Influence of Tire on Wireless Power Transfer from Road to Electric Vehicle

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Abstract. In order to reduce CO_2 emissions, it is necessary to expand the use of electric vehicles (EV), but there are technical issues such as the improvement of driving efficiency and extension of cruising distance. In-Wheel Motor which is disposed the drive system in the wheel has higher controllability than the conventional on-board mounted motor, and also can be expected to improve the drive efficiency. In addition, wireless power transfer (WPT) from the road to the EV during driving has attracted great attention in order to solve the problem of the cruising distance. In our laboratory, adding to In-Wheel Motor, a drive system that can further improve the efficiency from power transmission to driving by WPT with a coil placed at the unsprung are developed. However, due to the structure in which the tire and the receiver coil are close, the magnetic field generated from the transmitter coil passes through the tire, so there is a concern about loss in the tire. In this paper, the influence of tires on WPT is verified. The influence of four types of tire rubber and two types of belts used for vehicles on WPT efficiency were measured at frequencies of 85 kHz and 13.56 MHz, respectively. As a result, the influence of the rubber and the organic belt was very small, but the efficiency was reduced by the steel belt at 85 kHz. At 13.56 MHz, the efficiency was reduced by the rubber and belt. Among them, it is found that there are almost no loss by the tire which is composed of an organic belt in the WPT at 85 kHz. It is expected to develop of WPT using near the tire in the future.

1. Introduction

Electric vehicles (EV) have attracted great attention because of their superior environmental performance, but their spread has been interrupted by some technical issues such as the low driving performance and short cruising range. For this issue, the Wireless Power Transfer (WPT) and In-Wheel Motor (IWM) for EVs, are considered as effective solutions to these problems.

WPT system has been expected to improve safety, convenience, and reliability in transportation applications because of cablelessness [1]. Although there are several types of WPT system based on transmission frequency and circuit topology, the research on WPT based on magnetic resonance coupling becomes increasingly active since 2007 [2]. This research field intends to improve transmission efficiency even in case of the wide gap by using LC resonance, and is expected to be applied to various applications such as the home and medical devices. Among them, WPT system for EVs is one of the most remarkable technologies. The concept of WPT system in EVs is that power is supplied from a transmitter coil installed on the road to a receiver coil installed in each vehicle via magnetic field [3]. The implementation of this technology not only solves the problems that EVs have, but also enables to significantly reduce the onboard battery size [4].

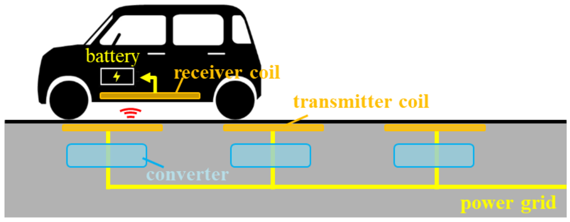


Fig.1 The concept of WPT to electric vehicles.

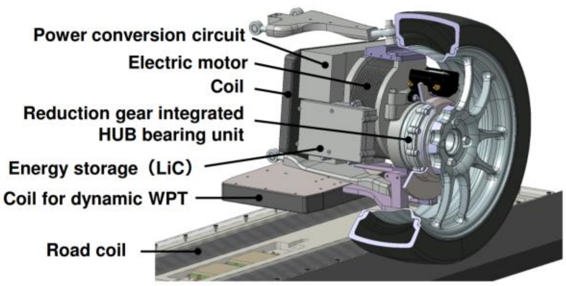


Fig.2 IWM and WPT system application in EV [6].

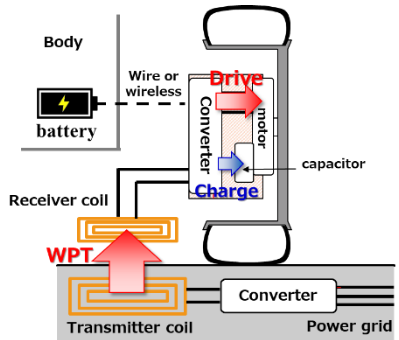


Fig.3 Illustration of WPT system and IWM in EV

Additionally, there are two types of EV drive devices: on-board mounted motor and in-wheel motor (IWM). IWM is normally placed inside the wheel and offers advantages such as the motion control performance improvement and cruising range extension by independent control of each wheel, as well as weight reduction due to fewer drive system parts [5]. However, the conventional research related to the WPT system application in the EV area assumes an on-board mounted motor which is mounted on the vehicle body, and the vehicle battery is charged from a coil installed on the bottom of the vehicle body. Still, it is inefficient for IWM because the loss increases if there is an extra transmission between battery and IWM.

Therefore, the authors has proposed a novel concept which is suitable for IWM. In our proposed method, IWM and WPT system are applied to the EV as shown in Fig.2 [6]. This combination increases the transmission efficiency since the receiver coil is installed nearer to the transmitter coil, and the distance between the transmitter and the receiver coils can be kept constant even the suspension is displaced because the receiver coil is installed at the IWM. However, due to this structure, the tire and the receiver coil are close with each other, and the magnetic field generated from the transmitter coil passes through the tire, so the energy loss might be caused by the tire. In this paper, the influence of tires on WPT is analyzed and verified.

2. The concept of WPT system in EV which is suitable for IWM

In previous research [6], the novel structure was proposed as shown in Fig.3. The electric power is transmitted to IWM directly. This proposed structure possesses three advantages: 1) Efficient transmission can be achieved because the electric power is transmitted to IWM directly. 2) The distance between the transmitter and the receiver coils can be kept constant even the suspension is displaced because the receiver coil is installed at the IWM. 3) The required power of transmitter coil decreases because there are two or four IWMs installed at the EV.

However, the power loss in tire might be occurred. Tire is consisted of metal and organic material such as treads (rubber), belt, bead wire, etc. It is generally known that inductive heating due to eddy currents occurs when the high conductive materials such as metals are exposed to magnetic field. It also brings resonant frequency shifts to cause system decoupling and efficiency decrease [7]. Among them, the transmission efficiency of WPT system drops significantly due to the influence of the materials in the tire.

3. Circuit topology in magnetic resonance coupling

WPT system conducts the power transmission using electromagnetic induction. When AC voltage is applied to the transmitter coil, magnetic field is generated. It passes through the receiver coil and induced current is generated. In this research, we use magnetic resonance coupling that is efficient and robust against misalignment of coils because of LC resonance. Fig.4 presents the Series-Series circuit topology of magnetic resonance coupling.

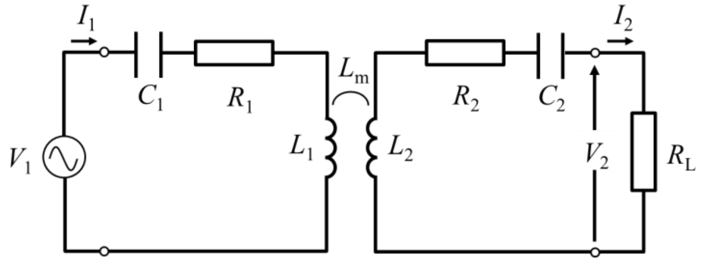


Fig.4 S-S circuit topology in magnetic resonance coupling.

$$\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} \quad (1)$$

Here ω_0 is the resonance angular frequency, L is the self-inductance, C is the capacitance. Subscripts 1 and 2 mean the primary (transmitter coil) and secondary sides (receiver coil), respectively.

When (1) is satisfied, the circuit equation is expressed as follows:

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 & j\omega_0 L_m \\ j\omega_0 L_m & R_1 + R_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (2)$$

Where L_m is the mutual inductance, and R_L is load resistance. By solving the above circuit equation, the efficiency can be expressed as follows:

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L)\{(\omega_0 L_m)^2 + R_1(R_2 + R_L)\}} \quad (3)$$

This equation means the transmission efficiency varies with load resistance value. By substituting the optimal load resistance, $R_{L,opt}$, which satisfies $\partial\eta/\partial R_L = 0$, the theoretical maximum efficiency, $\eta_{\max}$, can be expressed as follows[8]:

$$\eta_{\max} = \frac{(\omega_0 L_m)^2}{\left\{\sqrt{R_1R_2} + \sqrt{R_1R_2 + (\omega_0 L_m)^2}\right\}^2} \quad (4)$$

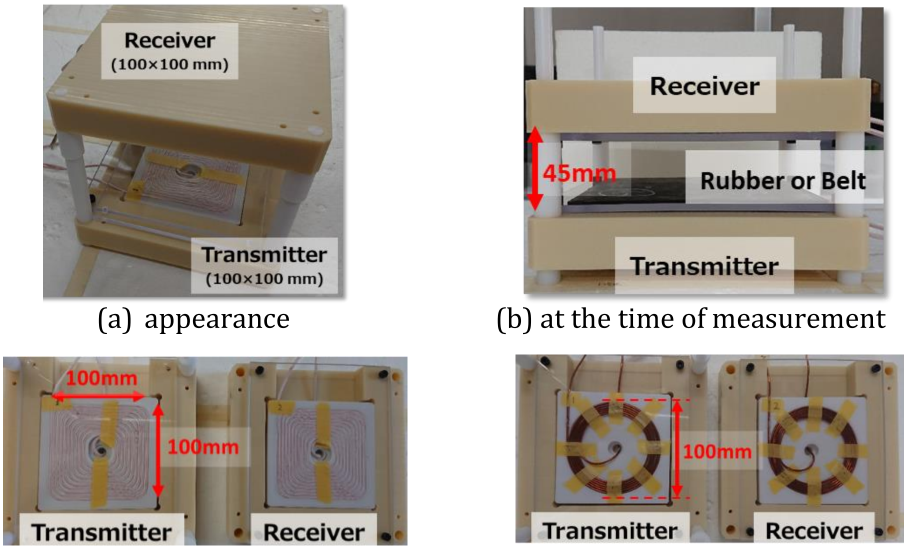
$$= \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \quad (5)$$

$$R_{L,opt} = \sqrt{R_2^2 + \frac{R_2(\omega_0 L_m)^2}{R_1}} \quad (6)$$

Where k is the coupling coefficient, Q_i is the quality factor. These are important parameters for WPT system. k is a parameter representing the coupling between the coils, and is affected by the relative position and permeability between the coils. Q_i represents the strength of resonance, and determined by the equivalent loss of material placed between coils and the coil design, such as the turns and the pitch distance.

$$k = \frac{L_m}{\sqrt{L_1L_2}} \quad (7)$$

$$Q_i = \frac{\omega_0 L_i}{R_i} \qquad (i = 1 \text{ or } 2) \quad (8)$$



(a) appearance (b) at the time of measurement

(c) 85 kHz coils (d) 13.56MHz coils

Fig.5 Characteristic evaluation equipment

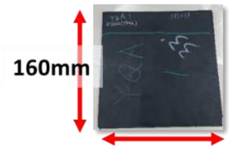


Fig.6 One of the rubbers used for measurement.

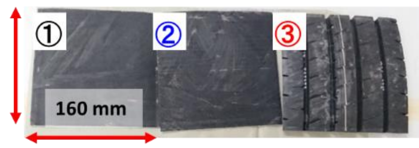


Fig.7 Cut tires used for measurement. (1:inner liner layer , 2:belt layer, 3:tread layer)

Tab.1 Each coil parameter without rubber sheet between coils.

(a) 85 kHz

	Transmitter	Receiver
Inductance L	18.4 μH	19.5 μH
Resistance R	65.6 mΩ	68.6 mΩ
Target frequency f	85.0 kHz	
Quality factor Q	150	152
coupling coefficient k	0.11	

(b) 13.56 MHz

	Transmitter	Receiver
Inductance L	12.4 μH	14.4 μH
Resistance R	13.0 Ω	16.4 Ω
Target frequency f	13.56 MHz	
Quality factor Q	81	75
coupling coefficient k	0.19	

4. Characteristic evaluation of experimental equipment

4.1. Experiment condition

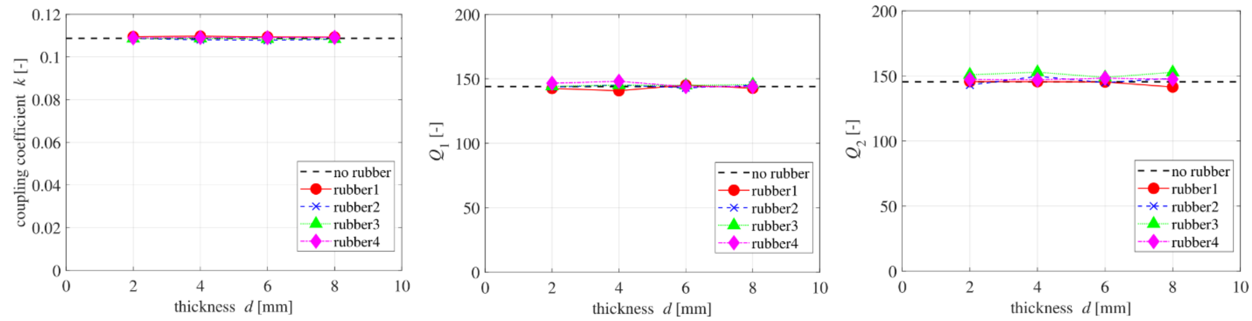
The influence of the tire in the WPT system is verified using the characteristic evaluation equipment shown in Fig.5. By placing the rubber and belt used as an actual tire between the transmitter and receiver of this equipment, the influence on the coupling coefficient, k, and quality factor, Q_i, is verified. These parameters are calculated by substituting the measured resistance, self-inductance, and mutual inductance into equation (7) and (8).

The resonance frequency is 85 kHz according to the SAEJ 2954 standard and 13.56 MHz which is the ISM band, and different coils are used (Fig. 5 (c) (d)). The 85 kHz coil has 10 turns of litz wire, and the 13.56 MHz coil has 6 turns of single wire. The parameters of each coil measured using the impedance analyzer function of Vector Network Analyzer (VNA, Agilent Technologies E5061B) are shown in Tab.1. Here, keep in mind that R_i and Q_i are the values measured without

Fig.8 Measurement of the rubber conductivity.

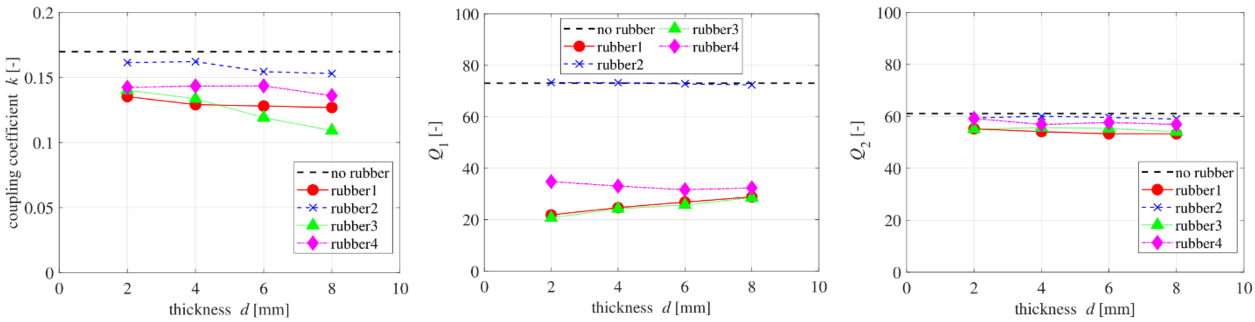
Tab.2 Physical property of rubber used for measurement.

	tanδ [-]	electrical conductivity[S/m] at 85kHz	electrical conductivity[S/m] at 13.56MHz
rubber1	100	1.75×10^{-2}	3.71
rubber2	71	9.22×10^{-3}	52.1
rubber3	54	1.54×10^{-2}	3.22
rubber4	36	1.01×10^{-2}	12.0



(a) k (b) Q_1 (c) Q_2

Fig. 9 The influence of rubber on coupling coefficient and quality factor at 85 kHz.



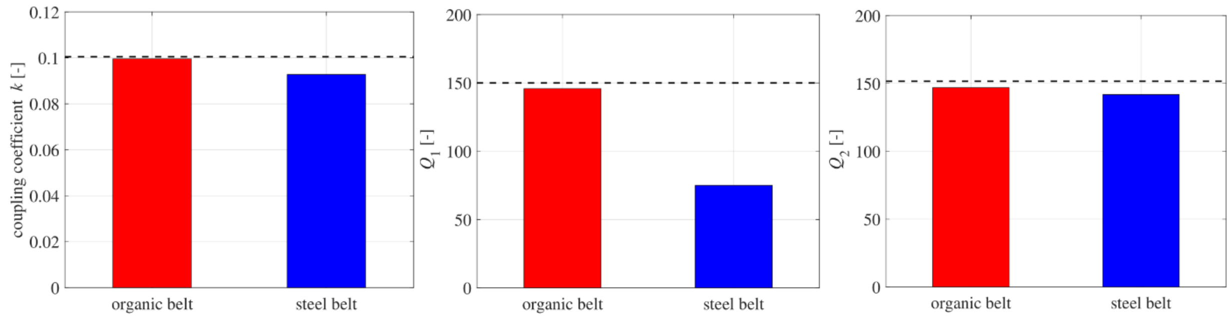
(a) k (b) Q_1 (c) Q_2

Fig. 10 The influence of rubber on coupling coefficient and quality factor at 13.56 MHz.

connecting the resonant capacitor, and ferrite is placed on the back side of the 85 kHz coil to improve the coupling between the coils. In addition, the distance between the coils was set to be 45 mm, in which the coupling coefficient was approximatedly the same as the actual WPT system for the EV.

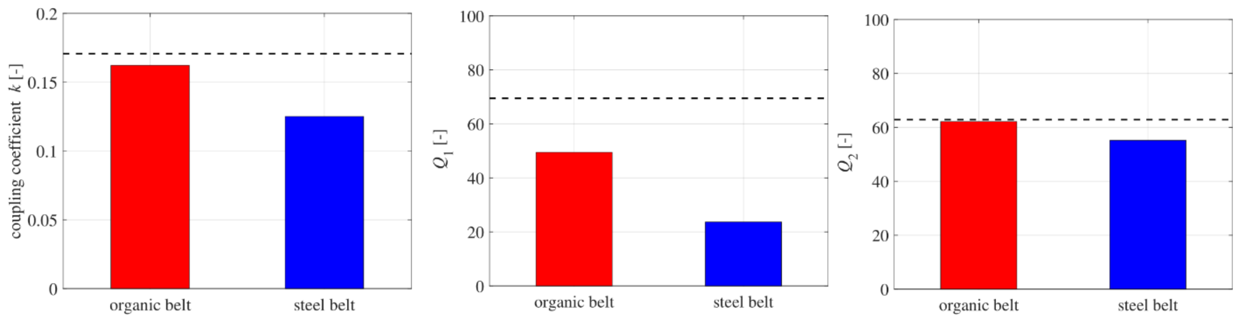
4.2. The influence of the rubber on k and Q_i

In this section, we show the results of calculating k and Q_i when tire rubber is placed between the transmitter and receiver coils at 85 kHz and 13.56 MHz. Four types of rubber sheets, which are different in dielectric loss tangent, tan δ (Index value), and electrical conductivity, σ, were prepared. These physical properties of each rubber show in Tab.2. The electrical conductivity is calculated from the shape of rubber sheet and the rubber resistance which is measured using VNA as shown in the Fig.8. The sheet size is about 160 × 160 × 2 mm (Fig.6), and the thickness can be changed by stacking a plurality of sheets. The rubber is placed on a 5 mm thick acrylic plate present on the transmitter coil. The measurement was conducted using the same VNA as in the previous section.



(a) k (b) Q_1 (c) Q_2

Fig.11 The influence of belts on coupling coefficient and quality factor at 85 kHz.



(a) k (b) Q_1 (c) Q_2

Fig.12 The influence of belts on coupling coefficient and quality factor at 13.56 MHz.

First, the results at 85 kHz are shown in Fig.9. The black dotted lines in the figure means each parameter without rubber sheet between coils. According to the Fig.9, it is found that the k and Q_i hardly change regardless of the thickness and type of the tire rubber. Therefore, considering that the theoretical maximum efficiency is expressed by Eq. 6, the tire rubber does not affect the transmission efficiency and the WPT system.

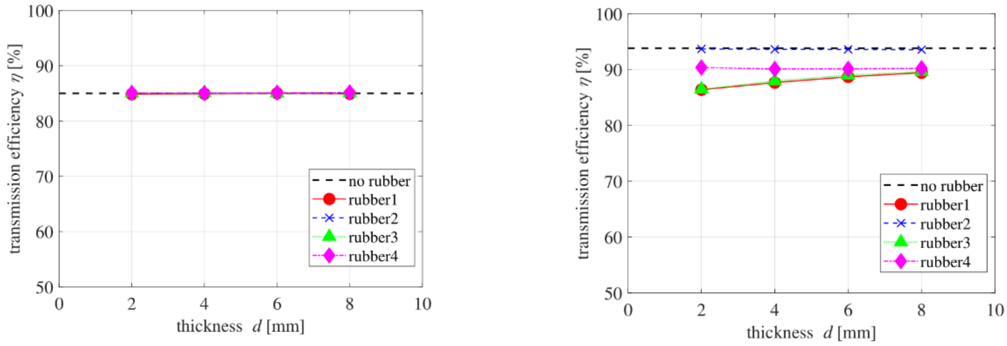
Next, the measurement results at 13.56 MHz are shown in Fig.10. It shows k and Q_1 are decreasing, which means that the magnetic field is reflected and absorbed at the rubber. Q_1 is significantly lower than Q_2 because the rubber is located close to the transmitter coil, so the loss appearing as an increase in resistance due to rubber appears significantly on the primary side. Additionally, it can be seen that the loss due to rubber differs depending on the frequency, and the loss tends to be larger at higher frequencies from these results.

4.3. The influence of the belt on k and Q_i

In this section, we show the results of measuring the k and Q_i when the tire belt is placed between the transmitter and receiver coils at 85 kHz and 13.56 MHz. Two type of belts, organic belt and steel belt, were prepared by cutting tires consist of organic belt and steel belt respectively. The cut tire has a three-layer structure consisting of a tread, a belt and an inner liner layer. These layers size are about 160 × 160 × 2 mm. The cut tire with the belt are deposed respectively, and measured the parameters.

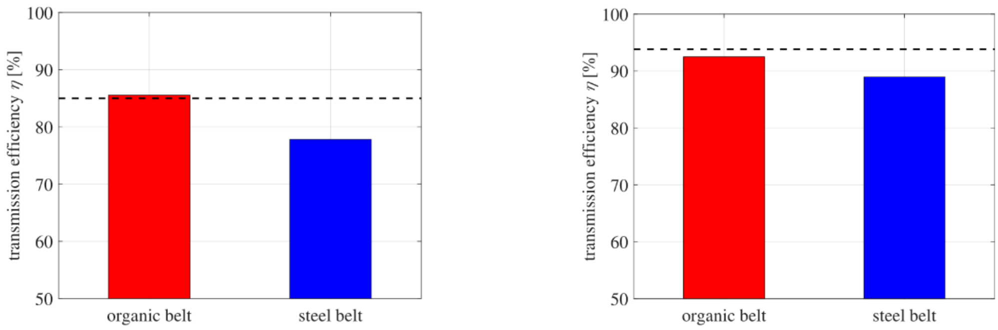
According to Fig.11, while the steel belt is caused decrease of each parameter because of the magnetic field reflection or absorption, the organic belt is almost no influence on these at 85 kHz. Therefore organic belt is suitable for WPT system in the EV.

Fig.12 indicates the same tend as the result at 13.56 MHz but Q_1. Q_1 with organic belt decrease at 13.56 MHz as well as that with rubber.



(a) 85 kHz (b) 13.56 MHz

Fig.13 The influence of rubber on transmission efficiency.



(a) 85 kHz (b) 13.56 MHz

Fig.14 The influence of belt on transmission efficiency.

5. The influence of tire on transmission efficiency

In the previous chapter, k and Q_i which are important parameters of WPT are measured. In this chapter, the effect of the tire on the WPT is verified by measuring the transmission efficiency using the above-mentioned evaluation equipment.

5.1. Experiment set up

Although the parameters of only the coil were used in the previous section, it is necessary to connect a resonant capacitor in order to actually conduct WPT verification of the transmission efficiency in the magnetic resonance coupling. By connecting a polypropylene film capacitor and a laminated ceramic capacitor with a small dielectric loss to the 85 kHz coil and 13.56 MHz coil respectively, each coil resonates at 83.8 kHz and 12.9 MHz.

5.2. Measurement result

The transmission efficiency is measured with VNA. VNA is connected to each coil, and the transmission efficiency is measured by sending small signals to the transmitter coil and measuring S-parameters that represent the transmission and reflection power characteristics of the system. In this measurement, a small signal equivalent to 10 V was input, and the load resistance was set to be the optimal load in the initial state of each resonance frequency.

Fig.13 shows the influence of the rubber on transmission efficiency. It indicates that the η hardly change regardless of the thickness and type of the tire rubber at 85 kHz, which agrees with the result of Fig.9. On the other hand, a decrease in transmission efficiency due to rubber is observed, and the drop differs depending on the type of rubber at 13.56 MHz. Although tan δ is one of the causes of loss at high frequency, this result cannot be explained only by tan δ. Considering that the rubber conductivity depends on frequency as shown in Tab.2, one of the causes is the eddy current loss accompanying the change of the conductivity in organic material. Fig.15 shows the relationship between the conductivity and the loss at 13.56 MHz. There is a correlation between the magnitude of the conductivity and the loss. The transmission efficiency is improved

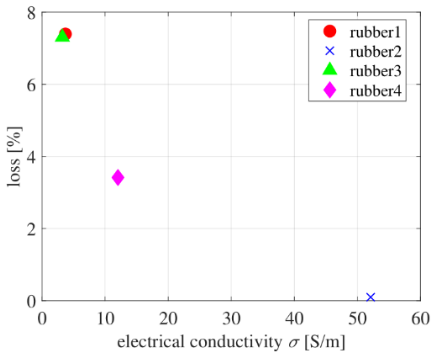


Fig.15 Relationship between the conductivity and the loss at 13.56 MHz.

as the thickness of the rubbers 3 and 4 increases in the Fig.14 (b) is considered that the electrical conductivity changes as the thickness increases.

According to Fig.14 which shows the influence of the belt on transmission efficiency, the efficiency drop by the steel belt is larger than the organic belt at both frequencies; While the drop by steel belt is 7.2% at 85 kHz and 4.9% at 13.56 MHz compared to the initial state, the drop by organic belt is 0.5% and 2.0%.

6. Conclusion

In WPT system for EV the influence of the tire rubber and belt on coupling coefficient, quality factor and transmission efficiency were investigated at 85 kHz and 13.56 MHz. As a result, the effect of rubber and organic belt at 85 kHz is very small. On the other hand, in the case of the steel belt, the efficiency drop was about 7.2%. In addition, at 13.56 MHz, the decrease in efficiency due to tire rubber and belt was observed. As the cause of this phenomenon, it was shown that the influence of the electrical conductivity could be considered besides the dielectric loss tangent.

Among them, it was found that the use of the organic belt tire can greatly reduce the influence of the tire on WPT system. In the future, we will analyze the loss due to the eddy current by simulation. In addition, the concept of arranging the receiver coil around the tire will be expected to develop in the future.

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