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3D-Printed Floating Cable Traps for MRI guided Microwave Ablation

Maik Ehses[1], Karen Meyer zu Hartlage[2], Thomas Gerlach[1],
J. Joaquin Löning Caballero[2], Daniel L. Reimert[2], Enrico Pannicke[1], Marcel Gutberlet[2],
Frank Wacker[2], Oliver Speck[3], Bennet Hensen[2] * and Ralf Vick[1] *

***Abstract*— Magnetic Resonance Imaging (MRI) guided Microwave Ablation (MWA) allows for real-time therapy monitoring with MRI-thermometry. The MWA generator emits Radio Frequency (RF) interference, which can limit the accuracy of therapy monitoring. The image quality is enhanced by Floating Cable Traps (FCTs) that are used to attenuate common mode currents on supply lines between a MWA generator, and its ablation applicator. The effect of an FCT on the Signal to Noise Ratio (SNR), and changes in the MRI spectrum are discussed in this paper. The application of FCT can bring significant improvements in both, the MRI spectrum and the SNR.**

***Clinical relevance*— Floating Cable Traps are user-friendly. FCT enable coaxial cables to reduce interferences emitted in MRI guided interventions. It is used to selectively attenuate frequencies in the MRI's range. This can increase the image's Signal to Noise Ratio.**

I. INTRODUCTION

Percutaneous minimal-invasive procedures allow for a patient-friendly treatment of tumors. One of the common methods of these procedures are thermal-ablative procedures such as Microwave Ablation (MWA), which can be used to treat tumors in the region of liver and kidney. Image guidance is used to monitor the correct placement of an MWA applicator. A strong increase in temperature of the surrounding tissue is achieved due to the power conversion of the electromagnetic fields. Magnetic Resonance Imaging (MRI) offers the possibility to create temperature maps to assess the extend of the ablation zone. A safety-margin greater than $5\,\mathrm{mm}$ can decrease the recurrence rate of tumors significantly [1]. Contrary to that, MRI is highly susceptible to Radio Frequency (RF) interference from external devices [2]. A possible source of interference are common-mode currents. It can spread along the long supply lines between the MWA generator and ablation applicator. The usage of non-magnetic common-mode chokes is a reasonable method to attenuate common mode currents [3]. The advantage of Floating Cable Traps (FCTs) [4] is that it does not have to be in direct electrical contact with the outer conductor of the coaxial cable. The FCT is a resonant structure that is placed on cables and offers a high impedance for common mode currents. In this paper FCT for clinical use in a Microwave Ablation is introduced. The efficiency is verified by comparing the MRI signal and the Signal to Noise Ratio (SNR) of phantom images.

[1]Maik Ehses, Thomas Gerlach, Enrico Pannicke and Ralf Vick are with the Faculty of Electrical Engineering and Information Technology, Department of Electromagnetic Compatibility, Otto-von-Guericke University, 39124 Magdeburg, Germany maik.ehses@ovgu.de

[2]Karen Meyer zu Hartlage, Daniel L. Reimert, J. Joaquin Löning Caballero, Bennet Hensen, Marcel Gutberlet and Frank Wacker are with the Department of Radiology, Hanover Medical School, 30625 Hanover, Germany

[3]Oliver Speck is with the Faculty of Natural Sciences, Department of Physics, Otto-von-Guericke University, 39124 Magdeburg, Germany

* Equal contributions to last authorship.

II. METHODS

A. Requirements for Floating Cable Trap

Certain requirements are mandatory to be fulfilled in order to derive the design of an FCT. The foremost being MRI compatibility. The FCT should be easily attachable to cables, and in turn also easily detachable. A support for two coaxial cables should be incorporated to use with the two cables of the MWA. One line is used to transport Radio Frequency (RF) power from the MWA generator to the applicator, the other is used to communicate with a built-in temperature sensor inside the applicator, which is part of this setting.

B. Structure and Design of a Floating Cable Trap

The general structure (see Figure 1) of an FCT is similar to a coaxial cable. It consists of an inner conductor and an outer conductor, which are separated by a dielectric. The inner and outer conductor are connected by the FCTs discrete capacitors. The capacitors are used to tune the resonance frequency of the FCT. The inner conductor has an elliptic shape, to account for the two cables, that have to fit into the trap (see Figure 1 and Figure 2).

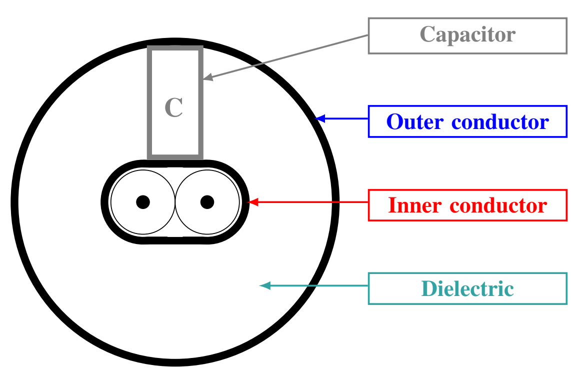

Fig. 1. Structure of a FCT

A railway system (see Figure 2) with a dead-end is implemented. The railway system ensures a feasible way to attach and detach the FCT and merge the two halves correctly.

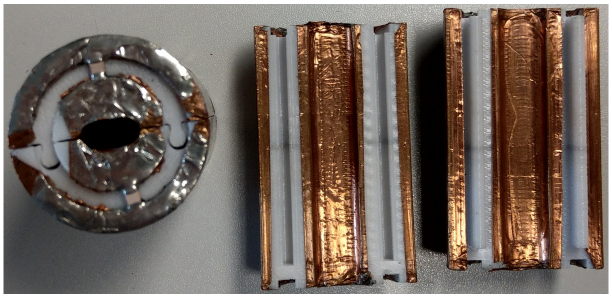

Fig. 2. Railway system of the FCT for simple application

C. Simulation

The FCT should be tuned to the Larmor-frequency of the MR-scanner, to have the highest impedance at this frequency. The attenuation depends on the precision of the tuning. As mentioned above, the resonance frequency is adjusted by the discrete capacitors. The discrete values are simulated with the layout depicted in Figure 3.

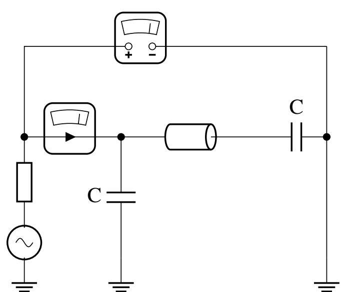

Fig. 3. Simulation layout for the capacitance value

The simulation is done with a source emitting the Larmor-frequency of the MRI, in this case $63.61\,\mathrm{MHz}$ for a $1.5\,\mathrm{T}$ MRI. Simultaneously, a parameter sweep for the capacitance C is performed. The length of the FCT, the radius of the inner conductor, the radius of the outer conductor, and the permittivity of the dielectric are other inputs. To determine the inner radius for the simulation, the area of the ellipse was initially calculated. Subsequently, a circle with the same area was assumed and its radius was determined. This radius was put into the simulation as the inner radius.
The FCT has the following values:

- Length L = $60\,\mathrm{mm}$
- Outer radius R_o = $18\,\mathrm{mm}$
- Inner radius R_i = $3.89\,\mathrm{mm}$
- Reltive permittivity ϵ_r = 3.5

D. Test setup with the Vector Network Analyzer

In this section, the attenuation response of a single FCT is established. A Vector Network Analyzer (VNA) (ZNB4, Rohde & Schwarz, Munich, Germany) is used in combination with two common-mode current probes connected to it. An S_{12}-measurement is performed. In this setting, one port is the transmitter. It modulates the RF signal to the cable's shield, while the other probe can receive and measure the RF signal. The current probe is based on a semi-rigid coaxial cable, which is wound around clamp-on ferrites. The inner conductor and outer conductor are short-circuited to obtain a measurement loop. The ferrites are placed on two cables. Between the ferrites an FCT could be placed to determine its attenuation profile. The measurement setup is depicted in Figure 4.

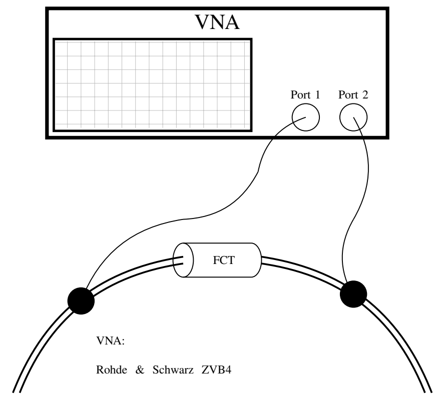

Fig. 4. Measurement setup to determine the attenuation response of a single Floating Cable Trap with a Vector Network Analyzer.

E. Test setup in the Magnetic Resonance System

This setup was used to demonstrate the FCT's performance inside of an MRI system. The MRI used for this experimental setup had a field strength of $1.5\,\mathrm{T}$ (MAGNETOM Avanto, Siemens Healthineers, Erlangen, Germany). The MWA generator (AveCure, MedWaves, San Diego, USA) was placed outside the MRI's shielding cabin, with its cables passing through a wave-guide to the inside of the shielding cabin. To establish a better electrical connection between the shielding cabin and the shield of the coaxial cables, copper wool was wound around the part of the coaxial cables that was placed inside of the wave-guide. (see Figure 5). It has been shown, that the increased grounding through the copper wool has positive effects on the SNR [5].

The measurement setup inside the shielding cabin is depicted in Figure 6. The ablation applicator was placed inside a bottle filled with water, to account for the temperature rise during ablation. The bottle was fixed with a foam-cushion, on which the applicator's cables were fixed with tape. Juxtaposed to the structure, an MRI phantom was placed. The complete structure was stabilized with sand filled bags. The FCT was placed on the cables at a distance of $90\,\mathrm{cm}$ from the applicator's shaft. The highest impact to the spectrum could be observed at that position.

The measurements with this setup were performed with the body-coil of the MRI, and include a spectral measurement around the Larmor-frequency, as well as Gradient Echo (GRE) images. All images of the MRI phantom were taken with the following parameters:

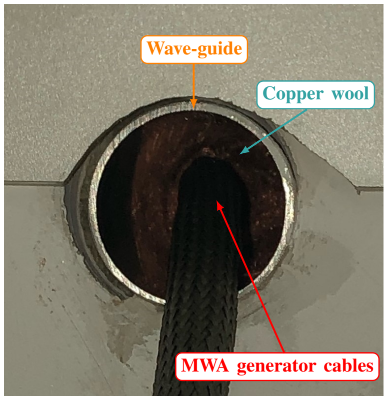

Fig. 5. Copper-wool around the MWA generator's cables inside of the wave-guide.

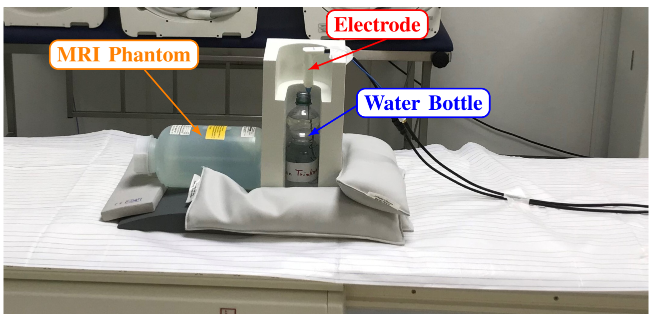

Fig. 6. Test setup in the Magnetic Resonance Imaging for determining the effectiveness of FCTs.

- TR: 20.0 ms
- TE: 7.0 ms
- Field of View (FOV): 150 mm x 150 mm
- Slice thickness: 5 mm
- Repetitions: 50
- Flip angle: 18°
- Bandwidth: 100 Hz/pixel

To get a reference data set, the spectrum and the GRE-image were measured without the MWA and its coaxial lines present. Additionally, two measurements with the ablation-system placed outside the shielding cabin and its coaxial lines connected were performed. These measurements were performed with an active MWA generator. The MWA generator was placed in a stand-by mode for 20 min, to account for any warm-up effects. Following, one measurement with an active ablation and no FCT on the cables was performed. Finally, a measurement with the MWA turned-on and a FCT placed at the described position was performed. The SNR of the GRE images were calculated according to the standard IEC 62464-1:2018 [6] to evaluate the impact of the FCT and to allow a direct comparison of the images [7]. A Region of Interest (ROI) is defined, in this case the water phantom, which correlates with the circular shape in the GRE images (Figure 9). The mean value S is calculated from this ROI. Next a pixel-by-pixel difference image is calculated between two GRE images, and the ROI is transferred into the difference image. The Standard Deviation (SD) is calculated. The SNR is formally calculated by [6] SNR $= \frac{S}{\frac{SD}{\sqrt{2}}}$.

III. Results

A. Measurement with Vector Network Analyzer

The FCT has been produced with the simulated capacitance of 680 pF. The results for the VNA measurement are depicted in Figure 7. In this plot the target frequency is marked in red, the S_{12} measurement without the FCT is shown in blue. The attenuation response with the FCT is depicted in orange, and aligns very closely with the target frequency. Indicating, that the simulation for the capacitance value is accurate.

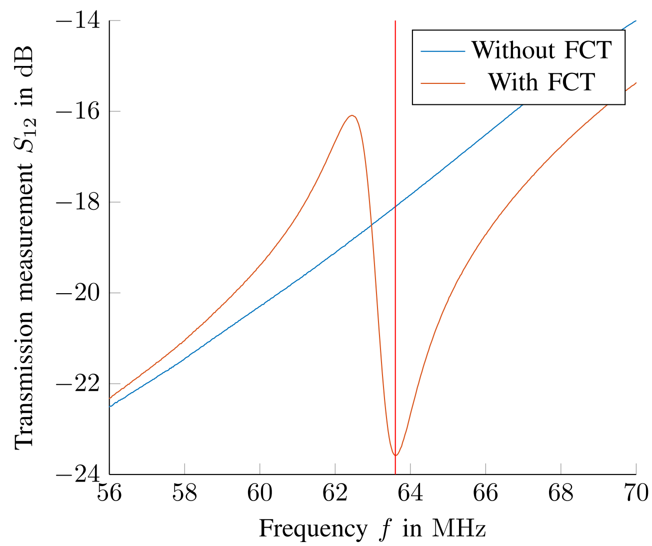

Fig. 7. Results for the attenuation measurement on the Vector Network Analyzer. The blue plot shows the attenuation profile without the cable trap, the orange plot depicts the attenuation profile of a single FCT with the target frequency (63.61 MHz) marked in red.

B. Measurement with the MRI

The typical noise spectrum of this MRI system is shown by the yellow curve in Figure 8. In this measurement neither the MWA was present nor its coaxial cables. After the warm-up of the MWA generator, operation in active ablation mode led to an increase of the spectral noise (Figure 8 red plot). After applying the FCT, the spectral curve is attenuated (green plot). Though the majority of the spectrum is attenuated by applying an FCT, at some frequencies an amplification is noticeable.

Figure 9 depicts different GRE images of the MRI phantom. Figure 9(a) shows the reference image with the MWA generator turned-off, and has an SNR of 17.74. The MWA generator operating in the ablation mode decreases SNR to 15.16. This can also be observed in Figure 9(b).

Applying an FCT to the coaxial lines of the MWA generator increases the SNR as shown in Table I. An SNR recovery of 17.30 could be achieved. The corresponding GRE image can be observed in Figure 9(c).

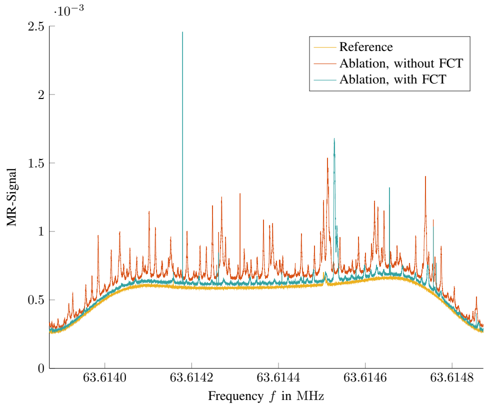

Fig. 8. Spectral measurements performed with the MRI.

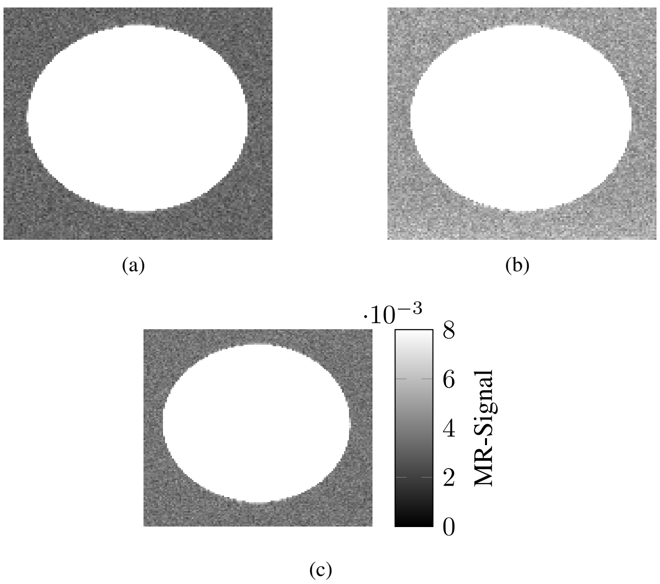

Fig. 9. GRE images (FOV 150 mm x 150 mm, 128 pixel x 128 pixel) of the MRI phantom: (a) As the reference image with the MWA generator turned-off, and no FCT on the connecting coaxial cables. (b) MWA in ablation mode and no FCT attached. (c) MWA in ablation mode and one FCT attached to the coaxial lines.

TABLE I
DIMENSIONLESS SNR RESULTS OF THE MRI MEASUREMENTS

	Reference, only imaging	MWA Ablation, no FCT	MWA Ablation, one FCT
SNR	17.7355	15.1561	17.3022

IV. DISCUSSION

This work demonstrates that a FCT offers the possibility to attenuate RF interferences introduced by coaxial cables into an MRI shielding cabin during an ablation procedure. Traditionally, RF chokes need to be in direct electrical contact with the coaxial cables shield. Fitting RF chokes on pre-built cables of an approved medical system is difficult for numerous reasons. One of them is impracticality due to sterility issues, another one is that such a modification to a medical device will void the manufacturers approval as a medical device. FCTs offer the significant advantage, that such an electrical connection is not necessary. It could be shown, that the FCT attenuated the frequencies in the MRI's spectrum, with some exceptions. At these exceptions an amplification is noticeable (see Figure 8 and Table I). The reason behind the amplifications should be investigated further. Despite these amplifications, an increase in the images SNR could be observed (see Figure 9). This in turn shows the efficiency in the MRI environment.

V. CONCLUSIONS

FCT can decrease undesirable noise introduced from cables of external devices inside of an MRI shielding cabin and thereby increase the SNR in GRE images. This could enable a better therapy monitoring, especially for MRI-thermometry measurements. Additionally, the railway-system offers the user a much more comprehensive, and user-friendly way to apply FCT to said cables.

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