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Wireless sensing of open loop micro inductors using Helmholtz coil

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Abstract- This paper reports wireless sensing of open loop micro inductors parameters i.e. distributed capacitance, inductance, resistance and Q factor in presence uniform magnetic fields generated by Helmholtz coils pair. A frequency dependent analytical model is developed which models the inductively coupled system including the effects generated by the presence of test micro coil in uniform magnetic field. Micro inductor parameters are extracted from the remotely measured impedance signal and compared with the developed modeled. Further to visualize the magnetic field coupling effects and numerically compute the micro inductor parameters, FEM simulation is performed using HFSS and COMSOL Multiphyscics.

Index terms***: Magnetic coupling, Helmholtz coils, micro inductors, HFSS.***

antenna with constant current distributions around the loop antenna. The idea of inductively coupled wireless capacitive sensor where the applied pressure, humidity, temperature and strain changes are measured using an LC circuit, are presented in [3, 4, 5, 6, 7, 8]. Investigation of temperature and magnetic field dependent radiofrequency electromagnetic absorption in polycrystalline by monitoring changes in resonance frequency and current of LC resonant circuit is reported in [9].Wireless read out of passive LC sensors is presented in [10] where the read out is performed using an analog front end circuit based on demodulation for mapping the real part of the reader coil impedance to a dc output voltage All of these publications focused on the concept based on passive inductive coupling and sensing the change in the capacitance of LC closed loop resonance circuit in presence of weak or non-uniform magnetic fields. Here we present a novel method to measure, test and analyze the open ended test micro coil in uniform magnetic field generated at the center of precisely designed Helmholtz coil pair. This paper is organized as follows. In section 2 we discuss the theoretical background of inductively coupled systems and Helmholtz coil. Section 3 focuses on the wireless measurement system. Results from measurement and simulations are presented in section 4. Conclusion and outlook are discussed in section 5.

2. Theoretical background

2.1 Inductively coupled systems

Inductive or magnetic coupling is one of the most frequently used and easily implementable techniques in direct sensing of non electrical information like humidity, pressure, temperature etc. The magnetic coupled system in general composed of two subsystems. The primary system is the reader or the excitation unit which is an AC transceiver creating an electromagnetic field in the surrounding region. Secondary unit is the sensing unit which is placed in the magnetic field generated by the reader unit. Figure 3 depicts the phenomena of the inductive coupled systems.
The sensing unit in inductively coupled passive sensor systems is embedded in an LC tank or a sensing coil. The inductance L_S and capacitance C_S of the sensing coil forms a resonant circuit.
Sensing element detects the stimulus signal and in effect changes the resonant frequency of the sensing unit

2.2. Theory of Helmholtz coil

Since decades Helmholtz coils are famous for generation of uniform magnetic field regions and used in many applications like sensor probes for EMI sensing or displacement sensing etc. Helmholtz coil pair consists of two circular set of coils of equal diameter and number of turns parallel along the axis joining the pair. Helmholtz coils can be configured (based on the application) in series or parallel aiding connection. The Helmholtz coil pair is separated by a distance equal to the diameter of the coils used. From the basic understanding of electromagnetic and Maxwell's equations we know that alternating electric field generates an alternating magnetic field and vice versa. In case of Helmholtz coil when the magnetic field is deliberately created between the pair of coils, it creates a series of electric and magnetic field in the test region where the uniform magnetic region is desired. Helmholtz coil pair may consist of single turn on each side or same multi-turns on each side. In case of constructing multi-turns Helmholtz coils the windings in both the pair should be same and the windings diameter in each coil must be less than the coil diameter, further the applied AC signal or the electrical current direction in both the coil pair should be same i.e. either clockwise or counter clockwise. Figure 4 shows a typical arrangement of a Helmholtz coil pair.

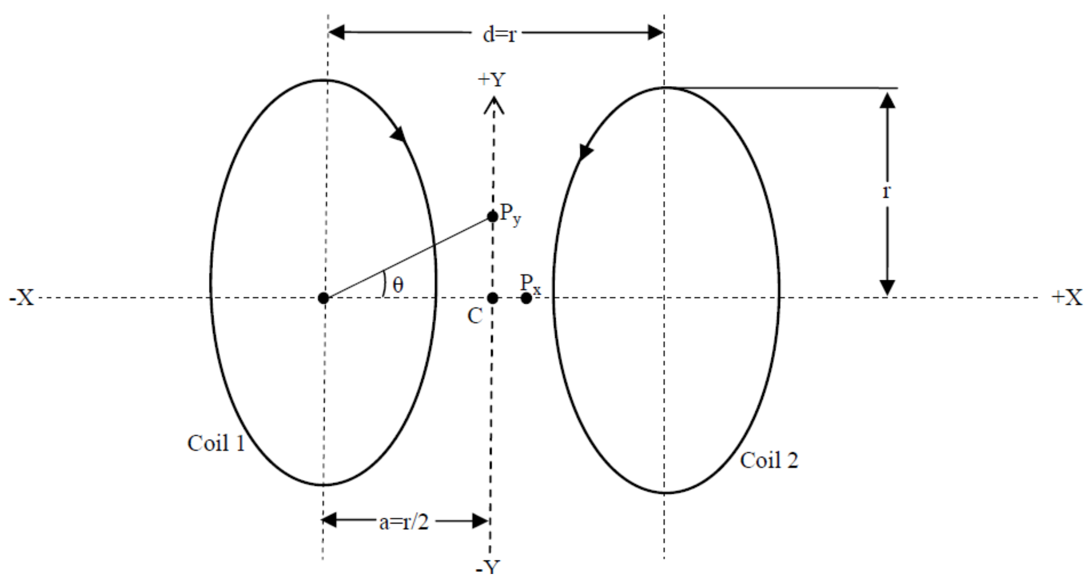


Figure 4: Helmholtz coil pair arrangement

The driving current through the Helmholtz coil pair generates a uniform magnetic field between the centers of the coil pairs. The magnetic field uniformity depends upon the accuracy with which

The open loop test micro coil is wirelessly measured using the network analyzer in uniform magnetic field generated by Helmholtz coil pair as shown in 5. Impedance magnitude (both real and imaginary) and return loss signal are wirelessly measured. From the return loss signal the quality factor is calculated using the half power bandwidth approach. The impedance magnitude and the wireless analytical model (modeling all the unknown parameters) are applied to the developed non linear least square estimation. Wired reference parameters of the micro coil and the wirelessly estimated parameters are then used to calculate the tolerance range between the wired and wireless readings.

3.1. Wireless Analytical Model

Equivalent lumped electrical parameter wireless model of the system is shown in figure 6.

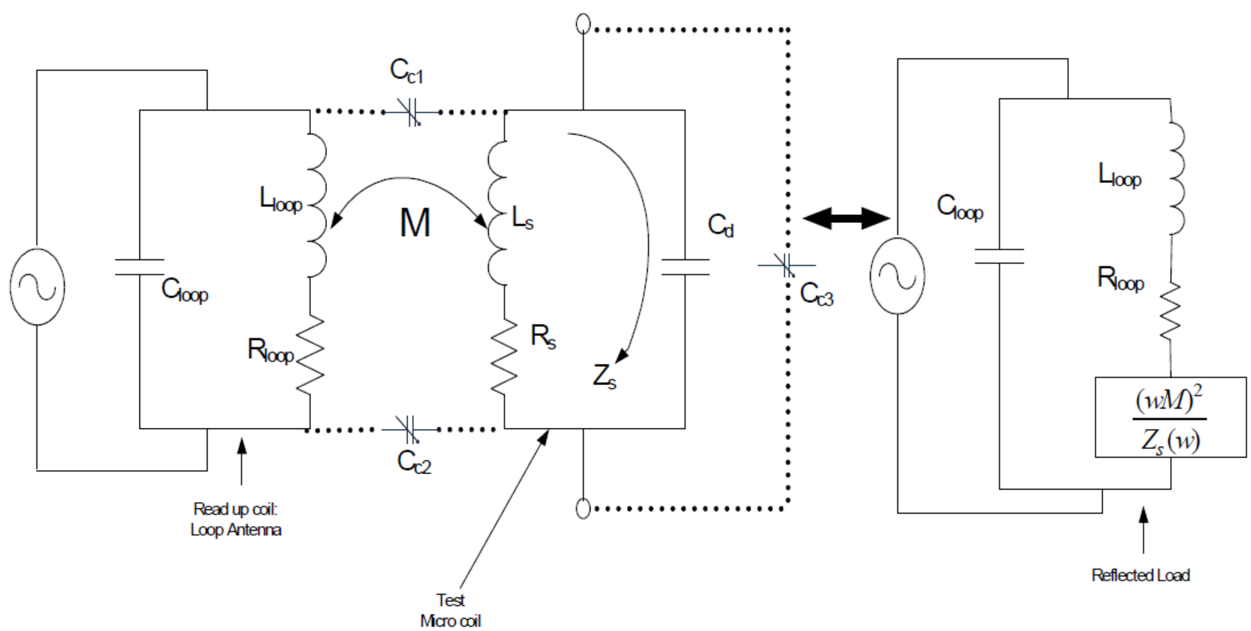


Figure 6: Equivalent circuit model of wirelessly inductive coupled system.

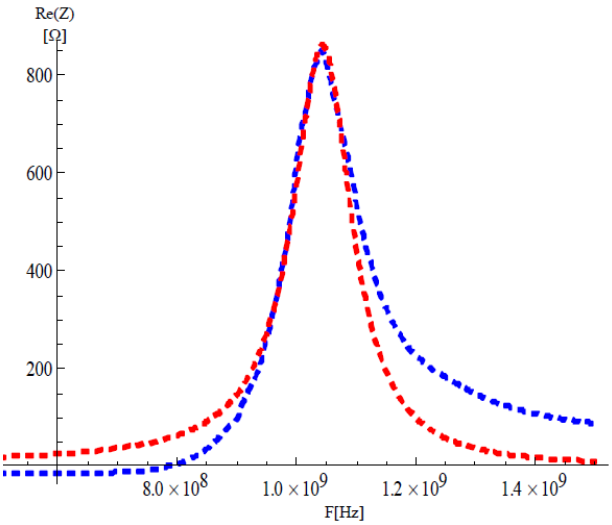
As shown in figure 6 Open loop micro coil parameters i.e. inductance, inter-winding capacitance and resistance are given by L_2, C_2 and R_2 with C_{c1} and C_{c2} are the frequency dependent coupling capacitors modeling the capacitive coupling effects between the Helmholtz coil pair and the test micro coil. The analytical model of the coupled system is given in equation 4 which is derived using standard transformer equations.

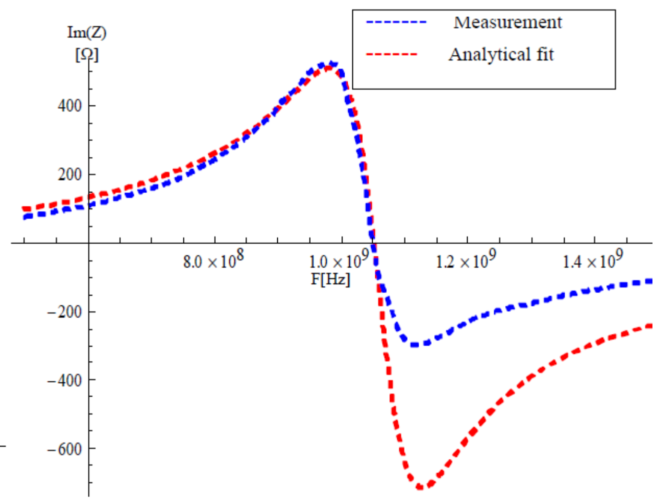
The specifications of the designed Helmholtz coil are given in table 1.

Table 1Design Specifications of the Helmholtz coil

N	r[cm]	D_h [cm]	W_h [cm]
1	0.75	1.5	0.4

Where N is turns equal on each side, r is the average radius or the separation between the series aided coils D_h is the diameter of the coils and W_h is the coil wire radius. In order to characterize the Helmholtz coil behavior at high frequencies, the Helmholtz coil is measured without the presence of device under test i.e. test open loop micro coil. Figure 8a and b shows the real and imaginary part of measured impedance and analytical fit.





(a) (b)

Figure 8: Helmholtz coil measured impedance (real 8a and imaginary part 8b) and analytical fit

Table 2 contains the Helmholtz coil measured parameters.

Table 2: Helmholtz coil measured parameters.

L_1 [μH]	C_1 [pF]	C_p [pF]	C_g [pF]	F_r [GHz]
0.025	0.22	0.60	0.75	1.04

Where F_r is the self resonance frequency of the Helmholtz coil.

Figure 9 shows normalized magnetic field strength relative to center Hρ/Hc versus the axial distance from the center x/r plotted for several values of the radial distance from the center y/r.

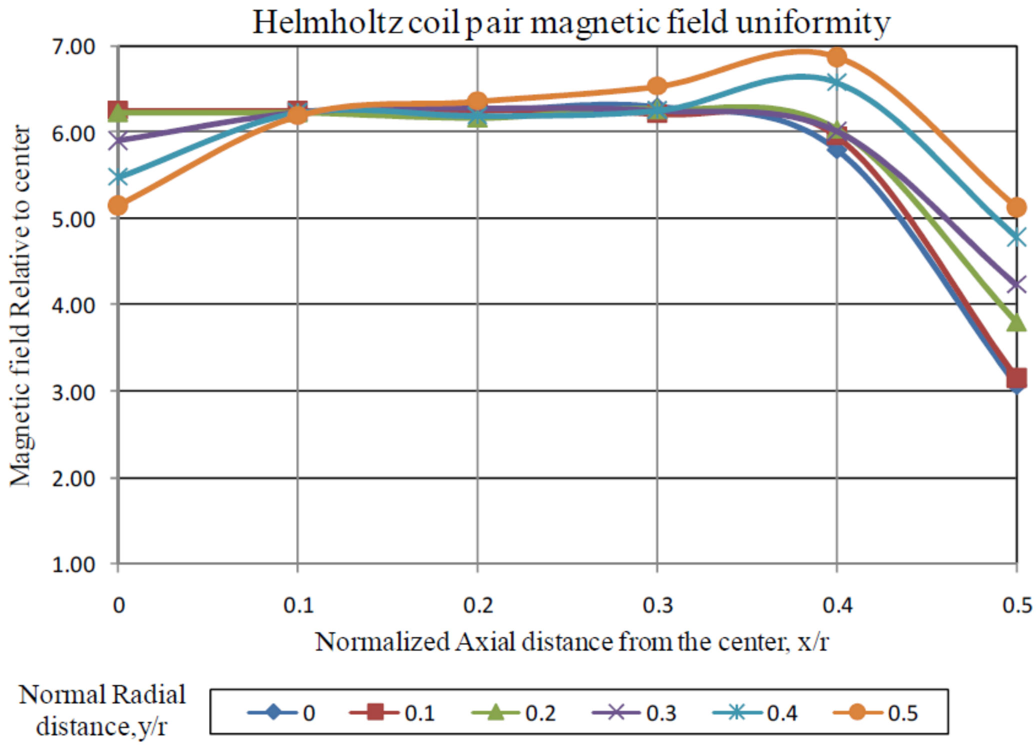


Figure 9: Normalized magnetic field strength.

3.2.2. Helmholtz coil and device under test (DUT) size limitations

Based on the dimensions of DUT, it is possible to determine the size requirement of Helmholtz coil pair (as given in [14]) for generating maximum uniform magnetic fields with uncertainties. Table 3 shows the magnetic field uncertainties for different values of normalized radii of the designed Helmholtz coil.

Table 3: Magnetic field uniformity of the designed Helmholtz coil for different values of normalized radii.

Field uncertainties	1%	3%	7%	10%
± x/r	0.2	0.3	0.4	0.5
± y/r	0.2	0.3	0.4	0.5

Equation 14 describes the method to calculate the maximum radii (r) of Helmholtz coil needed to test a DUT of given dimensions.

Similarly loaded Q factor is calculated by measuring the return loss signal and using the half power bandwidth formula (as described in [15]) as given in 15

$$Q_L = \frac{f_0}{\Delta f} \tag{15}$$

Where f_0 is the wirelessly measured resonance frequency and Δf is the frequency difference between the upper and lower half power bandwidth frequency points from the measured return loss signal. Table 4 and 5 contains the wired and wireless measurement of tested micro coils.

Table 4: Wired measurement of micro coils.

N turns	L_{wired} [μH]	C_{wired} [pF]	R_{wired} [Ω]	Q_{wired} factor	f_{wired} [MHz]
33	10.1	0.968	270	11.95	50.93
60	16.8	1.27	248	14.63	34.47
100	14.04	0.961	340	11.23	43.35
200	164	3.73	906	7.32	6.43
300	248	1.60	1238	10	7.99
500	738	3.18	1680	9.07	3.26

Table 5: Wirelessly extracted open loop micro coils parameters in uniform magnetic field:

N turns	L_2 [μH]	C_2 [pF]	R_2 [Ω]	Q_L factor
33	9.62	0.995	252	11.21
60	16.1	1.21	232	13.8
100	13.40	0.922	311	10.63
200	160.4	3.65	862	6.97
300	242.2	1.56	1169	9.63
500	718.3	3.15	1538	8.78

The wireless resonance frequency of the open ended test micro coils is calculated by using the following equation 16.

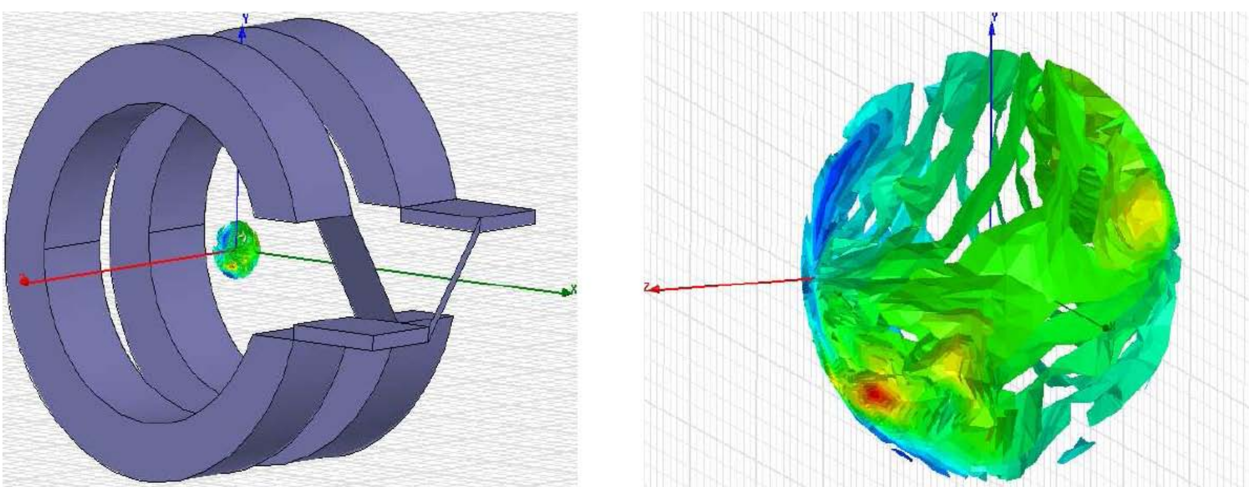
$$f_{wc} = \frac{1}{2\pi\sqrt{L_2 \Delta C}} \tag{16}$$

The reason behind the reduced errors is due to the maximum frequency of operation F_{op} limitations of the designed Helmholtz coil pair as given in [14].A practical F_{op} is achieved about 2 order of magnitude below the self resonance frequency of the Helmholtz coils. After this frequency the current of the Helmholtz coil pair falls and the magnetic field homogeneity is degraded. In the designed Helmholtz coil (with the specification given in table 1 and 2) the maximum frequency of operation is Fop is about 10MHz.Hence the micro coils having resonance frequency above 10MHz had more errors as compared to the other test micro coils having resonance frequencies below 10MHz.

4.2 Simulation results

4.2.1. Helmholtz Coil 3D simulation Model

High Frequency Structure Simulation (HFSS) is used to perform 3D electromagnetic simulation, hence assisting to study the uniform magnetic field behavior of the designed Helmholtz coil. Figure 11a shows the 3D simulation model of Helmholtz coil.



a) b)

Figure 11: 3D simulation model in 11a and magnetic field behavior in 11b.

In this simulation model a Helmholtz coil pair is modeled as shown in figure 7.Instead of a test micro coil a sphere region is created at the center of the Helmholtz coil pair. Magnetic field

minimum. 2D array of wire loops is constructed modeling the test micro coil cross section placed at the center of the Helmholtz coil (as shown in 13b).

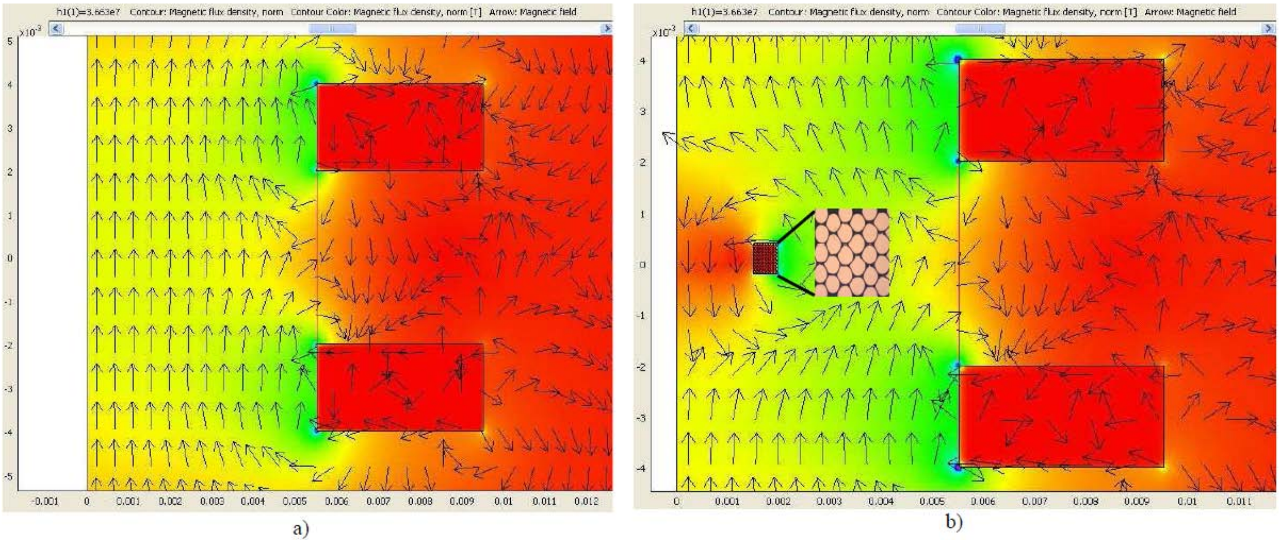


Figure 13: Magnetic field behavior and flux densities of the inductively coupled system without 13a and with a test micro coil 13b.

Since the tested micro coils are within the DUT limitations as discussed in section 2 the magnetic field is unchanged which can be seen in 13b where a test micro coil is placed in uniform magnetic region. The test micro coil parameters are numerically calculated by measuring the magnetic flux connecting the test micro coil Φ_{sim} at the constructed 2D coil array boundary and the total induced current I_{Total} through the Helmholtz coil pair rectangular cross sections is calculated by providing a frequency sweep. Using Φ_{sim} and I_{Total} , the test micro coil inductance L_{sim} is numerically calculated as given in equation 18.

$$L_{sim} = \frac{\Phi_{sim}}{I_{Total}} \times n^2 \tag{18}$$

Where n is the number of turns of the test micro coil. The effect of distributed frequency dependent capacitance is numerically calculated as given in 19.

$$C_{sim} = \frac{1}{w^2 \times L_{sim}} \tag{19}$$

Table 8 contains the inductances L_{sim}, distributed capacitance C_{sim} and the resonance frequency numerically calculated using COMSOL.

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