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ELECTROMAGNETIC FIELDS OF RFID TECHNOLOGY APPLICATIONS IN AS/RS STRUCTURES OF INDUSTRIAL LOGISTICS

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Abstract: *The objectives of this paper are to provide an understanding of the nature of the electromagnetic fields that can be created at both high frequencies (HF) and ultra high frequencies (UHF) in the vicinity of AS/RS shelves used in industrial logistic in manufacturing and warehouses.*

Key words: *RFID, industrial logistics, AS/RS shelves, electromagnetic field, tag, antenna.*

1. INTRODUCTION

In this section we will consider the nature of electromagnetic fields that are **changing in time**, as unchanging fields are not suitable for the transmission of information to or from electronic tags. We will consider fields in both the HF (3 to 30 MHz) region and the UHF (300 to 3 000 MHz) region. We will use the names for electric and magnetic field quantities as specified in ISO 1 000 and as appear below:

- electromagnetic fields vectors:
- electric field **E** [V/m]
- electric flux density **D** [C/m^2]
- magnetic field **H** [A/m]
- magnetic flux density **Φ** [Wb/m^2].

2. FREQUENCY – WAVELENGTH RELATION

Important properties of electromagnetic fields when they are propagating between an interrogator and the tag are the frequency f and λ wavelength (which are related by $c = f \cdot \lambda$), where c is the velocity of electromagnetic propagation in free space, and has the value 300,000,000 m/s.

Particular frequencies of interest are 13.56 MHz in the HF region, at which frequency the wavelength is 22 m, and 915 MHz in the UHF region, at which frequency the wavelength is 328 mm. Knowing the wavelength for the frequency in use is very important, as we shall see, that it establishes the boundary between the **near field**, in which the fields behave in one way, and the **far field**, in which the fields behave in quite another way, although both fields are useful in RFID systems.

3. ELECTRODYNAMIC LAWS

The basic laws of microscopic electrodynamics are Maxwell's equations, which are most economically written as:

$$\nabla \cdot E = -\frac{\partial \Phi}{\partial t}, \qquad (1)$$

$$\nabla \cdot H = J + \frac{\partial D}{\partial t}, \qquad (2)$$

where a font has been chosen for the field vectors to signify that in these equations the fields are not restricted to the sinusoidal steady state, but can have any time variation, including none. Fortunately, one does not have to be expert in vector calculus to extract significance from these equations. The significance for RFID systems, and in particular for the fields which couple to tags on products on AS/RS shelves, are developed in the next sections.

4. SOURCE AND VORTEX FIELDS

Although the laws of electrodynamics come from Maxwell, they are most readily comprehended in terms of the source and vortex interpretation of Helmholtz, and in terms of the field pictures of Michael Faraday.

Helmholtz has shown that vector fields may be regarded as the superposition of two different basic field types, known as source type and vortex type, both of which are illustrated in Fig. 1.

In the illustration of a purely source field, we see field lines of electric field originating in a region of positive charge. If those field lines terminate somewhere, it will be in a region of negative charge. These source type field lines never intersect, nor close upon themselves. In the illustration of a purely vortex field, we see field lines of magnetic field surrounding a wire carrying a current. These vortex field lines are always in the form of closed curves, and never have a starting point or an ending point. What we learn about electric fields from Maxwell's equations is that the electric field **E** can be either source type or can be vortex type, or can be a mixture of both. When electromagnetic fields propagate to a significant distance from their originating antenna, it is the property of time varying electric fields to create

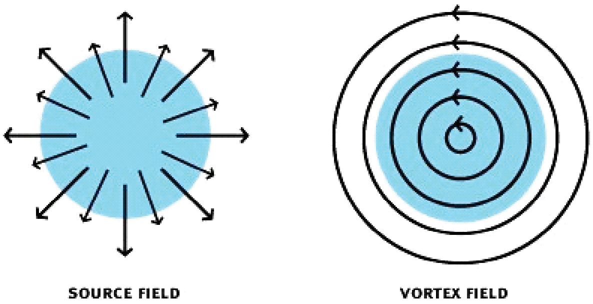

Fig. 1. Basic fields types.

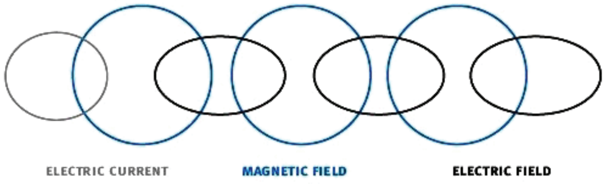

Fig. 2. Fields superposition.

surrounding vortices of magnetic field, and time varying magnetic fields to create surrounding vortices of electric field that might be regarded as providing the mechanism for further and further propagation, such as is illustrated in Fig. 2 above.

5. BOUNDARY CONDITIONS

When one is faced with the task of picturing a possible electromagnetic field that can exist in the vicinity of material objects, it is extremely useful to make use of some boundary conditions that time varying electric and magnetic fields must satisfy in the vicinity of metallic conductors. These boundary conditions are readily derivable from a combination of Maxwell's equations and the properties of metallic conductors. We are not, however, concerned here with their derivation, but with their use. The boundary condition for electric fields states that such fields must always meet a conductor at right angles.

There may easily be a component of electric field normal to the surface, but there will never be a component of electric field tangential to the surface. This restriction is illustrated in Fig. 3. The boundary condition for magnetic fields states that such fields must always approach a conductor tangentially. There may easily be a component of magnetic field tangential to the surface, but there will never be a component of magnetic field normal to the surface. This restriction is illustrated in Fig. 4.

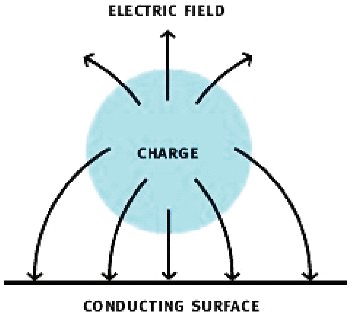

Fig. 3. Electric field.

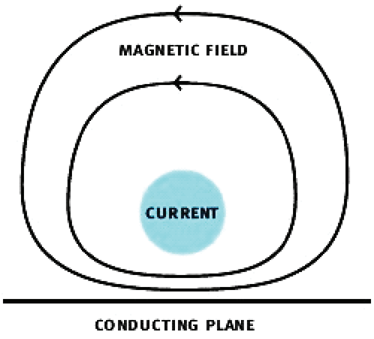

Fig. 4. Magnetic field.

6. COUPLING VOLUME THEORY

From the equations of lumped circuit theory applied to mutually coupled coils, it is easy to show that the ratio of the power P_r dissipated in the loss resistance of the tag coil to the power P_t which must be supplied to the loss resistance of the interrogator coil is given by equation (2)

$$\frac{P_r}{P_t} = k^2 \cdot Q_1 \cdot Q_2, \tag{3}$$

where Q_1 and Q_2 are the quality factors of the resonance of the interrogator and the tag coils respectively, both of which are assumed to have been tuned to resonance at the interrogation frequency, and k is the coefficient of coupling between the coils.

The coefficient of coupling k is a dimensionless ratio defined in terms of the mutual inductance M between the coils and the self inductances L_1 and L_2 of the coils as:

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}}. \tag{4}$$

The power ratio relationship shows the importance of employing high quality factors in the resonance of each of the participating coils, and the importance of achieving a good coupling factor between the coils, but it does not point directly to optimization procedures which may be applied separately to the interrogator and tag coils, although intuition suggests that such procedures should exist. To derive such optimization procedures, it is first shown that the power transfer relation may be re-written as:

$$\frac{P_r}{P_t} = \frac{V_c}{V_d} \cdot Q_1 \cdot Q_2, \tag{5}$$

in which new quantities known as coupling volume V_c and dispersal volume V_d appear. Their formal definitions are:

$$V_c = \frac{\text{Reactive power in the label inductor when short circuit}}{\text{Reactive power density per unit volume at the label position}}$$

and

$$V_d = \frac{\text{Reactive power flowing in the transmitter coil}}{\text{Reactive power density per unit volume at the label position}}.$$

The benefit of this formulation is that the two quantities just defined are capable of individual optimization. As an example, it may be shown that the coupling volume for a planar tag or of N turns, each of which has cross sectional area A, and tag self inductance L is given by:

$$V_c = \frac{\mu_0 \cdot N^2 \cdot A^2}{L}, \tag{6}$$

$$\text{Power} = \frac{g_t \cdot P_t}{4 \cdot \pi \cdot r^2}, \tag{7}$$

where g_t is a gain of the transmitter antenna and P_t the power which it transmits, and r is the distance from the transmitter antenna to the tag position. In using this formula, we are implicitly assuming that the tag has been placed in the direction of strongest radiation from the interrogator antenna. The power P_r that may be extracted under optimum conditions of tuning and matching by a lossless tag antenna placed at the above position is given by:

$$P_r = A_{er} \cdot \text{Power}, \tag{8}$$

wherein A_{er} is a property of the tag known as its **effective area**. It is unrelated to the physical area of the antenna, (which if it is just piece of thin wire, does not have a physical area), but has the desirable property that we may imagine the tag antenna collects all of the radiated power which flows through that effective area which may be thought of as surrounding the tag antenna.

The **Lorenz reciprocity theorem** of electrodynamics may be used to show that the effective area of a receiving antenna is related to the gain g_r it would have in a transmitting role by the equation

$$A_{er} = \frac{g_r \cdot \lambda^2}{4 \cdot \pi}. \tag{9}$$

Before leaving this section we produce two results, which are simply rearrangements of the several relations above. These are:

$$\frac{P_r}{P_t} = g_r \cdot g_t \cdot \left(\frac{\lambda^2}{4 \cdot \pi} \right)^2 \tag{10}$$

and

$$\frac{P_r}{P_t} = \frac{A_{et} \cdot A_{er}}{\lambda^2 \cdot r^2}. \tag{11}$$

These two results have the benefit of showing clearly the equal contribution that the transmitter antenna gain and receiver antenna gain make towards the power transfer, and of emphasizing the reciprocity property that the two antennas could be interchanged without changing the optimum power transfer ratio.

7. PROPERTIES IN COMMON

We now list the properties, which coupling volume theory and radiating antenna theory have in common.

The first is that they both exhibit a **reciprocity property**, which indicates that, when a single pair of terminals is used for connection to each of the interrogator and label antennas, the propagation loss in the direction from the interrogator antenna to the label antenna is the same as the propagation loss in the direction from the label antenna to the interrogator antenna.

This conclusion is relevant to the question of whether a label can be strongly excited but its reply could be too weak to be heard.

8. LOSSES IN ANTENNAS

The first of these is the extent to which losses in each of the antennas has been considered. In coupling volume theory, the quality factor of the transmitter antenna is entirely due to its intrinsic losses. The effect of any radiation resistance in this antenna is assumed to be negligibly small. There does not seem to be a practical situation in which this policy needs to be varied. In near field coupling therefore, most of the power delivered to the transmitter antenna is converted to heat.

These facts may not matter, as what we are seeking to do is to create energy storage fields close to the transmitter antenna, not generate radiation there from, which radiation is in fact unwelcome, as it is subject to electromagnetic compatibility regulation.

In the coupling volume theory, at the label end, the quality factor of the label antenna is caused by both its intrinsic losses and by power, which may be drawn from the label circuit. If one is interested in the question of how to deliver the maximum power to the label circuit, this result may be obtained when the power to the label circuit is equal to the power lost in the intrinsic resonance circuit losses, and the quality factor of the label circuit at which this occurs is just half of the quality factor which occurs when no power is delivered to the label circuit.

So it may also be that a significant amount of power, which reaches the label, is also converted to heat.

Such powers should not necessarily be regarded as wasted. The label makes its reply felt back at the interrogator through having a significant amount of reactive power flowing in the label circuit, and any power necessarily dissipated in sustaining the oscillation within the label circuit may be regarded as usefully expended. It does not follow that we require the label circuit to consume as much power as is dissipated in sustaining the tuned circuit losses. Provided we can establish a large amount of reactive power in the label circuit, and successfully modulate it, we are entirely happy if the control circuit that accomplishes this consumes very little power.

In radiating antenna theory, we have avoided the question of whether or not of the interrogator-transmitting antenna is efficient by simply defining P_t as the actual power, which is radiated. In practical situations there will be some small loss in the transmitter antenna, and because of this the transmitter will have to supply a power slightly in excess of what is radiated. There is no practical difficulty in taking this into account.

In far field coupling, it is generally true that the transmitter antenna is reasonably efficient, in that most of the power delivered to it is actually radiated, which is what we want to have happen, as the fields to which the label couples are inextricably linked with radiation. It is also true that most of the power that we can potentially extract from the label antenna can really be extracted without the losses in the label antenna intruding too much. Achieving this result does require that we achieve reasonably low loss matching to the very small radiation resistance of the label antenna and the very much greater reactance which stands between that radiation resistance and the terminals of an equivalent circuit for that antenna. It is a standard result of antenna theory that as the antenna is becoming electrically small this problem begins to become acute, but for UHF antennas of a credit card size it is not particularly severe.

When, however, label antennas become very small, the extraction of the theoretically available source power for a loss less antenna becomes an impracticable aim, and coupling volume theory may usefully be employed at the site of the label antenna.

9. LABEL ORIENTATION EFFECTS

It has already been indicated that the basic coupling mechanism is through magnetic flux linking the coil of the label antenna. Mostly the magnetic field oscillates in a single direction, but with difficulty we can make it move around so that it oscillates with different phases into directions, but those two directions are still confined to lie in a single plane. It is impossible with a signal of the bandwidth required by regulators to move the field around in all three directions of space – two is the limit. Thus there are null coupling orientations for the label antenna. The only way to overcome this is to be energizing the transmitter antenna generating one field shape, and later to energize another transmitting antenna generating a different field shape.

This happens in principle also at UHF, but in practice it seems to matter less, probably because a number of factors at UHF, such as movement of labels or nearby objects, can produce field stirring without any deliberate changes being made in the interrogator configurations. When, however, labels do not move and the environment does not change, field stirring that can be achieved through multiplexing between different antennas is needed.

10. RECIPROCITY

Reciprocity is a fundamental property of electromagnetic fields subject to a static environment and where a single pair of terminals is used to energize whatever transmitter and receiver system is in use in the interrogator, and another single pair of terminals is used to deliver signals from whatever label antennas system is used in the label circuit. This is the normal arrangement.

Basically, the reciprocity theorem states that in the circumstances described above the coupling from the interrogator to the label is equal to the coupling back from the label to the interrogator.

The theorem allows us to expect that a strongly excited label will give a strong reply. Also we do not expect a label to be able to give a strong reply and not be able to clearly receive command signals from the interrogator.

11. CONCLUSIONS

The modern industrial logistics combines the new use of AS/RS with the RFID technology. The basic principles of electromagnetic theory relevant to the design of readers and antennas for RFID tags for products on the AS/RS shelves have been explained. Of particular importance is the understanding of both near field and far field coupling, and of the boundary conditions that electromagnetic fields must obey in proximity to metal structures.

A comprehensive list of issues in RFID reader design and tag antenna design has been identified. Some simple interrogator architectures have been described. More complex architectures are acknowledged without detailed description.

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