The Resonance Frequency Measurement Method of PICCs and the Environmental Influence

Wei Lin; Bernd Geck; Hermann Eul
Leibniz Universität Hannover
Hannover, Germany
lin@hft.uni-hannover.de

Christian Lanschützer; Peter Raggam
Infineon Technologies Austria AG
Graz, Austria
Christian.Lanschuetzer@infineon.com

***Abstract* – A chipcard- or RFID-system operating at 13.56 MHz normally consists of three main components: A Proximity Coupling Device (PCD), a Proximity Integrated Circuit Card (PICC) and a host computer. The PICC consists mainly of a loop antenna which provides the magnetic coupling with the PCD and the IC which is needed for the communication between PCD / PICC and digital data processing. The loop antenna and the input circuitry of the IC together form a resonance circuit whose resonance frequency has a great impact on the efficiency of the magnetic coupling and is therefore an important parameter to characterize the PICC. In this paper the resonance frequency of a PICC is defined and derived by using the circuit analysis. Then a resonance frequency measurement method is investigated and its performance is analyzed theoretically. The influence of the environment on the accuracy of the method is analyzed by simulation and reference measurements. Finally, a setup for the practical implementation of the measurement is presented.**

I. INTRODUCTION

RFID- or PICC- systems can be categorized by operating frequency, operating range, data rate, etc. This paper is focused on systems working at 13.56 MHz which are described in more detail in the ISO standard 14443 [1]. The wavelength of the system is about 22 m and therefore much greater than the distance between the PCD and the PICC; thus it is possible to use only magnetic coupling to describe the functional principle of the system.

In principle, the system is made up of three components: the host computer, the PCD and the PICC. The PCD generates a high frequency magnetic field of 13.56 MHz. When a PICC approaches the PCD, the magnetic field penetrates the antenna of the PICC and induces a voltage which is then rectified and used as the supply voltage for the IC inside the PICC. Not only the power supply but also the communication is performed by using the magnetic coupling. The data communication is accomplished via load modulation. It is obvious that the quality of the magnetic coupling has a great influence on the system's performance. As described in [2], the efficiency of the magnetic coupling will be maximal if the resonance frequency of the PICC is exactly the same as the sending frequency of the PCD, namely 13.56 MHz. Due to the fact that the sending frequency of the PCD is constant according to the ISO standard, the choice of the PICC resonance frequency becomes very important for the overall system performance. In practice, it is much more complicated to choose an appropriate resonance frequency of the PICC because this value also depends on the environmental scenario. A typical example is the multi PICC-scenario which leads to lower resonance frequencies of the PICCs. Thus, by designing a PICC, a trade-off has to be made and oftentimes a frequency recommendation is provided by IC suppliers or RFID organizations. Due to the significance of the resonance frequency of PICCs it is very important for both PICC designers and manufactures to have an effective method for measuring the resonance frequency of PICCs.

II. DEFINITION OF THE RESONANCE FREQUENCY

The resonance frequency of a circuit can be defined in different ways. The most popular definition is the frequency, at which the impedance of the circuit is real [3,4]. This definition is widely used because of its simplicity. If the desired parameter is not the impedance but the voltage across or the current in a specific component, then the definition is not always appropriate as depicted in [5]. In RFID applications the voltage of interest is the voltage across the IC. Thus, the resonance frequency should be defined as the frequency point at which the voltage across the IC reaches its maximum.

A PICC consists mainly of a loop antenna, an IC, and an optional additional capacitor C_{Ext} to tune the resonance frequency to the desired value. The equivalent circuit model of the PICC is shown in Figure 1. The voltage over the IC is named $\underline{U}_2$.

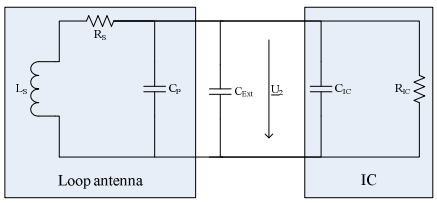

Figure 1 – Equivalent circuit of a PICC

For the derivation of the resonance frequency the capacitance C_p , C_{Ext} and C_{IC} are combined in C and the induced voltage is represented by a voltage source which is proportional to the frequency and the current I_1 in the PCD antenna. The equivalent circuit is shown in Figure 2.

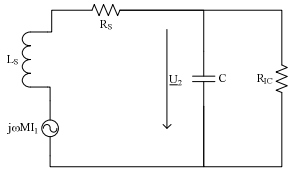

Figure 2 – Simplified equivalent circuit of a PICC with induced voltage

By using the equivalent circuit the voltage $\underline{U}_2$ can be derived:

$$\underline{U}_2 = \frac{j\omega M \underline{I}_1}{(1-\omega^2 L_S C + \frac{R_S}{R_{IC}}) + j\omega(CR_S + \frac{L_S}{R_{IC}})}$$

$$\Rightarrow |\underline{U}_2| = M|\underline{I}_1| \frac{\omega}{\sqrt{(1-\omega^2 L_S C + \frac{R_S}{R_{IC}})^2 + \left[\omega(CR_S + \frac{L_S}{R_{IC}})\right]^2}}$$

$$\frac{d|\underline{U}_2|}{d\omega} \overset{!}{=} 0 \Rightarrow \omega_{res} = \sqrt{\frac{1+\frac{R_S}{R_{IC}}}{L_s C}} \qquad (1)$$

The frequency described by (1) is the frequency at which the voltage $|\underline{U}_2|$ reaches its maximum and can be defined as resonance frequency of a PICC.

III. MEASUREMENT METHOD

For the practical realization of the resonance frequency measurement, the voltage $\underline{U}_2$ has to be measured, however, PICCs are usually laminated in the form of an ID card and the voltage $\underline{U}_2$ is not directly measurable. In the literature [2] a measurement method which uses magnetic coupling between an impedance analyzer and the PICC is presented. The setup is shown in Figure 3. The resonance frequency is determined by measurement of the real part of the impedance over the frequency. The resonance frequency is defined as the frequency where $\mathrm{Re}\{\underline{Z}\}$ reaches its maximum.

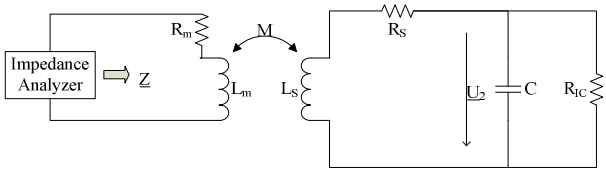

Figure 3 – Measurement setup

To prove the validity of this procedure the impedance $\underline{Z}$ measured by the analyzer is determined analytically.

$$\mathrm{Re}\{\underline{Z}\} = R_m + \frac{\omega^2 M^2 \left(\frac{1+\frac{R_S}{R_{IC}}}{R_{IC}} + \omega^2 C^2 R_S \right)}{\left(1+\frac{R_S}{R_{IC}} - \omega^2 L_S C\right)^2 + \omega^2 \left(\frac{L_S}{R_{IC}} + C R_S\right)^2} \tag{2}$$

$$\mathrm{Im}\{Z\} = \omega \left\{ L_m + \frac{\omega^2 M^2 \left(C(1-\omega^2 L_S C) - \frac{L_S}{R_{IC}^2} \right)}{\left(1+\frac{R_S}{R_{IC}} - \omega^2 L_S C\right)^2 + \omega^2 \left(\frac{L_S}{R_{IC}} + C R_S\right)^2} \right\} \tag{3}$$

To find the maximum of $\mathrm{Re}\{\underline{Z}\}$,the equation $\frac{d\,\mathrm{Re}\{\underline{Z}\}}{d\omega} \overset{!}{=} 0$ has to be solved. This equation is solved with Maple [6]. The result is simplified with the following assumptions which are generally true for PICCs:

$$\begin{aligned} R_S &<< R_{IC} \\ R_S &<< \omega L_S \end{aligned} \tag{4}$$

After some simplification the final result is very simple:

$$\omega_{res} \approx \frac{1}{\sqrt{L_S C}} \tag{5}$$

The comparison of (1) with (5) makes clear that the measurement described earlier determines nearly the same frequency as the theoretical resonance frequency, as long as $R_S << R_{IC}$ is true. Under the conditions described in (4), this method will provide a very accurate resonance frequency.

The accuracy is not the only advantage of this method. For a practical implementation of this method only an impedance analyzer and a measuring coil are needed. And since the data is acquired through magnetic coupling, a direct galvanic contact with the DUT is not needed.

A more detailed inspection of (2) shows that the parameters which are dependent on the measuring coil, namely R_m, L_m, M, vanish in the equation $\frac{d\,\mathrm{Re}\{\underline{Z}\}}{d\omega} \overset{!}{=} 0$. This means that the measuring coil will not influence the measurement result in an ideal case and the user is free in choosing the measuring coil.

IV. INFLUENCE OF THE MEASURING COIL

In the section above, it has been proven that the measurement method is very accurate and easily performed. However, in the real implementation one has to pay more attention to the measuring coil. By choosing an inappropriate measuring coil and setup, the measured resonance frequency can significantly vary from the correct one. In this section the influence of the measuring coil is taken into account. The measuring coil can cause measurement errors in two ways:

a) The measuring coil is not only an inductance but also a resonance circuit itself because of the stray capacitance C_m between the turns. This resonance behavior will influence the measured result. The system is shown in Figure 4. The impedance analyzer will measure the impedance $\underline{Z}_m$, which varies from the desired value $\underline{Z}$ because of the stray capacitance.

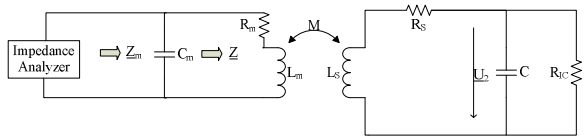

Figure 4 – Measurement system with stray capacitance C_m

With the known $\underline{Z}$ derived before, $\underline{Z}_m$ can be calculated:

$$\underline{Z}_m = \frac{1}{\frac{1}{\underline{Z}} + j\omega C_m} = \frac{1}{\frac{1}{\mathrm{Re}\{\underline{Z}\} + j\,\mathrm{Im}\{\underline{Z}\}} + j\omega C_m}$$

After some manipulations the formula is simplified to:

$$\mathrm{Re}\{\underline{Z}_m\} = \frac{\mathrm{Re}\{\underline{Z}\}}{(1-\omega C_m\,\mathrm{Im}\{\underline{Z}\})^2 + (\omega C_m\,\mathrm{Re}\{\underline{Z}\})^2}$$

According to (3) $\mathrm{Re}\{\underline{Z}_m\}$ can be rewritten by using the following substitution:

$\mathrm{Im}\{\underline{Z}\} = \omega L_{eqv}$ with

$$L_{eqv} = L_m + \frac{\omega^2 M^2 \left(C(1-\omega^2 L_S C) - \frac{L_S}{R_{IC}^2} \right)}{\left(1+\frac{R_S}{R_{IC}} - \omega^2 L_S C\right)^2 + \omega^2 \left(\frac{L_S}{R_{IC}} + C R_S\right)^2}$$

$$\mathrm{Re}\{\underline{Z}_m\} = \frac{\mathrm{Re}\{\underline{Z}\}}{\left(1-\omega^2 C_m L_{eqv}\right)^2 + (\omega C_m\,\mathrm{Re}\{\underline{Z}\})^2} \tag{6}$$

As we can see from the formula above, the wanted curve of $\mathrm{Re}\{\underline{Z}\}$ is changed due to the two extra terms in the denominator. The first term $\left(1-\omega^2 C_m L_{eqv}\right)^2$ represents the resonance behavior of the measuring coil under the influence of the coupling with the DUT. As the stray capacitance C_m is small (typical only of few picofarads), the resonance frequency of the measuring coil will be much higher than the RFID operating frequency of 13.56 MHz. Therefore, this term will decrease with the frequency in the interested frequency range from 10 MHz to 20 MHz. The other term is increasing with ω^2 and the importance of this term is greatly influenced by the factor $\mathrm{Re}\{\underline{Z}\}$. For a better understanding it is useful to make a separation depending on the coupling factor k between the measuring coil and the DUT:

- By a very loose coupling with small k, $\mathrm{Re}\{\underline{Z}\}$ is diminutive and the first term will dominate. The denominator will decrease with the frequency. This means that the curve $\mathrm{Re}\{\underline{Z}\} = \mathrm{Re}\{\underline{Z}\}(f)$ is multiplied with a factor increasing over the frequency and the measured resonance frequency should be shifted to a higher value.
- By a very good coupling with big k the second term can be dominant and the denominator is increasing with the frequency. Thus, the measured resonance frequency is shifted to a lower value.
- The turning point between the two extreme situations is determined by the other parameters, e.g. R_{IC}, C_m, etc.

For demonstration of this effect, formula (6) is used to calculate $\mathrm{Re}\{\underline{Z}_m\}$ as an example combination of DUT and measuring coil with the varying coupling coefficient k.

The example DUT is modelled with:

$R_s = 4.91\,Ohm, R_{IC} = 1000\,Ohm, L_s = 1.72\,\mu H, C = 57.53\,pF$.

The resonance frequency of this DUT is 16.03 MHz according to (1).

The example measuring coil is modelled with:

$R_m = 2.13\,Ohm, L_m = 1.4\,\mu H, C_m = 3.08\,pF$

The coupling coefficient varies from 0.05 to 0.8.

From the calculated $\mathrm{Re}\{\underline{Z}_m\}$ curve the resonance frequencies are read out and plotted:

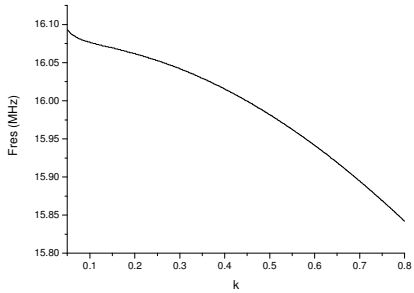

Figure 5 – Resonance frequency obtained from $\mathrm{Re}\{\underline{Z}_m\}$

This plot proves the earlier analysis. The resonance frequency is higher than 16.03 MHz for small coupling values k and lower than 16.03 MHz for strong coupling.

For a real measurement the first case with small k is of more interest since in most cases the coupling of the measuring coil with the DUT is kept loose to prevent extra stray capacitance (will be described in more detail in the next subsection).

As described above the error of the measured resonance frequency also depends on the DUT parameters. To determine the error, the following measurement is performed. Three measuring coils and two DUTs are produced by precise laser processing:

	Measuring Coil 1	Measuring Coil 2	Measuring Coil 3
Number of turns	2	3	4
Size (mm*mm)	72*42	72*42	72*42
Track width (mm)	0.54	0.50	0.54
Gap (mm)	0.66	0.70	0.66
Conductor height (µm)	17.5	17.5	17.5
L_m (µH)	0.74	1.40	2.17
C_m (pF)	2.52	3.08	3.44
R_m (Ohm) At 16 MHz	1.38	2.13	2.63

TABLE 1: PARAMETER OF THE MEASURING COILS

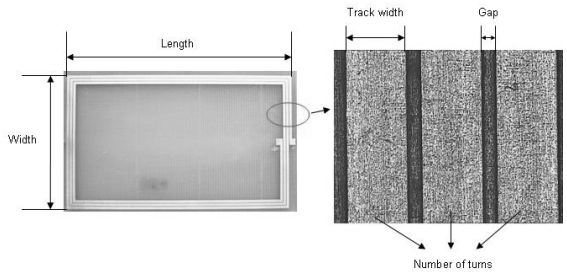

Figure 6 – Layout of the measuring coils

Figure 6 shows that the track width of the turns and the gap between the turns is very well defined throughout laser processing technology. The base material of the coils is FR4.

	DUT 1	DUT 2
Number of turns	3	6
Size (mm*mm)	80*48	80*48
Track width (mm)	0.20	0.20
Gap (mm)	1.22	1.44
Conductor height (µm)	17.5	17.5
L_s (µH)	1.72	4.32
R_s (Ohm) at 16 MHz	4.91	8.68
R_{IC} (Ohm)	1000	1000

TABLE 2: PARAMETER OF THE DUTS

At first, both DUTs are tuned to have a resonance frequency of exactly 16.0 MHz by using a measuring coil of one turn and without R_{IC} being connected. Then R_{IC} of 1000 Ohm is added and the DUTs are measured with the three measuring coils. The distance between the DUT and the measuring coil is 23 mm.

The measured resonance frequencies are given in the following table.

	Measuring coil 1	Measuring coil 2	Measuring coil 3
DUT 1	16.06 MHz	16.07 MHz	16.08 MHz
DUT 2	16.16 MHz	16.22 MHz	16.29 MHz

TABLE 3: MEASUREMENT RESULTS

To investigate the influence of the DUT parameters on the errors the following calculation is performed: Two series of DUTs according to the DUTs measured above are considered. For the first series: R_s : 4.91 Ohm. R_{IC} : 1000 Ohm. L_s varies from 1 µH to 3 µH. For the second series: R_s : 8.68 Ohm. R_{IC} : 1000 Ohm. L_s varies from 3 µH to 5 µH. For each value of L_s , C is tuned for resonance at 16 MHz according to the definition. The coupling coefficients are simulated for the above setup by field simulation with Ansoft HFSS [7] and listed in the following table:

	Measuring coil 1	Measuring coil 2	Measuring coil 3
Series 1	0.104	0.111	0.114
Series 2	0.120	0.126	0.132

TABLE 4: COUPLING COEFFICIENTS

By using these parameters, the errors are calculated and shown in Figure 7.

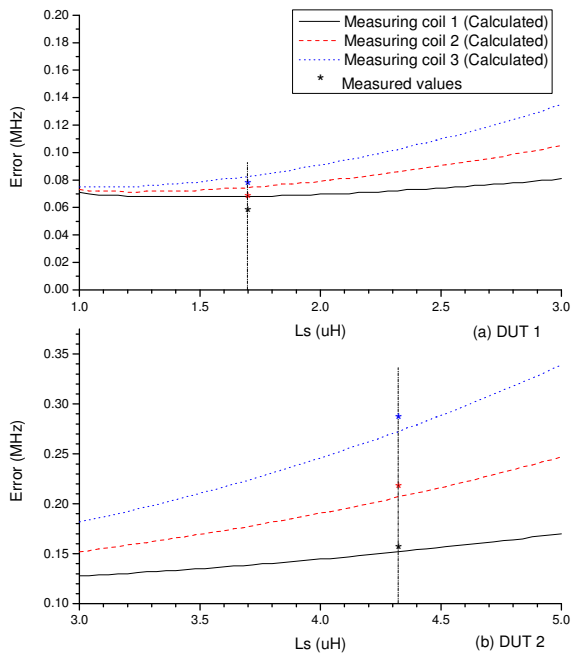

Figure 7 – Calculated and measured errors

The agreement of the measured and calculated values proves the earlier analysis. The calculated curve shows that in the defined setup the error increases with a rising L_s .

b) During the measurement the DUT is placed on top of the measuring coil. The overlap of the windings causes a parasitic capacitance between the two coils and thus causes a second source of measurement errors. From our experience, the simulation of this effect is critical. Therefore, we made these investigations by measurements. A planar device with the following geometry data is used as DUT: Size: 80 mm*48 mm; Number of turns: 5; Track width: 0.2 mm; Gap: 1.8 mm.

The IC of the DUT is modelled with a load resistance R_{IC} of 1000 Ohm in parallel with a capacitance C_{IC}. The distance between the DUT and the measuring coil is varied from 0 mm to 20 mm. The measurement result is shown in Figure 8.

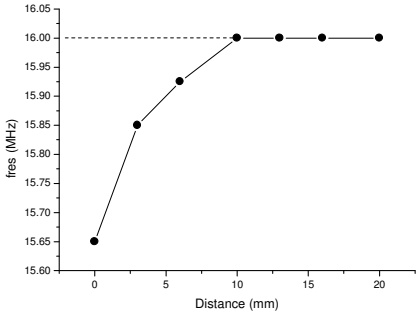

Figure 8 – Measured resonance frequency fres vs. distance

It is obvious from Figure 8 that the parasitic capacitance decreases with the increasing distance, so that the measured resonance frequency increases with the distance between the DUT and the measuring coil. Above a certain threshold the influence of the parasitic capacitance is so small that the resonance frequency is almost constant. For this example, a maximal measurement error of 0.35 MHz can be observed. This numerical value is only valid to test DUT since this effect strongly depends on the DUT geometry.

As we can see from the analysis above, the various effects have different influence on the measurement result. A stray capacitance between the measuring coil and the DUT will decrease the measured resonance frequency. A small k and a small R_{IC}, which means a high current consume by the IC, will cause an increase of the measured resonance frequency. Thus, the geometry of the measuring coil and the distance between the measuring coil and the DUT have to be designed carefully by considering all these effects.

V. INTEGRATION INTO EXISTING ISO SETUP

By choosing a measuring coil which has a resonance frequency much higher than the one of the PICC and an appropriate distance holder between them, the influence of the measuring coil can be minimized. For a better usability of this method, a measurement setup has to be defined. In ISO standard 10373-6 a measurement assembly is already defined for measuring many characteristic system parameters, such as PCD field strength, modulation index etc. [8]. This setup can be extended to perform the resonance frequency measurement by adding a measuring coil for the resonance frequency on the board of the sense coil A, as shown in the following figure:

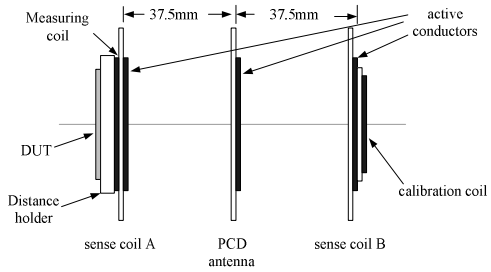

Figure 9 – Extended test PCD assembly

The ISO standard 10373-6 defines the PCD antenna with its matching network. Two PCD antennas with Q=16 and Q=30 are used in the following simulation. First, the coupling factors between the three coils (DUT, measuring coil and PCD antenna) are calculated. Then the measurement setup is simulated by a circuit simulator.

The IC of the DUT is modelled with a load resistance R_{IC} in parallel with a capacitance which is tuned for the desired resonance frequency in each simulation. Three parameters: DUT coil inductance L_s, IC resistance R_{IC} and the theoretical resonance frequency f_{res} are varied to represent various PICCs. The deviation between the simulated resonance frequency and the theoretical one is calculated and plotted in the following figure for certain parameter combinations.

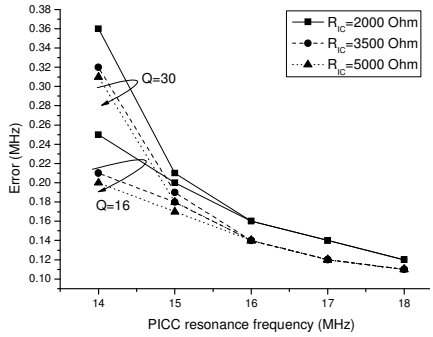

Figure 10 – Calculated error by $L_S = 3\,\mu H$

As we can see from Figure 10 the errors depend mainly on the resonance frequency of the PICC. The closer the resonance frequency is getting to the system frequency 13.56 MHz, the bigger the error. The second parameter which has a big influence on the error is the quality factor of the PCD antenna. The other factors also affect the error; however, their influence is small. This error results from the measuring setup. The PCD antenna with an impedance matching network also forms a resonance circuit with a resonance frequency at nearly 13.56 MHz. This circuit is also coupled to the measuring coil. Thus, the measured curve at the measuring coil is a superposition of two resonance curves.

VI. SUMMARY

In this paper the resonance frequency of a PICC has been defined by theoretical analysis with respect to the HF RFID applications. Then a measurement method which uses a magnetically coupled measuring coil has been investigated theoretically. The analysis shows that the measurement method is precise and easily performed. However, in a real implementation the measuring results will be influenced by the measuring coil itself and therefore the results are erroneous. These errors are analyzed theoretically and verified by measurement. The result shows that in some cases the influence of the measuring coil causes errors which are not neglectable. The theoretical analysis also shows that the error sources sometimes compensate each other, thus, it is possible to design an effective measuring setup to minimize the errors. Furthermore, a suggestion for integration of this method into the ISO measurement assembly has been made and the influence of the PCD antenna in this setup on the measuring accuracy is analyzed.

REFERENCES

[1] ISO/IEC 14443, Proximity cards(PICCs). http://wg8.de/sd1.html

[2] K. Finkenzeller. *RFID-Handbuch*. Hanser Fachbuchverlag, 2002.

[3] H. Frohne, K. Löcherer and H. Müller. *Grundlagen der Elektrotechnik*. B. Teubner Verlag, 2002.

[4] B. Bleaney. *Electricity and Magnetism*. Oxford University Press, 1989.

[5] H. Haase, H. Garbe. *Elektrotechnik*. Berlin: Springer Verlag, 1998.

[6] http://www.maplesoft.com/

[7] Identification cards - Test methods - Part 6: Proximity cards. http://wg8.de/sd1.html

[8] http://www.ansoft.com/