Study on the Effective Loading Pattern of Magnetic Sheet for Receiving Coil in WPT System

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***Abstract*—Wireless Power Transfer (WPT) system in accordance with Qi standard is being installed in smart phone in recent years. But the transmission efficiency is greatly deteriorated due to nearby metallic objects. To solve this problem, magnetic sheet with high permeability is set between WPT coil and nearby metallic objects. In order to make thickness of these materials thinner, we propose amorphous magnetic sheet. Besides this amorphous magnetic sheet causes to increase the transmission efficiency.**

I. Introduction

Wireless Power Transfer (WPT) system in accordance with Qi standard [1], [2] is being installed in smart phone in recent years. The principle of electromagnetic induction is adopted for the WPT system, and its efficiency is greatly deteriorated due to nearby metallic objects. [3]. The reason is that actual electric current on the WPT coil is suppressed by the induction electric current generated on nearby metallic objects. In that situation, to prevent from this suppression by the induction electric current, the magnetic thin sheet with high permeability is inserted instead of the air gap between the WPT coil and metallic objects. However, the high permeability magnetic sheet has its property of large magnetic loss. Therefore, to improve transmission efficiency of the WPT system, some tact is necessary for the ways of using magnetic sheet insertion. By the way, it is reported regarding HF-RFID system that the technique to control the magnetic loss by changing its shape of high permeability magnetic sheet [4]. It is considered whether these techniques can be applied to the improvement of transmission efficiency for the WPT coil with nearby metallic objects. The Qi specification regulates 3 types of positioning procedures for WPT's coil [1],[2]. There is some freedom for the design of the receiver even though the transmitters design is strictly regulated in Qi standard. Therefore it is important to optimize the design of receiver in corresponding to these 3 types of transmitter. In case of the position guide transmitter, a magnet to suck up subsidiary coil is set at the center of the primary coil. In this report, considering two type of WPT's transmission coil (expressed as Tx-coil), one is a magnet-less Tx-coil which correspond to the position free type in Qi standard. The other is a Tx-coil that has a guide magnet. However, it is expected that the insertion effect of the magnetic seat for the efficiency improvement of WPT's receiving coil (expressed as Rx-coil) is deteriorated by the existence of guide magnet. Thus, as result, the study about the quality control of Rx-coil by changing shape of magnetic sheet is described in this report.

II. Maximum efficiency of WPT system via electromagnetic induction

In wireless power transmission system, there are non-resonance type and a resonance type. Non-resonance type system has only the inductor, and the capacitor is not included. On the other hand, the resonance type system has the inductor and the capacitor, and is categorized into the series resonance type and the parallel resonance type by the connection method for each other. The optimized ratio of the primary resistance (oscillator's internal resistance R_1) and the subsidiary resistance (load resistance R_2) of each type is summarized in Table 1[5]. The figure of merit, the quality factor of primary-coil Q_s and the subsidiary-coil Q_l are shown by using the element constant of the equivalent circuit like the following expressions;

$$\alpha \equiv k^2 Q_s Q_l \tag{1}$$

$$Q_s = \frac{\omega L_1}{R_1} \tag{2}$$

$$Q_l = \frac{\omega L_2}{R_2} \tag{3}$$

here ‘ k ’ is inductor ’ s coupling coefficient.

TABLE I: Maximum efficiency and optimum load of each circuit

Circuit	Efficiency η	Optimum Load $\frac{R_l}{R_2}$
No resonance	$(1+\frac{2(1+(1+\alpha+Q_l^2)^{1/2}}{\alpha})^{-1}$	$\sqrt{1+\alpha+Q_l^2}$
Series resonance	$(1+\frac{2(1+(1+\alpha)^{1/2}}{\alpha})^{-1}$	$\sqrt{1+\alpha}$
Parallel resonance	$(1+\frac{2(1+(1+\alpha)^{1/2}}{\alpha})^{-1}$	$\sqrt{1+\alpha}+\frac{Q_l^2}{\sqrt{1+\alpha}}$

As for the non-resonance case and the series or parallel resonance case, the relations between the maximum transmission efficiency and the figure of-merit are shown in Fig.1. Considering the situation of stable transmitted power between two WPT coils, the coupling coefficient k is fixed to some value. Therefore it is important for transmission efficiency to increase quality factor of two coils.

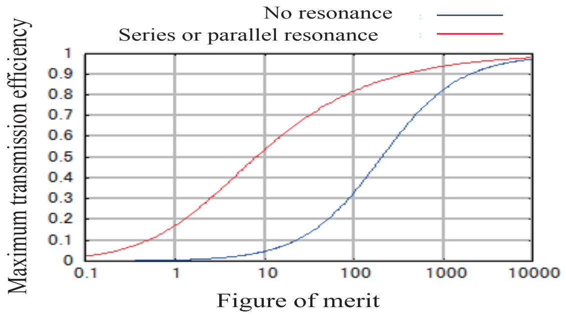


Fig. 1: Maximum transmission efficiency along plotted along figure of merit

III. The loading pattern of magnetic sheet with Rx-coil

The system configuration of WPT measurement system is illustrated in Figure 2. Also detail measurement condition are listed in Table II. In this report, two models of the following are assumed as the WPT measurement situation between the Tx-coil (transmitter) and the Rx-coil (Receiver);
Model-1:The transmitter unit is composed by Tx-coil, sintered ferrite sheet and metallic plate
Model-2: The transmitter unit from which guide magnet is added to center of Tx-coil of Model-1

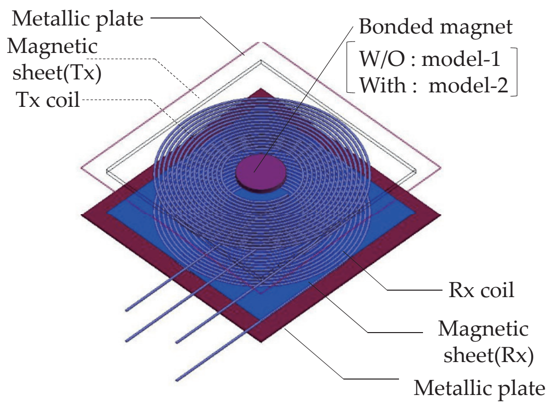


Fig. 2: The configuration of WPT measurement model

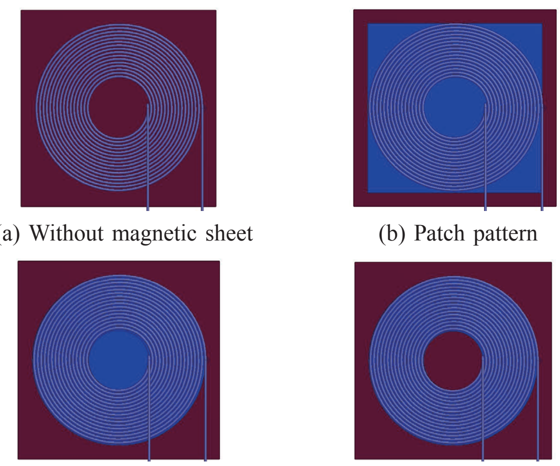
TABLE II: Conditions of measurement model

Frequency	150 kHz
Inner diameter of WPT coil	21 mm
Outer diameter of WPT coil	43 mm
Turn of WPT coil	10
Layer of WPT coil	2
Structure of magnetic sheet	PET cover film, adhesive and magnetic sheet
Magnetic sheet with Tx-coil	sintered ferrite sheet
Magnetic sheet with Rx-coil	amorphous sheet
Bonded magnet	12.5 x 2.0 mm
Thickness of metallic plate	0.3 mm

The measurement situation Model-1 corresponds to the free positioning-moving coil type in Qi standard. The measurement situation Model-2 corresponds to the position guide type in Qi standard. Simplify, Rx-coil and Tx-coil are prepared same coil in these measurement. The properties and dimension of magnetic sheet used for this measurement are listed in Table III. The coil's effective impedance is strongly influenced by relative permeability of attached magnetic sheet [4]. On the other hand, Rx-coil in WPT system is expected to be able to be thinned when high-permeability sheet like amorphous sheet is attached in the vicinity of Rx-coil. It is necessary to pay attention to both the thickness suppression and the coil impedance matching of Rx-coil. Therefore, it is attempted to control the coil impedance matching by changing the shape though the thickness of amorphous sheet is fixed. Figure 3 shows three loading patterns of the amorphous sheet attached to Rx-coil.
(1)Patch pattern: Square amorphous sheet which completely involves Rx-coil
(2)Circular pattern: Circular amorphous sheet that is completely corresponding to outline of Rx-coil
(3)Loop pattern: Doughnut-shape amorphous sheet that is completely corresponding to outline of Rx-coil.

TABLE III: The characteristic of magnetic sheet

magnetic sheet	Thickness[μm]	Permeability μ_r(150kHz)	tanδ
sintered ferrite sheet (Tx-coil)	1200	50	0.01
amorphous sheet (Rx-coil)	20	8000	0.54



(a) Without magnetic sheet (b) Patch pattern
(c) Circular pattern (d) Loop pattern

Fig. 3: Location procedure of magnetic sheet attached with Rx-coil

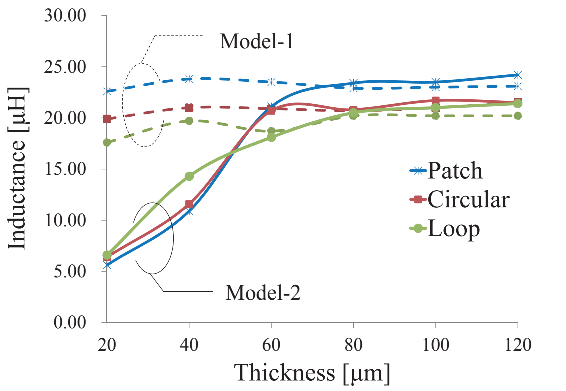
IV. Measurement result of inductance and quality factor of Rx-coil

Table IV shows the impedance of Tx- and Rx- coil under the initial condition (the amorphous sheet are not attached to

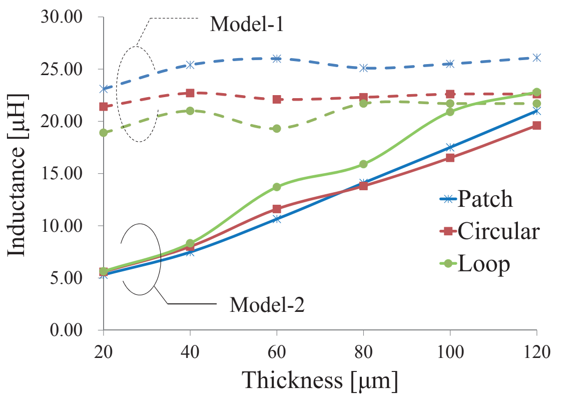
Rx-coil). The inductance of Rx-coil is remarkably decreasing by induction electric current generated with metallic objects. Quality factor of Rx-coil is also greatly deteriorated compared to the case of without a metallic plate.In this measurement, the distance d between Tx- and Rx- coil is set to 10 mm or 5 mm. To consider the dependence on thickness of magnetic sheets, amorphous sheets are prepared 1 to 6 layers (thickness per sheet is around 20 μm).

TABLE IV: Measurement result of Rx-coil and Tx-coil impedance of each model

	Model	$R_s[\Omega]$	$L_s[\mu H]$	Q_l
Rx-coil (Cf. initial condition)	1	0.37	15.5	39.5
Rx-coil on metallic plate	1	0.59	3.98	6.35
Rx-coil (Cf. initial condition)	2	0.40	15.7	37.0
Rx-coil on metallic plate	2	0.60	3.87	6.08
Tx-coil	1	0.66	24.0	34.2
Tx-coil	2	0.78	26.0	31.4



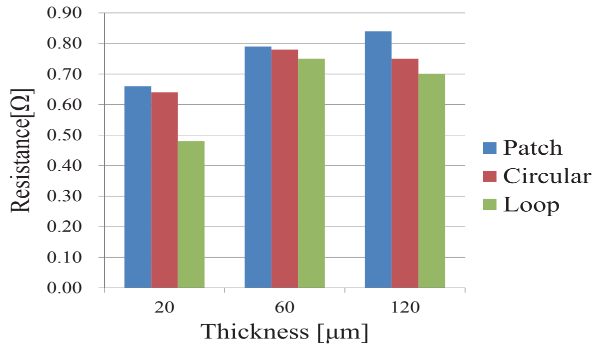
(a) $d = 10$ mm



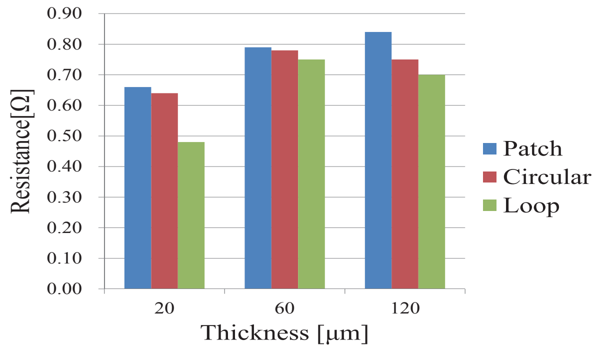
(b) $d = 5$ mm

Fig. 4: Measurement result of Rx-coil inductance according to loading pattern of amorphous sheet

Figure 4 shows the measurement results of Rx-coil's inductance as a function of the amorphous sheet thickness in each measurement model. The loading pattern dependency of inductance of Rx-coil is also shown in this figure. In case of Model-1, the inductance of Rx-coil is steady for the sheet thickness. These results predicts that the magnetic flux penetration depth becomes shallow when permeability of amorphous sheet is high. In addition, patch pattern is most effective for recovering inductance because influence with the metallic plate is suppressed by increasing surface area of amorphous sheet. In Model-2, the inductance of Rx-coil shows rapid change to the sheet thickness in contrast with Model-1. When the distance between Tx- and Rx-coil set to 10 mm, the inductance emphasis effect with each pattern sheet in Model-2 comes to equals Model-1 according to an increase in the sheet thickness.



(a) Model-1 ($d = 5$ mm)

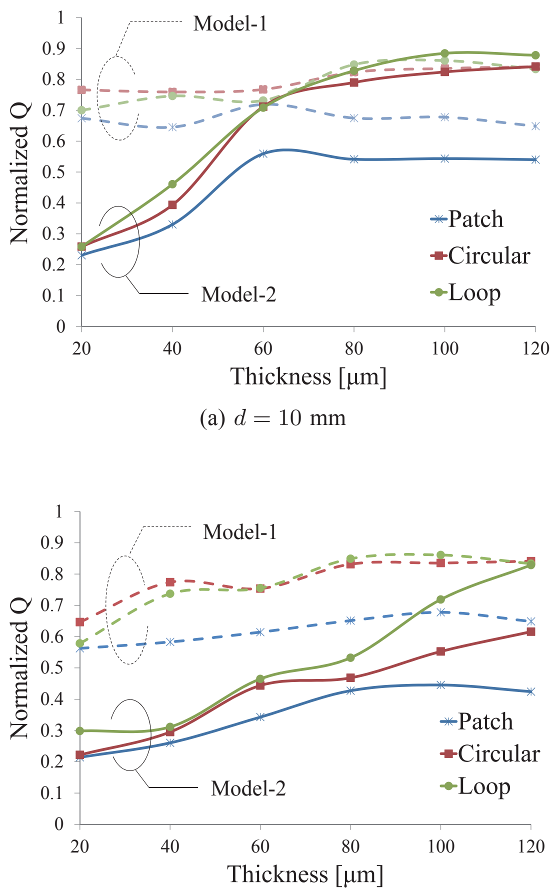


(b) Model-2 ($d = 5$ mm)

Fig. 5: Measurement result of Rx-coil resistance according to loading pattern of amorphous sheet

The reason for this phenomenon is thought as follows. Static magnetic field radiated with guide magnet with Tx-coil causes saturation magnetization for amorphous sheet near Rx-coil. It is presumed to deteriorate the inductance emphasis effect with amorphous sheet near Rx-coil. However, because saturation magnetization is eased with an increase in the amorphous sheet thickness, the inductance of Model-2 becomes equal to that of

Model-1. In contrast, it is confirmed that loop pattern sheet most promptly recovers the effect of the inductance emphasis when the distance between Tx- and Rx-coil set to 5 mm. Under this situation, static magnetic flux with guide magnet will penetrate deep of amorphous sheet. In this case, even if the amorphous sheet thickness is increased, it is difficult to reduce static magnetic flux. However, it is thought that the influence of static magnetic flux is reduced if the appearance area of saturation magnetization is removed. Figure 5 shows the evaluation result of the influence which amorphous sheet of each pattern gives to the resistance of Rx-coil. The interval of the Tx- and Rx-coil is set to 5mm. In any case of Model-1 and -2, the area reduction of magnetic sheet contributes to the resistance decrease in Rx-coil.



(b) $d = 5$ mm

Fig. 6: Measurement result of quality factor of Rx-coil according to loading pattern of amorphous sheet

The quality factor of Rx-coil which is normalized by initial condition (see Table IV) is shown in Figure 6. In Model-1, the quality factor is stable for the amorphous sheet thickness in each sheet pattern. However, the quality factor shows the tendency to decrease oppositely because the resistance of Rx-coil increases with the magnetic sheet area increasing. So loop or circular pattern is better than patch one in the viewpoint of quality factor. In Model-2, the quality factor is recovering with increasing sheet thickness and also loop pattern is the most effective loading pattern. The performance of Rx-coil is most improved with the loop pattern amorphous sheet in both models.

V. Conclusion

In this report, inductance and quality factor of Rx-coil in WPT system are mainly measured with respecting for thickness and loading pattern of the amorphous sheet. The situation of measurement systems are identified two models as followings; the first one is Tx-coil without a magnet and the second one is Tx-coil with a magnet. In the first model, inductance and quality factor are stable for each thickness and loading pattern of amorphous sheets. In the view point of quality factor, loop or circular pattern is the proper loading pattern for Rx-coil by relation with impedance and surface area of magnetic sheet. In the second model, inductance and quality factor of Rx-coils behavior is dramatically changed in comparison with the previous one. The static magnetic field from a magnet causes amorphous sheet magnetization and it causes deterioration of Rx-coil's inductance. Therefor it is effective for recovering permeability of amorphous sheet from magnetization to increases the thickness of amorphous sheet. Furthermore, it is also great important for reducing the influence of the static magnetic field from a magnet to consider the loading pattern of amorphous sheet. The loop pattern with rejected surface area surrounded from inner diameter of Rx-coil is the most effective especially as a case of Tx-coil with a magnet. Finally, it is possible to make the thickness of amorphous sheet thinner to make the total thickness of receiver thinner in WPT system and simultaneously to be applicable for the case of a guided positioning type with a magnet by optimization the loading pattern. From now on, we will investigate the actual transmitting efficiency and simulation at the same time to optimize the amorphous sheet loading pattern and thickness according to WPT system.

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