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Contactless Transmission of Measurement Information Between Sensor And Conditioning Electronics

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Abstract *– Contactless transmission can be, in a lot of cases, a good answer when the measurement environment has characteristics unsuitable for the classical cable-transmission. In this article the contactless transmission problem is analyzed also when the distance between readout circuit and sensor circuit changes. A new measurement method that comprise also the evaluation of the distance is proposed. A parameter, that has a very little sensitivity to sensing capacitance and high sensitivity to the distance, is identified. The measurement method has been tested in the laboratory and the experimental results are reported.*

Keywords *– inductive telemetry, contactless measurements, biological measurement, vacuum measurement, high temperature measurement.*

I. INTRODUCTION

In a lot of applications, it is not possible to connect the sensitive element to the conditioning electronics, because the environment measurement can have characteristics unsuitable for the correct working of the electronics or the traditional cable connecting the sensitive part with the processing electronics can not be used. Some examples are:

- Measurement with high temperatures.
- Measurement into environment that is not accessible like hermetic boxes or others.
- Measurement inside human body.
- Measurement on rotating systems.

For some of the previous examples, traditional wireless techniques can offer an aid, but they need a supply system that periodically requires maintenance or substitution. In this paper we propose a different approach, consisting of two systems: one is the sensitive element, that is passive and can have characteristics compliant with the extreme conditioning of the measurement environment, and the second is the processing electronics hosted in an appropriate environment. The two parts are connected by a magnetic field.

Recent literature reports some telemetry techniques and describes prototypes especially for pressure measurements: these systems are used in many fields, from industrial control processes [1],[2],[3] to biomedical systems [4],[5],[6]. The intra-ocular monitoring [6] is an example where the sensitive element is an inductor-capacitor resonant circuit, made by a capacitive pressure sensor in parallel with an internal planar coil, and the readout circuit is positioned on a particular spectacles frame. In the field of industrial application the wireless strain monitoring using electrical capacitance change of tire could be quoted [4]: the transducer is a passive resonant element made of some fibers of the tire, and it is tested by the readout circuit with electromagnetic waves. These papers describe telemetry systems consisting of a planar spiral, in the sensing circuit, and coil inductance, in the readout circuit, whose diameter is much larger than that of the planar one. In most cases the configuration of the measurement system is modeled as an ideal transformer, but when the capacitance of the transducer is comparable with that of the parasitic of the secondary or the readout circuit use also a planar inductor, the presence of the parasitic capacitances can not be neglected and a more accurate model has to be kept into consideration. Moreover, the distance between the two inductors (sensing and readout) can change due to the practical use and its effect on the measurement need to be evaluated.

To give a contribution to the previous problems, the paper propose a study of a telemetry system that consists of planar coupled inductors, where a capacitive transducer is connected on the first while the readout circuit on the second one, and the distance between the two coils can change. On the readout coil, the impedance is measured and its plot shows two resonances and one anti-resonance frequencies. We have studied the relation of these frequencies with the transducer capacitance, but evidences show that these frequencies depend also on the parameters (also parasitic) of the system.

In the following paragraph we propose a model, identifying each element with its physical principle and some analytical consideration are reported. After that we have implemented software simulations with PSpice using values of the model parameters measured by real planar inductors. Preliminary experimental results convalidate the theoretical considerations and show the possibility to compensate distance variations.

II. MODEL AND MEASUREMENT METHOD

In the previous papers [1-6], the inductive telemetric system consists of a planar inductance, in the sensing circuit, and a coil inductance, in the readout circuit, with a diameter much larger than that of the planar one. The equivalent circuit proposed in the papers is reported in Figure 1: the planar inductance is modeled with an inductor (L_s), a series parasitic resistance (R_s) and a variable capacitor (C_x) representing the capacitance sensor. The readout circuit is modeled with an inductor (L_e) and a series parasitic resistance (R_e). When the two circuits are closed, there is a mutual inductance coupling (*M*) between the inductor *Ls* and the inductor *Le*. The readout circuit measures the impedance and the frequency at which the phase, in a short frequency interval, is at its minimum value.

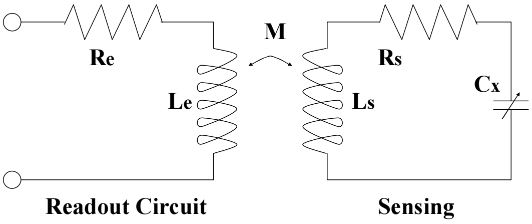

Figure 1. A model, commonly used, to analyze telemetric systems.

In some applications this model shows some limits. For example to measure the response of a low value capacitive sensor of low value, it can be necessary to keep into consideration the parasitic capacitances of the system.

With the purpose to increase the accuracy of the contactless measurement, a new model of the system is proposed; it is shown in Figure 2: *Rp*, *Rs* are equivalent resistances of readout and sensing circuit; *Cp*, *Cs* are parasitic capacitances of the readout and sensing circuit; *Lp*, *Ls* are the readout and sensing circuit leakage inductances; *Cx* is the sensing element; *Cps* is coupled capacitance of sensing with readout circuit; *Lm* is referred to coupled flux; N_1 and N_2 are the number of the equivalent inductor windings.

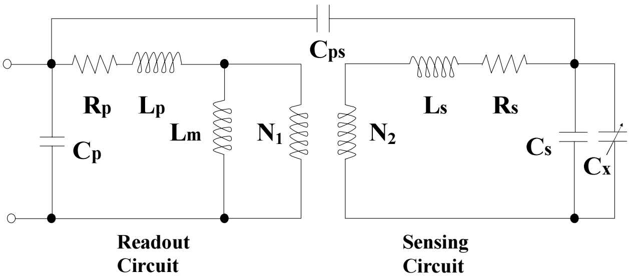

Figure 2. Physical model of a system composed by two coupled planar inductances.

For some cases, the coupling capacitance *Cps* has very little value compared with the other capacitance parameters of the model. So neglecting *Cps* and reporting the secondary on the primary side, the model of Figure 2 could be simplified into that reported on Figure 3, where *L* and *C* are respectively equal to n^2Ls and $(Cs+Cx)/n^2$ with $n=N_1/N_2$.

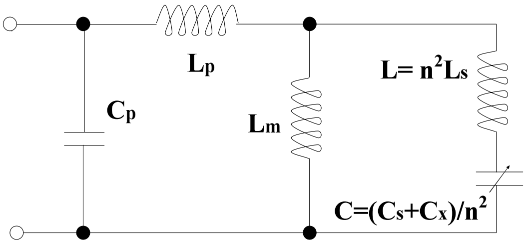

Figure 3. Simplified model for mathematically study with $n=N_1/N_2$.

As seen from the terminal of the circuit of Figure 3 the impedance is:

$$Z(s)=\frac{s^3(L_mLC+L_pC(L_m+L))+s(L_m+L_p)}{s^4C_p(L_mLC+L_pC(L_m+L))+s^2(C_p(L_m+L_p)+C(L_m+L))+1} \quad (1)$$

that has a frequency response shown in Figure 4.

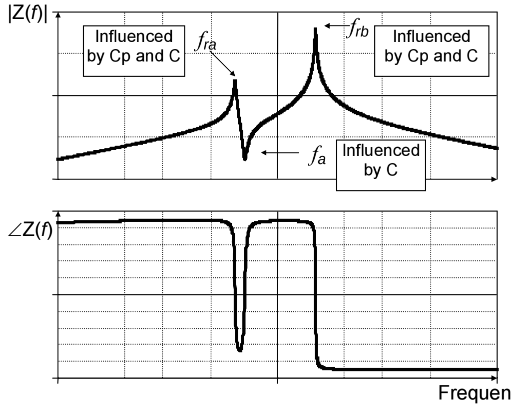

Figure 4. Frequency response of circuit of Figure 4.

In Figure 4 the presence of two resonances and one anti-resonance frequencies is noticed. The two resonances are influenced by *Cp* and *C* while the anti-resonance is influenced only by *C* (equations 2 and 3), suggesting that the frequency of the anti resonance should be the parameter to measure.

$$fa=\frac{1}{2\pi\sqrt{C\left(L+\frac{L_mLp}{L_m+Lp}\right)}} \quad (2)$$

$$(2\pi f_{ra,b})^2=\frac{1}{2C\left(L+\frac{L_pL_m}{L_p+L_m}\right)}+\frac{1}{2C_p\left(L_p+\frac{LL_m}{L+L_m}\right)}\pm$$

$$\sqrt{\frac{1}{4C^2\left(L+\frac{L_pL_m}{L_p+L_m}\right)^2}-\frac{1}{4C_p{}^2\left(L_p+\frac{LL_m}{L+L_m}\right)^2}-\frac{L_m{}^2-L_pL_m-LL_p-LL_m}{2CC_p(LL_p+LL_m+L_pL_m)^2}} \quad (3)$$

Moreover a sensitivity analysis has been conducted by making two planar inductors, measuring their parameters and simulating with the aid of PSpice.

III. TELEMETRIC SYSTEM AND EXPERIMENTAL APPARATUS

Two planar identical inductors have been made and the parameters of the equivalent system has been measured. The planar inductor consist of 27 square windings; the inter-windings distance is 0.2mm and the thickness of the trace is 0.2mm.

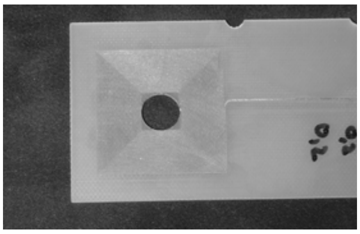

Figure 5. One planar inductance realized.

The single planar inductor can be represented like an equivalent circuit in which there are a series of an inductor (*Lser*) and one resistor (*Rser*) and a parallel capacitance (*Cpar*), the values measured are reported into Table 1.

Table 1. Values of equivalent circuit parameters for one singular spiral realized.

Lser	***Rser***	***Cpar***
19.9µH	7.28 W	1.94pF

Afterwards the parameters of the model of Figure 2 have been obtained [7] and calculated at distance of about 15mm between readout and sensing circuit. They are reported in Table 2.

Table 2. Values of equivalent circuit parameters for the two coupled spirals realized.

Lm	6µH	***Cp***	1.9pF
Lp	14 µH	***Cs***	1.9pF
Ls	14 µH	***Rp***	7.3Ω
N	1	***Rs***	7.3Ω

The two inductors are fixed in an L-shaped support; these inductors are placed horizontally, faced one to the other with the two central axes coincident. The inductor clamp is plastic-made and the handling system is an aluminium micrometer screws. Figure 6 reports a photo of the supporting system: it is possible to note the presence of two micrometer screws: the vertical one regulates the distance between the two inductors from 0 to 25 mm, while the horizontal one is used for alignment purpose.

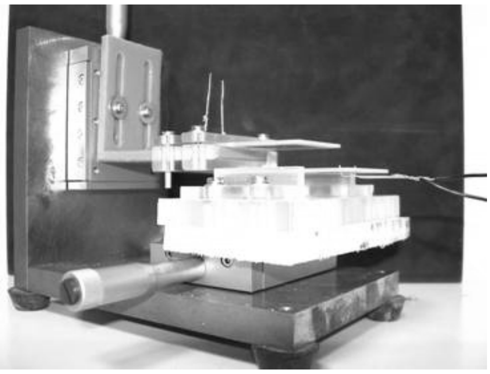

Figure 6. Experimental system structure to obtain a measurable distance between readout circuit and sensing circuit.

IV. SIMULATIONS

The sensitivity analysis has been conducted on the equivalent system of the telemetric circuit with the simulation software PSpice using the circuit of Figure 3. The parameters of the equivalent circuit are reported in Table 1 and Table 2.

The simulation results show that the changes of *C* influences both the two resonances and the anti-resonance, but with different sensitivity: the results give 4.4MHz/pF for the anti-resonance and for the other resonance: 2.6MHz/pF (first) and 1.8MHz/pF (second).

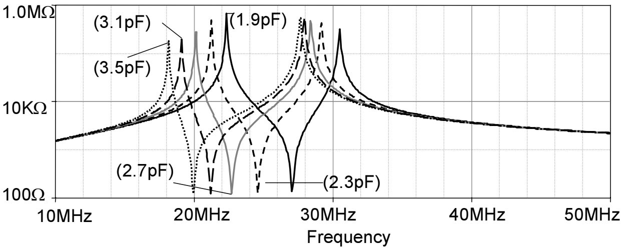

Figure 7. Impedance module of circuit of Figure 3 with different value of *C*.

Figure 7 shows that the anti-resonance is more sensitive and this is a valid reason to use, as the measurement parameter, the anti resonance frequency.

A second analysis has been done on the parasitic capacitance *Cp* and its possible variation due, for example, to temperature (Figure 8).

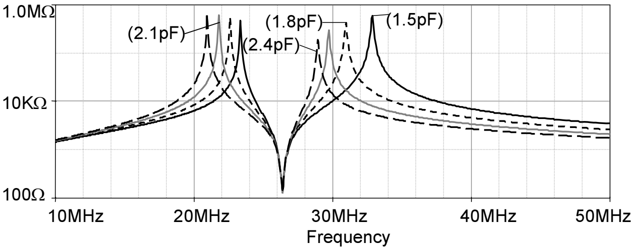

Figure 8. Impedance module of circuit of Figure 3 with different value of *Cp*.

Figure 8 shows the impedance module changing *Cp* from 1.5pF up to 2.4pF; as it can be seen the anti-resonance is not influenced.

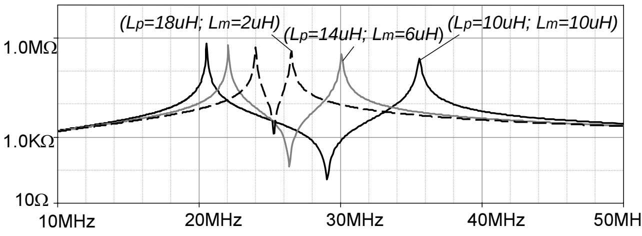

Figure 9. Impedance module of circuit of Figure 3 with different value of *Lm*, *Lp* and *Ls*.

In a contactless system, the distance between the sensitive and readout component can change: so it is important to know also the dependence of parameters under measurement on the distance and its variations. When the distance changes, the magnetization and leakage flux change too, so *Lp Lm* and *Ls* can change. In this case all the frequencies, previously described, are interested and change as reported in Figure 9.

It has been studied the possibility to found a parameter that depends only on distance. Combining the formula of the resonance and anti-resonance frequencies it is possible to individuate an expression, called *"F"*, reported in the following.

$$F = (2\pi f_{ra})^2 + (2\pi f_{rb})^2 - (2\pi f_a)^2 \tag{4}$$

Substituting equation (2) and (3) into (4) it is obtained:

$$F = \left[C_p\left(L_p + \frac{L_m L}{L_m + L}\right)\right]^{-1} \tag{5}$$

The parameter *"F"* does not depend on *Cs* and *Cx*, but on *Cp*, *Lp*, *Lm* and *L*. If *Cp* can be considered fixed *"F"* depends only on magnetization and leakage fluxes, that change according to the geometry of the system, and in particular to the distance between the primary and secondary coils. To convalidate equation (4) an experimental test has been made.

V. EXPERIMENTAL RESULTS

The experimental tests have been conducted on the planar inductances previously used to obtain the parameter of the simulation. Using an impedance analyzer (HP4194A) the three frequencies have been measured changing the value of *Cx* and the distance between the two coupled planar inductances. In Figure 10 it is reported the module and the phase of the impedance measured when the sensor capacitance is 2pF and the distance form the readout circuit is 25mm. It can be noticed the two resonance frequencies and the anti-resonance frequency.

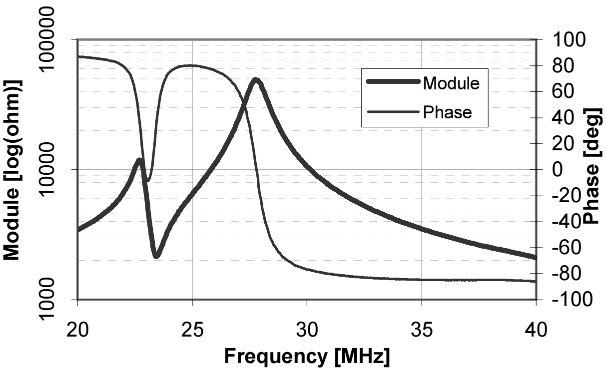

Figure 10. Module and Phase of the impedance measured on the primary with Cs+2pF @25mm.

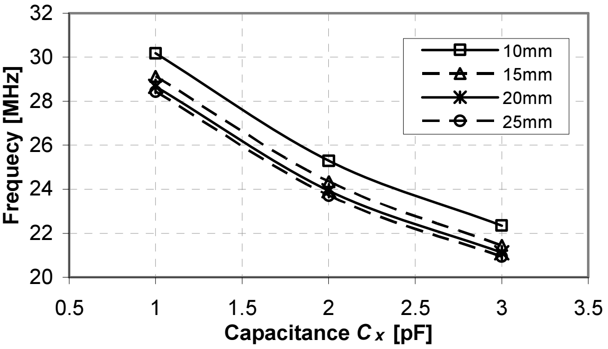

Figure 11. Anti-resonance frequency values for different distances measured changing *Cx*.

In Figure 11 it is observed that the anti-resonance frequency decreases when the capacitance *Cx* increases, but it can be noticed that the distance also changes the anti-resonance frequency.

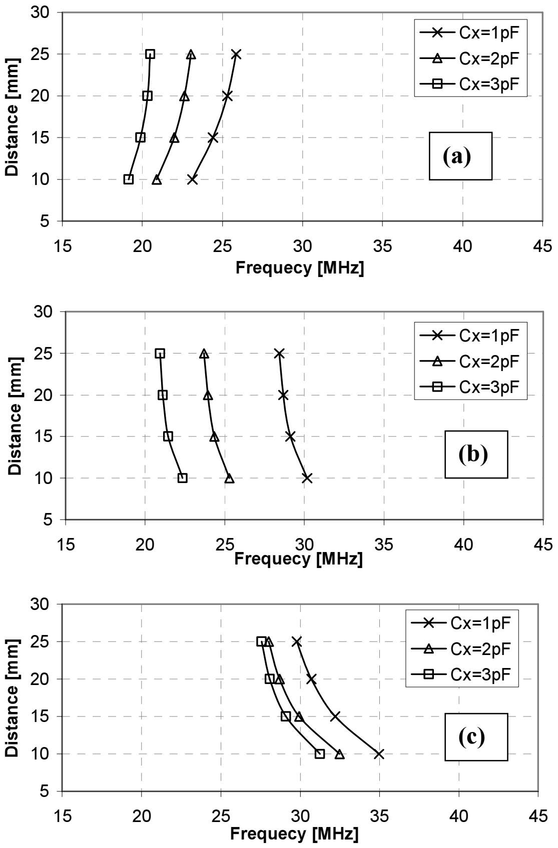

Figure 12. Experimental resonance frequencies obtained for different values of sensing capacitance and different distances. The resonance frequency *fr1* (a), the anti-resonance frequency *fa* (b) and the resonance frequency *fr2* (c).

Figure 12 shows three different graphs, one for each previously identified frequencies. It can be observed that all of them change when the distance between readout and sensing circuit changes. It is also considered for each distance three different values of sensor capacitance. As it is expected the increasing of the sensor capacitance shifts the value curves to the low frequencies.

Table 3 reports the three frequencies when the Cx changes of 2pF (ΔC_x). The anti resonance frequency has the highest sensitivity. This is in according with the Figure 7, also the sensitivity values, obtained with the simulation, have a good correspondence with these experimental results.

Table 3. Frequency variation for different distances measured changing C_x of 2pF.

ΔC_x [pF]	dist. [mm]	Δf_{ra} [MHz]	Δf_a [MHz]	Δf_{rb} [MHz]
2	10	3,975	7,825	3,725
2	15	4,525	7,675	3,1
2	20	4,975	7,563	2,613
2	25	5,363	7,493	2,205

The values of the parameter *"F"* has also been calculated. For each value of distance the two resonance frequencies and the anti-resonance frequency have been measured, so that it is possible to calculate the parameters *"F"* according to equation (4). These experimental texts are carried out with different values of C_x.

Figure 13 reports the values of parameter *"F"* .

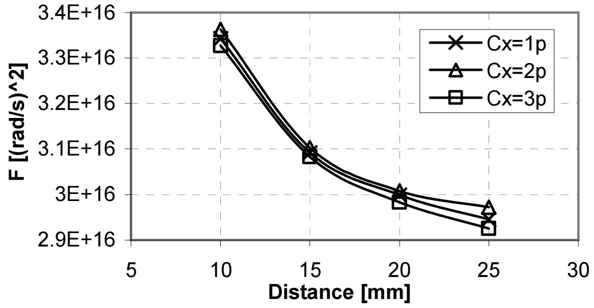

Figure 13. Values of *"F"* measured with different C_x and at change of distance between two coupled inductors.

The results demonstrate that the parameter *"F"* depends mainly on distance, showing a very little sensitivity to C_x.

VI. CONCLUSION

In the paper, a model of an inductive telemetric system considering also the parasitic capacitances and the leakage fluxes is proposed. Experimental proofs evidences a good agreement with the theoretical behavior of the model proposed. Three noticeable frequencies (two resonances and one anti-resonance) have been identified as possible measurement parameters: the anti-resonance frequency shows more sensitivity and no dependence on the parasitic capacitance of the read-out circuit, and can be chosen as measurement parameter.

An analysis on the effect of the distance variation between the readout and sensing inductances highlights that all the previous three frequencies change. Anyway a parameter, obtained from appropriate combinations of the resonance and anti-resonance frequencies, has been identified: it measures the distance and can be, consequently, used to compensate the changing of the anti-resonance frequency to the distance variation.

Experimental results conducted in the laboratory on an inductive telemetric prototype system previously described demonstrate the previous considerations.

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