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Optimization of Tag Antenna for RFID System

Dan Wang, Lei Xu, Huiming Huang, Daoheng Sun

Department of Mechanical and Electrical Engineering, Xiamen University, Fujian, CHINA, 361005
hongqistreet@yahoo.com.cn, charlie1975@163.com, xmhhm@126.com, sundh@xmu.edu.cn

Abstract —**Tag antenna can make RFID tags be read at a distance and do not require a line of sight between tag and reader. This paper describes design and optimization aspects of antenna coil of tag for RFID system in High Frequency (HF) band. An equivalent circuit of tag is established and a new detailed design method is demonstrated. An experimental formula with high efficiency is used to calculate the inductance of the coil. It also presents a method for inductor optimization for tag antenna design which can set different objective functions and constraints for corresponding purpose in different conditions easily. Through the calculation of Matlab, the result of this method is feasible and globally convergent.**

Keywords-RFID; tag antenna; equivalent circuit; design flow; optimization; Q factor

I. INTRODUCTION

Radio Frequency Identification (RFID) technology is a non-contact automatic identification technology. The great appeal of RFID is that it allows information to be stored and read without requiring either contact or a line of sight between tag and read. It has become very popular in many services in the industry such as automotive systems, access control, distribution logistics and material flow system. Compared to other automatic identification procedures (barcodes, magcards, contact-based smart card), RFID system is proven to be very advantageous [1]. It must be going to trigger a revolution in identification systems in the future.

An RFID system is always made up of two components: the tag and the reader. When the tag enters the RF field of a reader, its antenna receives energy from the field. In this system, the reader antenna is the primary coil that transfers voltage to tag antenna that acts as the secondary antenna. Since the energizing and communication between the reader and tag is accomplished though antenna coils, the antenna design plays a key role in RFID system. It directly influences on the reliability of data transmission and the read range.

There have been many studies on tag's antenna already. However, it's mainly involved in design of particular classes of antennas used for different situations and analysis of their electromagnetic fields in UHF and microwave bands[2-4] and physical model and quality of antennas used as integrated inductors[5-8].Very few papers provide a overview of specific tag antenna design in HF. Andre. A [9] came up with a method that how to supply contactless IC cards with energy. But he didn't point out the way to design the antenna and calculate its quality factor (Q). In the current article, we reviewed design acquirement for RFID tag antennas in 13.56 MHz, outlined the design process. And we presented a new numerical method to optimize the geometric dimensions of tag antenna.

II. DESIGN AND OPTIMIZATION

A. Design principles and modeling

The voltage induced in the tag coil is used to provide the power supply to the microchip of the tag. In order to significantly improve the efficiency of the equivalent circuit of tag, the capacitor of microchip is connected in parallel with the tag coil to form a parallel resonant circuit with a resonant frequency that corresponds with the frequency of the RFID system.

Figure 1 shows the equivalent circuit of the whole label. The microchip (the tag's data carrier) is represented by the grey box.

The voltage U induced in the tag coil L2 is:

$$U = \mu_0 \cdot A \cdot N \cdot \omega \cdot H \tag{1}$$

Where the constant μ0 is vacuum permeability, A is the average area of antenna's each loop, N is the number of the turns, ω is the angular frequency of the resonant circuit

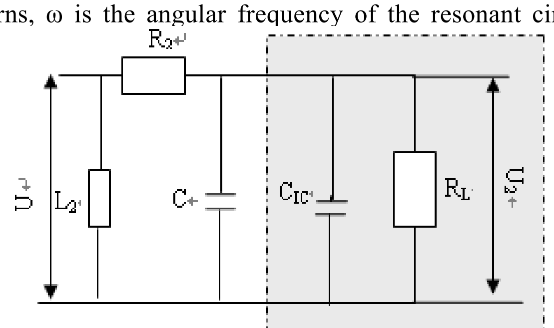

Figure 1. Figure 1 equivalent of the circuit

(ω=2 π f), H is the field strength within the interrogation zone of a reader.

The voltage U2 can be measured at the data carrier load resistor RL in the equivalent circuit shown in Figure 1:

$$U_2 = \frac{U}{\sqrt{(\frac{\omega L_2}{R_L} + \omega R_2 C_2)^2 + (1 - \omega^2 L_2 C_2 + \frac{R_L}{R_2})^2}} \tag{2}$$

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When the operating frequency is equal with the frequency of the resonant circuit, the quality factor (Q) is:

$$Q = \frac{1}{\frac{R_2}{\omega L_2} + \frac{\omega L_2}{R_L}} \tag{3}$$

From what we have discussed above, we can safely draw a conclusion that the voltage U2 which tag antenna provide to the microchip (data carrier) is determined by U (the voltage induced by antenna coil) and Q (the quality factor of the resonant circuit).For a certain RFID system, operating frequency f is also fixed, therefore, in order to get sufficiently high voltage U, an enough total equivalent area A · N must be guaranteed. However, we can not simply say that the higher U and Q are, the better. This is because the total area, the inductance L and the Q factor are all related to the geometric dimensions of antenna coil, they interact with each other. This should always be taken into consideration when designing antenna coils, because it can be exploited to optimize the energy range of the RFID system.

B. Coil design procedure

In order to maximize the communication range between reader the tag, the resonant frequency of the circuit shown in Figure 1 should correspond with the operating frequency of the system. The resonant frequency can be calculated using the Thomson equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

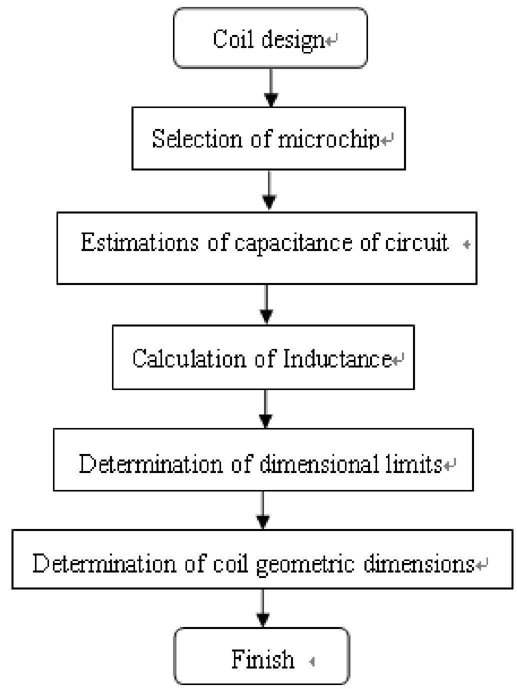
Where L is the inductance of coil inductor, C is the total capacitance of the circuit. This capacitance C can be split up into the microchip capacitance, the coil capacitance and the connection capacitance. And the microchip capacitance is its main part.

In a RFID system, operating frequency is fixed, consequently the resonant frequency is fixed. In order to be able to calculate roughly the objective inductance L of the coil, it is necessary to estimate the capacitance C of the circuit. The microchip's capacitance is determined, the value of the coil capacitance and the connection capacitance can be estimated by choosing a number from 5 to 10(pF). As a result, objective L is:

$$L = \frac{1}{(2\pi f)^2 \cdot C} \tag{5}$$

The inductance of the coil depends upon its geometric dimensions. Therefore, we must make sure the inductance of the antenna that we designed is equal to the value of L calculated in equation 6. It is an important constraint

The design flow is:



C. Antenna Optimization

In the design flow above, the step of "Determination of coil geometric dimensions" is the most important part in design process. Designers always determine coil geometry by experience in the traditional method. They can only calculate out the inductances of the antenna coils after the designs are finished, which may not be the optimized solution, or even not qualified for the requirement. Thus, they can only revise the parameters over and over again. Such method is low in efficiency and can not get the optimal antenna parameters. However, few papers provide a proper algorithm to solve this problem, because the optimization of the inductor is a multiple variables nonlinear program [9], with substantial independent variables. If we choose a normal algorithm, the result is not always feasible and convergent.

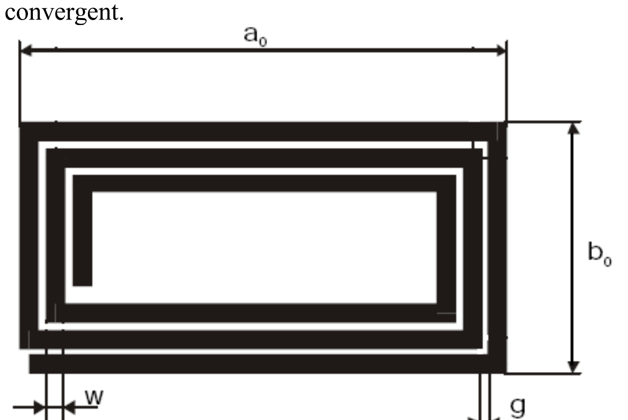


Figure 2 spiral rectangular antenna coil

Optimization model is described as:

$$\min f(x)$$
$$G_i(x) = 0 \qquad (i = 1, \ldots\ldots, \; m_e)$$
$$G_i(x) \le 0 \qquad (i = m_{e+1}, \ldots\ldots, \; m)$$
$$x_1 \le x \le x_n \tag{6}$$

Where x is the geometric parameter vector, f(x) is the objective function and G(x) is the constraint.

And in our practice process of optimization, we can also add objective functions and constraints for corresponding purpose easily. For example, some designers need minimum loss of the coil, and he can set the objective function as minimum resistance of the coil; some designers need maximum Q factor, and thus he can set the objective function as maximum Q factor; in some cases, the loops of the antenna circles need to meet a certain dimension restraint, which we can set as a constraint.

To confirm the practicability of this algorithm, we can calculate a sample. The graphic model is shown in Figure 2 and the mathematical model is:

Max $$Q = \frac{1}{\dfrac{R_2}{\omega L_2} + \dfrac{\omega L_2}{R_L}} \tag{7}$$

Subject to: $$L_{calculated} = \frac{1}{(2\pi f)^2 \cdot C_{circuit}} \tag{8}$$

$$a \le a_0 \,,\; b \le b_0 \tag{9}$$

$$w \ge w_0 \,,\; g \ge g_0 \tag{10}$$

$$t = t_0 \tag{11}$$

$$a - 2 \cdot N \cdot (g + w) - \frac{1}{3} a \ge 0 \tag{12}$$

$$b - 2 \cdot N \cdot (g + w) - \frac{1}{3} b \ge 0 \tag{13}$$

Where a and b are the overall dimensions of the coil, w is the track width, g is the gap between tracks, t is the track thickness, N is the number of turns. Equation 7 is the objective function which we set it as maximize the Q factor; Equation 8-13 are the constraints. In order to make sure the resonant frequency corresponds to the operating frequency, the calculated inductance of the coil must be equal to the value of objective inductance which is described in Equation 8. Equation 10 means the overall dimensions of the antenna should accord with the dimension limitations such as it can not be larger than the outer dimensions of the tag which the antenna located in. The values of w, g, and t are limited by technological parameters in Equation 10 and 11. In order to narrow the search-space to speed up the convergence rate, we can attach a number of constraints such as Equation 12 which means the inner dimensions are not smaller than one third of the outer dimensions.

It is really obvious that, to count out the antenna geometry, we first need to solve two problems. One is to calculate the inductance of antenna coil in Equation 8; the other is to choose a proper algorithm for the optimization issue.

1) Inductance of antenna coil

Antenna coils in HF band are always spiral coils with rectangular cross sections, Figure 2 is the antenna coil of the tag. The calculation of coil's inductance which depends only on geometrical parameters plays an important role in design process. Although various empirical formulas exist in literature for estimating spiral inductance [10-13], the Greenhouse method [14] offers superior accuracy. However, with the increase of the coils number of turns, the computing time will increase exponentially because the foundation for computing inductance by Greenhouse is built on the concepts of the self inductance of each section wire and the mutual inductance between a pair of wires. So its efficiency is low. Therefore, in this paper, we use the empirical formula in coil design guide of Philips [15] in our inductor model. Three different induction coils were fabricated for measurement to investigate the error of this method. Figure 3 is the samples of antenna coils.

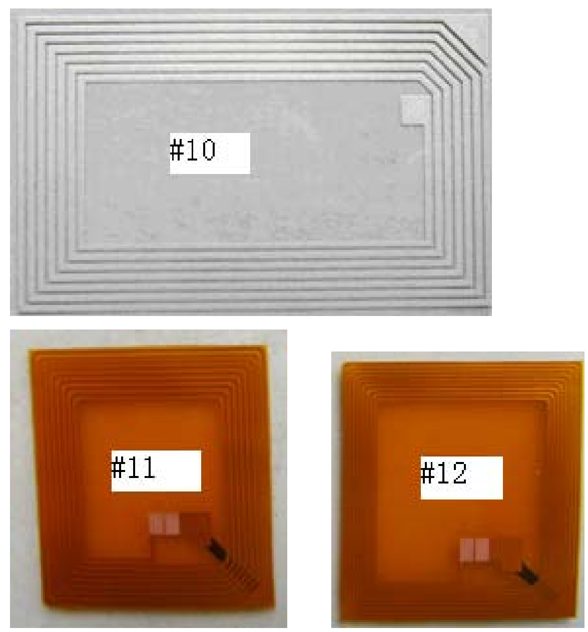


Figure 3 samples of antenna coils

a0, b0, w, g are the geometric dimensions shown in Figure 2. N is the coil number of turns, and t is the track thickness. Results are summarized in Table 1. It will be noted that the relative error is lower than 4% which can be accepted in the design process.

TABLE I. COMPARISON BETWEEN MEASURED INDUCTANCE VALUES AND CALCULATED

Inductor	N	a0(mm)	b0(mm)	w(mm)	g(mm)	t(mm)	Calculated Inductance(μH)	Measured Inductance(μH)	Relative Error
NO. 1	8	45	45	0．8	0.3	0.018	4.1	3.95	3.8%
NO. 2	8	44	44	0.6	0.2	0.018	4.63	4.76	2.7%
NO. 3	7	65	40	0.6	0.6	0.018	3.91	3.76	3.9%

TABLE II. COMPARISON OF Q FACTOR FOR DIFFERENT DESIGN METHOD

Method	Microchip: ICODE1 , the capacitance of the chip:23.5(pF)		
	Equation 8: objective L=4.12 (μH)		
	Equation9: $a \le 60$(mm) , $b \le 60$(mm)		
	Equation10 ,11: $w \ge 0.5$(mm) , $g \ge 0.1$(mm) , t=18 (μm)		
	Overall Dimensions(mm)	**Calculated inductance(μH)**	**Q factor**
Optimization Algorithm	a=48.23, b=48.23	4.12	36
Empirical Method	a=58.5, b=47	4.04	32

2) *Algorithm of optimization*

In order to solve this problem, we use Sequential Quadratic Programming (SQP) method. In this method, the algorithm solves a quadratic programming (QP) sub problem at each iteration. An estimate of the Hessian of the Lagrangian is updated at each iteration using the BFGS formula. The benefit of SQP lies in: The number of iterations is usually less than that of other algorithm because it can provide optimum direction of search and step length.

Furthermore, by using this algorithm, we can avoid revising the coil geometry over and over again, and thus the calculation efficiency highly improved

By calculating the mathematical model in matlab, we got the optimal geometric dimensions (mm) as listed: a=43.23, b=43.23, w=1.5, g=0.15, t=0.018, N=10. The comparison with the results calculated by experience method is summarized in Table 2. From the table above, we can see though the optimization, the Q factor of the coil has been improved.

III. CONCLUSIONS

In this paper, we present a method to design the antenna coil of the tag and an algorithm to optimize its geometric parameters. We use a experimental formula to compute the inductance of the coil, with the error within 4%.With the optimization we've discussed above, it is unnecessary to revise the parameters of the coil over and over again which is time consuming as we know ,and can get an optimal high Q inductor. Furthermore, it is easy to get different results of optimization depending on the purpose in different conditions by setting the objective function.

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