI. CONCLUSIONS

A new method for the calibration of current clamps has been developed. Its fundamental advantage over present methods is that it measures the current directly at the position of the current clamp. This greatly reduces the need for data correction and provides a simple test setup that can be used for a variety of current probes.

Its main advantages are

- The geometry of the setup is not a critical design parameter.
- The requirement for wave termination is not strong.
- The setup is suitable for calibrating a multitude of current clamps, as the dimensions of the current clamp (outer diameter, inner diameter, and thickness) are not used to establish a specific impedance of a transmission line.
- Complex transfer impedance can be determined from the complex S_{21} data by shifting the phase reference plane from the calibration plane (at the "current port") along the semi-rigid cable to the position of the current sensing resistor; and,
- The setup is an open setup, i.e., this allows varying many secondary parameters for observing their influence. Examples are off-centered current clamps, tilting of the current clamp, ferrite loading of the current clamp coax cable etc.

The proposed method has also been tested using the F-2000 current clamp up to 3 GHz showing similar results.

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