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A MODEL BASED ANALYSIS OF THE MEASUREMENT ERRORS IN INDUCTIVELY COUPLED PASSIVE RESONANCE SENSORS

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Abstract – A lumped element model was used to predict the measurement results of an inductively coupled resonance sensor. Errors related to the inductive coupling and the reader coil self-resonance were studied. The model was compared with measurements made with a physical circuit.

Keywords: passive resonance sensor, inductive coupling, lumped element model, measurement error

1. INTRODUCTION

Inductively coupled passive resonance sensors enable to make a short range wireless measurement by using a very simple sensor structure. A typical measurement system consists of a reader coil, RLC resonance circuit and a method to measure the reader coil. The measurement methods range from simple slope detectors [1] to impedance analysers [2]. A measurand can be coupled to any of the components in the RLC circuit. Since the reader coil and the sensor coil are inductively coupled, the effect of the measurand can be detected when certain properties of the reader coil are measured. Many of the typical measurands can be converted into the measurement of resistance, capacitance or inductance and thus this measurement concept has a large range of applications. Some of the most interesting applications are the measurement of biopotential signals [1] and pH [3], just to name a few.

In this measurement concept, the inductive coupling between the reader and sensor coils is often unknown and can vary. The changes in the inductive coupling will create an error in the measurement. Another problem is the sensitivity to the environment due to the parasitic electrical fields which often extend outside the casing of the sensor. It is also worth of mentioning that the inductive link cannot be used to measure sensors inside metallic containers and the metal objects in the nearby environment cause measurement errors.

An impedance analyser is a very common instrument to measure inductively coupled passive resonance sensors. The impedance analyser makes a frequency sweep within preset frequencies. Thus the measured data is a set of vectors containing values at those frequencies. The measured complex impedance is expressed as the real and imaginary parts of impedance. Alternatively, the same data can be expressed as the magnitude and phase of the impedance. This type of data can be used to determine the characteristics of the resonance sensor. The often used features are the frequency at which the real part of the impedance has its maximum value [2], [3] and the frequency of the phase-dip [4], [5]. These frequency-valued features can be reliably detected from the wirelessly measured data and they can be used to monitor the changes in the resonance frequency of the sensor especially if the coupling coefficient is constant. These frequency features are closely linked to the resonance frequency of a resonance sensor but a systematic error is often made if they are considered to be same.

An electrical model of the impedance measurement arrangement is used in this study to understand the origin of the problems arising from the inductive coupling. The model should be able to predict the results of an impedance analyser measurement. The modelling was selected as a tool for investigating this problem because in the simulation, all the component values and the resonance frequency of the sensor are known. Thus the extracted frequency features can be compared with the resonance frequency of the sensor to estimate errors occurring due to the inductive coupling.

On the other hand, the model should be simple enough so that the values for the components can be reliably acquired. By using an adequate model, it is possible to investigate how the individual components of the measurement setup affect the results. Thus the measurement system and its components can be optimized to be less prone to the changes in the inductive coupling.

The reader coils are often designed to have as high self-resonance as possible. The frequency is typically higher than the frequency of the resonance sensor. Since the self-resonance of the coil affects the measurement and these design rules do not tell anything about the magnitude of the possible errors, this situation was studied in more details.

In this paper, a model for an inductive coupled passive resonance sensor measurement was investigated. The model was used to predict the possible results of an impedance analyser measurement when the inductive coupling in the model was varied. The functionality of the model was verified by comparing the simulated results with the measurements made with a real sensor.

2. METHODS

The analysis presented in this work is based on a model of an inductively coupled passive resonance sensor when the sensor is measured with an impedance analyser. A Matlab® software was used to express this lumped element model as complex-valued impedances, voltages and currents and then the results of the impedance analyser measurement were calculated.

2.1. Lumped element model

The simplified idea of an inductively coupled passive resonance sensor measurement is shown in the schematic in Fig. 1a. The most important electrical components of the measurement setup are the reader coil (L_r), the sensor coil (L_s) and the sensor capacitor (C_s). The reader coil and the sensor coil are inductively coupled. This is expressed by their mutual inductance *M*. The sensor coil and capacitor determine the resonance frequency of the sensor which is the most fundamental feature of a resonance sensor. The equation for the resonance frequency of the sensor is defined in (1).

$$f_0 = \frac{1}{2\pi\sqrt{L_S C_S}} \quad (1)$$

In order to simulate the actual measurement, a more detailed lumped element model was used in this work (Fig. 1b). This lumped element model is based on the models and calculations published in [1], [5]. The inductive link between the reader coil and the resonance sensor was modelled by placing a reflected impedance component (X) in series with the reader coil. The impedance of this component was calculated in a similar manner as found in [1]. The effects of the coupling coefficient k were also included in the model by using this component. The model has a voltage generator (V_t). The impedance (R_t) models the output impedance of the impedance analysers which is typically 50 Ω. The voltage V_m represents the measured voltage.

Some parasitic components of the measurement system have to be included to make the model to better correspond to the real devices. The parallel capacitance of the reader coil (C_r) has to be included to create a self-resonating frequency (f_{Lr}) to the reader coil since this feature is easily measurable and it significantly affects the measured data. The resistance of the sensor (R_s) and the resistance of the reader coil (R_r) were added. Their purpose is to set the shape and magnitude of the resonance curves.

2.2. Simulation

The lumped element model was used to simulate the measurement results of an impedance analyser. The simulation was done by calculating the complex impedances in the model at the discrete frequencies. The measured voltage (V_m) was solved and then it was used to calculate current (I_t) through the test impedance (R_t). The same current also goes through the reader coil and thus the impedance of the reader coil can be calculated with the Ohm's law. This calculated impedance was considered to model the actual measurement of an impedance analyser in this simulation.

The component values used in the simulation are shown in Table 1. Since the functioning of the model was planned to be verified by using physical devices, the values used in the simulation were based on them. The value of the reader coil was calculated based on its dimensions. The sensor coil and the reader coil have the same shape. The value of the sensor capacitance was based on the nominal value of the bulk capacitor that was used in the resonance sensor. The resonance frequency of the simulated sensor was 136 MHz. The resistances of the coils are actually frequency-dependent values because of the skin effect and dielectric losses. These effects were not included in this initial simulation and thus the constant value of 1Ω was used. The value of C_r was based on the measurement of the resonance frequency of the reader coil without the presence of the resonance sensor which was 332 MHz. The value of the coupling coefficient in the measurements is typically unknown and thus in the simulations it is considered as a variable. The maximum coupling coefficient was set to be 0.32 to make the signal levels of the real part of impedance roughly equal with the measured signal levels. This coupling coefficient corresponds to a situation in which the coils were at 3.1 mm distance from each other.

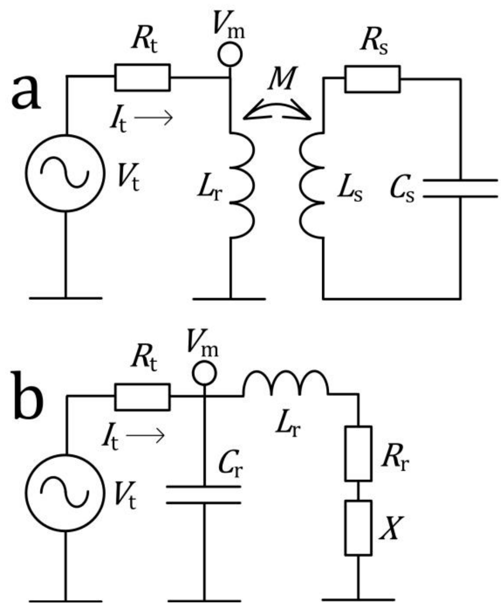

Fig. 1. a) A schematic of an inductively coupled passive resonance sensor measurement. b) The lumped element model of the measurement used in the simulations.

Table 1. Initial values of the simulation

Component	L_r, L_s	C_s	C_r	V_t	R_s, R_r	R_t
Value	137 nH	10 pF	1.68 pF	1 V	1 Ω	50 Ω

A multitude of features can be extracted to describe the measured or simulated curves. The frequency of the maximum value of the real part of the impedance (f_{max}) and the frequency of the phase dip (f_p) are the most commonly used. Measurement errors were calculated by subtracting the resonance frequency of the sensor (f_0) from the extracted features. This was done to investigate the situation in which the value of these features is considered to be the same as the resonance frequency of the sensor.

2.3. Verification measurements

The results of the simulated impedance measurement were compared with the real measured data. Thus a commercial impedance analyser (Agilent 4396B with an impedance test adapter) was used to measure a reader coil and an inductively coupled passive resonance sensor. The results of the complex impedance measurement were saved as four vectors, each containing 801 elements. The quantities of these vectors were the real and imaginary parts of impedance and the magnitude and phase of the impedance since all these quantities are the typically used in passive resonance sensor measurements. The coupling coefficient was altered by changing the distance between coil pair from 3.1 mm to 9.3 mm by 3.1 mm intervals.

3. RESULTS

3.1. Verification of simulation

The results of the simulation were compared with the verification measurement data (Fig. 2). The simulation appears to be able to predict the shape of all the measured curves. The model was also able to predict the behaviour of curves as the coupling coefficient decreases rather well. To demonstrate this, the simulations made with the coupling coefficients of 0.16 and 0.08 are shown in Fig 2. The resonance frequencies found in the simulation and measurement data are not the same. The main reason for this is that the values of the capacitance and inductance of the modelled sensor do not exactly match with the physical circuit.

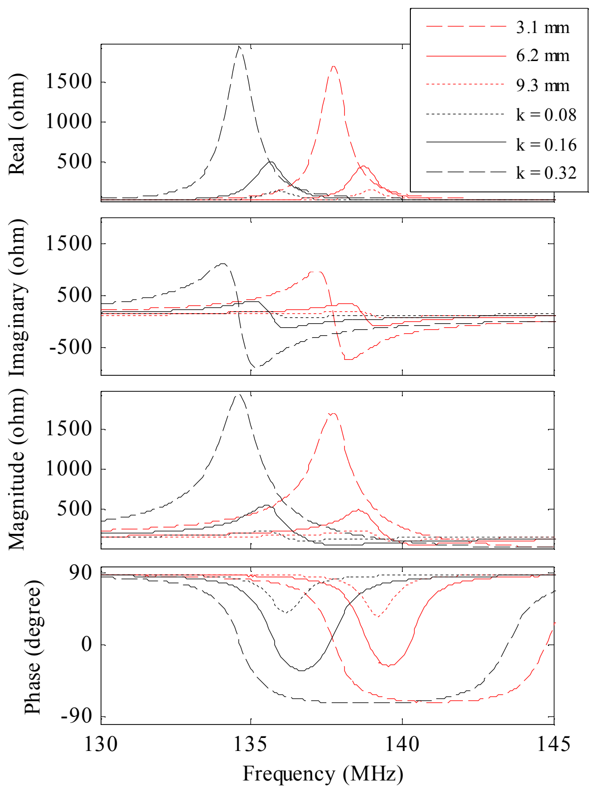

Fig. 2. The simulated (black) and measured (red) frequency responses.

3.2. Effects of self-resonance of reader coil

The frequency responses of the inductively coupled resonance sensor were simulated in two cases (Fig. 3). The first case A was a simulation of a typical measurement situation in which the self-resonance of reader coil frequency was higher (f_{Lr}=190 MHz) than the resonance frequency of the resonator circuit. In the case B self-resonating frequency was set (f_{Lr}=82MHz) below the resonance frequency of the sensor. The adjustment of the self-resonating frequency of the reader coil was done by changing the value of the parallel capacitor. The case B corresponds to a situation in which a large multi-turn reader coil is used. The other variable in these simulations was the coupling coefficient *k*. The black line in the figure indicates the resonance frequency of the sensor (f_0).

The overall signal levels in the case B were much smaller than in the case A. In the case of the phase responses, the drop in the signal levels was not as significant when compared with the rest of the simulated signals. It can be noticed that as the coupling coefficient increases the resonance curves appear to move away from the resonance frequency of the sensor. The direction of the movement is dependent on the relation between the self-resonance frequency of the reader coil and the resonance frequency of the sensor. In the case A, the variation of the coupling coefficient does not appear to have significant effect on the frequency of the dip in the phase curve.

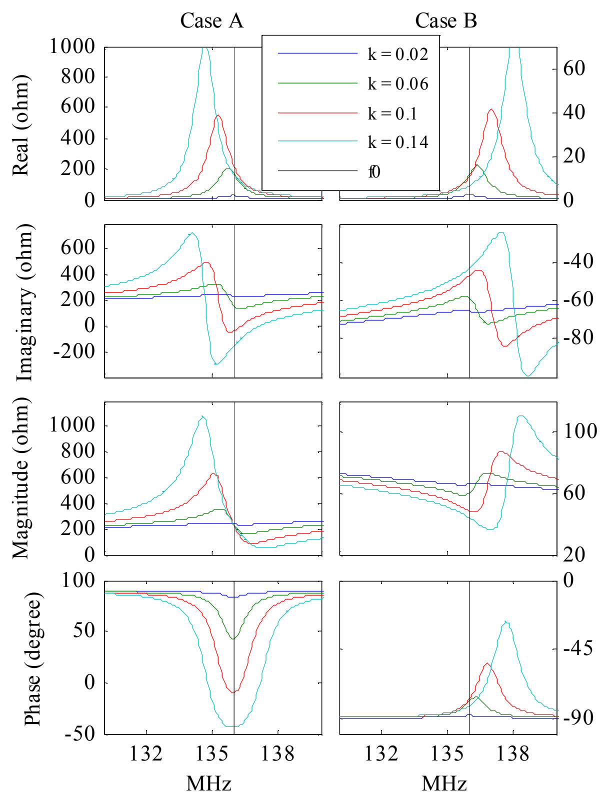

Fig. 3. The simulated responses of an inductively coupled resonance sensor measurement in two cases A and B. In the first case A self-resonance frequency of the reader coil was higher than the frequency of the resonance sensor. In the case B self-resonating frequency was lower than resonance frequency of the sensor.

3.3. Simulated measurement error

The curves in the Fig. 3 appear to be dependent on the coupling coefficient and the ratio of the resonance frequencies, the same must apply to the extracted features. A set of frequency responses were simulated by altering the self-resonance frequency of the reader coil (f_{Lr}) and the coupling coefficient. Then the features f_{max} and f_p were extracted and the measurement errors were calculated. The errors are shown in Fig. 4.

All the calculated errors are small when the coupling coefficient is small. In the case of f_{max} the errors are getting smaller when the self-resonance frequency of the coil is increased. However, the errors related to feature f_p have their minimum when the ratio of the resonance frequencies was near 1.4.

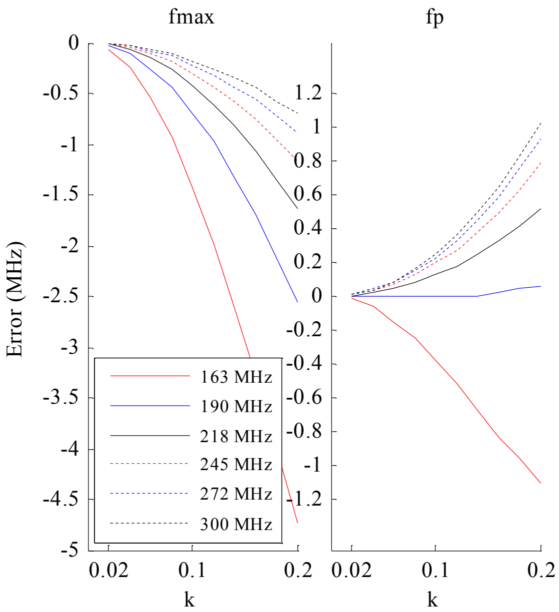

Fig. 4. The errors between the features f_{max} and f_p and the resonance frequency of the sensor when the self-resonance frequency of the reader coil was increased.

4. DISCUSSION

According to the preliminary verification measurements, the presented model was able to predict the shape of the signals that are typically measured with an impedance analyser. The model was used to predict the measurement results when the coupling coefficient and the self-resonance frequency of the coil were altered. The simulated measurement results were used to study the behaviour of two frequency-valued features (f_{max} and f_p) that are can be extracted from impedance analyser data. These features are dependent on the coupling coefficient and thus they cannot be directly linked to the resonance frequency of the resonance sensor without making a systematic error. The error typically increases as the coupling coefficient increases. The methods presented in this paper can be used to investigate the magnitude of that error.

The simulations predicted that the resonance curve of a sensor can be detected even if the self-resonating frequency of the reader coil was set lower than the resonance frequency of the sensor. However, the signal levels were much lower. This kind of situation may occur while a small, high-frequency resonance sensor has to be measured from a distance and the large reader coil is used to increase the reading distance. The self-resonating frequency of the reader coil is a parasitic feature which depends on coil dimensions thus it cannot be freely designed.

The phase-dip technique was least prone to the variation of the coupling coefficient when the self-resonance frequency of the reader coil had certain value. This result is interesting since typically the self-resonance frequency of the reader coil is designed to be as high as possible. The self-resonating frequency of a coil can always be lowered by adding parallel capacitance. This finding has to be confirmed and studied. The finding could be utilized to mitigate the coupling coefficient based errors.

The initial testing of the presented methods has been done to demonstrate their usability. The verification of the presented lumped element model was done by using one reader coil and one sensor. Thus the limitations of the model have to be studied by comparing the predicted data with the data measured with well-known physical components in various measurement configurations. The presented modelling methods can be used in many ways which were not demonstrated in this work. The methods can be utilized for example to test new features and new feature extraction methods, especially, if the noise of the measurement is included into the simulation.

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