Voltage Sensitivity of Tag Antennas for Inductively Coupled RFID Systems

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Abstract. This paper describes a parameter of voltage sensitivity to recognize the performance differences of tag antennas for inductively coupled RFID systems. Based on the equivalent circuit model of the RFID tag and reader, an expression for the voltage sensitivity is educed. Then, the design steps of measuring platform to obtain the voltage sensitivity of tag antenna are introduced in detail. Finally, the feasibility of the proposed method was verified with the market available tag antennas through the measuring platform.

1. Introduction

Radio frequency identification (RFID) is a relatively new technology that utilizes the radio frequency waves to transfer data between a reader and a tag through their respective antennas\cite{1}. Depending on how the reader and tag work, the RFID systems can be generally divided into two categories: inductive coupling systems and electromagnetic backscatter coupling systems. The typical operating frequencies of the former are 125kHz, 134.2kHz and 13.56MHz, and that of the latter are 433MHz, 860~960MHz, 2.45GHz. In comparison, the reading range of the inductively coupled RFID system in low frequency (125kHz/134.2kHz) is very short but can penetrate dielectric materials, like water or soil. Thus, it has been widely used for detecting the buried unexploded ordnance\cite{2-3}, continuous glucose monitoring\cite{4}, downhole tool control\cite{5} and tracking underwater pebbles\cite{6-7}. When designing these RFID systems, different manufacturers or even the same manufacturer's air-core RFID tag antennas and ferrite-core RFID tag antennas have different sizes, which make it quite difficult to choose and use. The common antenna parameters, such as inductance and resistance, give very little information about the performance. Therefore, it is necessary to introduce a suitable parameter to recognize the performance differences of tag antennas.

Obviously, the parameter of sensitivity that characterizes the ability to receive signals from the reader antenna can be used to compare various tag antennas, that is, higher sensitivity means longer reading distance and the ability to receive weaker signals. In order to make fair comparisons, the sensitivity measurement method must produce consistent and reproducible results. However, little published literature has focused on these areas\cite{8}, especially for low frequency RFID systems. Therefore, introducing a proper sensitivity definition, calculating it and measuring it, which is presented in this paper, is beneficial.
2. Voltage Sensitivity Parameter

For the low frequency inductively coupled RFID systems, the time-varying magnetic field $H$ that is produced by the reader antenna can induce a voltage $U$ in the tag antenna, which activates the tag. Thus, the magnetic field $H$ and induced voltage $U$ in the tag antenna are two important parameters, and the voltage sensitivity of the tag antenna is defined as the ratio of $U$ and $H$:

$$\text{Sensitive} = \frac{U}{H},$$

which gives performance information about how sensitive the tag antenna to the time-varying magnetic field $H$ produced by the reader antenna. The voltage sensitivity of the tag antenna can be derived as follows.

![Fig.1 Inductive coupling equivalent model of RFID tag and reader.](image)

According to Faraday's law of induction, the induced voltage $UL$ of the tag antenna $L_2$ can be obtained:

$$UL = \frac{d}{dt} = \frac{Nd}{dt},$$

where $N$ is the number of the tag antenna turns, and $d$ is the magnetic flux though the one turn.

The magnetic flux can be written as:

$$BdS = SB_0\cos(\psi),$$

where $B_0$ is the amplitude of magnetic induction intensity $B$, $S$ is the loop area of the tag antenna and $\psi$ is the angle of arrival of the magnetic induction intensity $B$. Substituting (3) in (2), the induced voltage $UL$ can be calculated:

$$UL = NSB_0\cos(\psi).$$

When the resonance frequency of the tag antenna is the same as the frequency of the magnetic field $B$, the tag antenna will be in a resonance state. In this case, the amplitude $U_0$ of the voltage $U$ on the tag chip can be obtained:

$$U_0 = QU_L,$$

where $Q$ is the quality factor of the tag antenna. Substituting (4) in (5), gives:

$$U_0 = 2fNSQB_0\cos(\psi).$$

Then, the voltage sensitivity of tag antenna can be obtained:

$$\text{Sensitive} = \frac{U_0}{H_0} = 2fNSQ\mu_0\cos(\psi),$$

where $\mu_0$ is the magnetic permeability of the vacuum. For a tag, the values of parameter $f$, $N$, and $S$ are fixed. And the $Q$ remains unchanged until the tag is activated. In this case, when selecting a
specific angle, the voltage sensitivity of tag antenna is a constant value, which then can be used to compare the performances of different tag antennas. Higher voltage sensitivity means larger voltage $U_0$, leading to longer reading distance.

3. Measurement of Voltage Sensitivity

According to the above analysis, in order to obtain the voltage sensitivity of the tag antenna, the induced voltage of the tag antenna needs to be measured in a series of magnetic fields. It is known to all that Helmholtz coil, as shown in Fig. 2 is a common way to provide a uniform magnetic field in a cylindrical space at the center of two parallel coils.

Using superposition principle of magnetic field, the magnetic field at the center of the Helmholtz coils can be obtained:

$$H_0 = \frac{4}{5}(4/5)^{3/2} n I / r,$$

where $n$ is the turn number of antenna coil, $I$ is the current on the Helmholtz coil, and $r$ is the radius of coil.

From (8), it is clear that for a specific Helmholtz coil, the magnetic field $H_0$ is proportional to the current $I$. Then by introducing a constant coefficient $k$, (8) can be written as:

$$H_0 = k I.$$

The Helmholtz coils with different structures from different manufacturers have different $k$ value, which in this paper is 78.956. Then, substituting (9) in (7), gives:

$$Sensitive = \frac{U_0}{k I}.$$

Considering that the low-frequency RFID tag needs a sinusoidal time-varying magnetic field with a frequency of 125kHz, the signal generator with the waveform amplifiers are often used to provide the current on the Helmholtz coil. Then Fig. 3 shows a typical measurement platform for the voltage sensitivity, which consists of a signal generator, a waveform amplifier, a Helmholtz coil, a high-precision multimeter and an oscilloscope. The oscilloscope which in parallel with the tag chip is used to monitor and record the peak-to-peak value of the induced voltage on the tag antenna.
Fig. 3 Measuring platform for voltage sensitivity.

By calculation, the impedance of the Helmholtz coil used in this paper is 1000 at 125kHz. However, the maximum voltage that the common waveform amplifier of TS250 can provide is 40V. Then if only the waveform amplifier is used to drive the Helmholtz coil, the maximum of the current is 40mA. Obviously, this current value is not large enough to provide the required magnetic field. So, a series capacitor C is introduced between the waveform amplifier and the Helmholtz coil to achieve a larger current, which can cancel the inductance of the Helmholtz coil and reduce the total impedance of the reader antenna loop.

In order to improve the accuracy of the test results, a high-precision multimeter is employed to measure the current on the Helmholtz coil, which can determine the magnetic field of the Helmholtz coil. Besides, the direction of the RFID tag antenna, which is placed in the center of the Helmholtz coil, must be parallel to the direction of the Helmholtz coil.

Then, with the induced voltages on the tag antenna, and the currents on the Helmholtz coil from the measuring platform above, the voltage sensitivity of the low frequency RFID tag can be obtained based on (10).

4. Experimental Test

Five market available low frequency RFID tags are employed for experimental test, as shown in Fig. 4. The tag A, tag B and tag C are circular tags without magnetic core, and their diameters are 9mm, 15mm and 23mm, respectively. The tag D and tag E are cylindrical tags with magnetic cores, and their sizes are 16.25mm and 10.12mm, respectively.

Fig. 4 Market available low frequency RFID tags.

Fig. 5 shows the physical map of the measuring platform. The tag is placed in the uniform magnetic field of the Helmholtz coil, and the plane of its antenna coil is parallel to the plane of the Helmholtz coil. The current on the Helmholtz coil is changed in spacing of 5mA by adjusting the amplitude of the Tektronix AFG1062 function signal generator, which then can provide different magnetic field strengths. A digit precision multimeter of Fluke 8845A is adopted to measure this current value, and the induced voltage is obtained through the oscilloscope.
Fig. 5 Physical map of the measuring platform.

The voltage sensitivity of the tag is an inherent parameter, and the ratio of the current on the Helmholtz coil to the induced voltage value of the tag antenna should be a fixed value. When there are multi-setup measurement data, to reduce the error of the voltage sensitivity, the linear least square method is selected to fit measurement data to a straight line, as shown in Fig. 6. And, the corresponding fit linearity are shown in the Table 1, which also gives the calculated voltage sensitivities of the low frequency RFID tags based on (10). From Table 1, it can be found that, the fit linearity is higher than 0.999. As the closer the fit linearity is to 1, the better the line fits the measurement data, then the ratio of induced voltage to the current in Fig. 6 can be used to calculate the voltage sensitivity of the tag, and the results can testify the theoretical analysis above.

Table 1. Voltage Sensitivity and Fitting Evaluation

| Tag  | A     | B     | C     | D     | E     |
|------|-------|-------|-------|-------|-------|
| Voltage sensitivity (V m/A) | 0.16912 | 0.34393 | 0.43083 | 0.31924 | 0.13072 |
| Fit linearity      | 0.9997  | 0.9993  | 0.9993  | 0.9997  | 0.9995  |

For the tags without the magnetic core (tag A, tag B and tag C), it can be found that the increase in the diameter of the antenna coil, which increases the loop area of the tag antenna $S$ can improve the voltage sensitivity of the tag antenna effectively. This is consistent with (7). As for the cylindrical tags with magnetic cores (tag D and tag E), the voltage sensitivity of tag D with the large size of the core is much higher than that of tag E. When comparing the two types of antenna coils, it can be seen that although the diameters of the tag D and tag E are much smaller than the tags without magnetic cores,
their voltage sensivities are raised a lot due to the magnetic cores, but still smaller that of tag B and tag C with larger diameters. Therefore, increasing the diameter of the antenna coil is the most effective way to improve the voltage sensitivity, and the ferrite core with high permeability can improve the voltage sensitivity and reduce the volume of the tags.

Besides, when the chip of the tag is determined, the required minimum working voltage for the tag can be obtained by querying its chip manual. Then with the voltage sensitivity of the tag, the minimum magnetic field produced by the reader antenna can be calculated, which is very useful for the design of the reader antenna.

5. Conclusion
This paper introduces a parameter of voltage sensitivity to recognize the performance differences of tag antennas. A method to calculate and measure the voltage sensitivity by the Helmholtz coils has been proposed, which is verified by the experimental measurements. Experimental results show that increasing the diameter of the antenna coil is the most effective way to improve the voltage sensitivity, and the ferrite core with high permeability can improve the voltage sensitivity and reduce the volume of the tags. The presented method with the measured voltage sensitivity can be useful to choose the tag and design the reader antenna for inductively coupled RFID systems.

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