Analysis of Distance between ATS and ATP Antenna for Normal Operation in Combined On-board Signal System

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Abstract

Railroad signaling systems are to control intervals and routes of trains. There are ATS, ATP, ATO and ATC system. Trains are operated in the section which is met on the signaling system because various signaling systems are used in Korea. Hence, trains are not operated in the section which is used in the other signaling system. To solve this problem, recently combined on-board system has been developed. The combined on-board system designed by doubling the ATS, ATP and ATC system to ensure the safety of system. The inductance of antenna is change and in return the resonance frequency of antenna is varied by the electromagnetic induction. Therefore, the information signal is not received exactly in the combined on-board system and in return accidents between trains occur. In this paper, electric model of the combined on-board system for considering the ATS and ATP antenna is presented. Moreover, the mutual inductance including the distance between the ATS and ATP antenna is calculated. As a result of the frequency response of the antennas, the mutual inductance met on operation range of resonance frequency is defined.

Keywords: Combined on-board signal system, Frequency response, Mutual inductance, Magnetic coupling

1. Introduction

Railroad signaling systems perform controlling intervals and routes between trains. Referring to the way of transmitting the information, there are the transmitting it to the on-board system of a train using the track circuits, the another transmitting it from wayside devices and the other transmitting it from wireless devices. The one is the method of using the track circuits as a conductor for composing the part of the track and attaining the information by transmitting the information to the track. It is used for the high-speed railroad and the subway. Another method of using wayside devices is to attain the information by installing transmitters between rails. The other method of using wireless devices is to attain the information by installing wireless antenna.

In railroad signaling systems, there are ATS (Automatic Train Stop), ATP (Automatic Train Protection), ATO (Automatic Train Operation) and ATC (Automatic Train Control) system.

Currently, the ATP and ATC system have been used in high speed transit and the ATS, ATP and ATC systems have been used in subway. Various signaling systems are used in Korea. Hence, flexibility of trains is very low. Recently, a combined on-board system has been developed to increase the flexibility of trains. As the railroad signaling systems are vital, the combined on-board system is designed by doubling devices such as ATS, ATP and ATC antenna. Hence, the number of total antennas is six. Because electromagnetic induction occurs between antennas, inductance of antenna is changed. Hence, the information for controlling trains is not received exactly in the combined on-board system. Therefore, it is needed to define mutual inductance between antennas without any interference. As a result of the mutual inductance, the distance between antennas is defined.

In this paper, electric model of the combined on-board system for considering the ATS and ATP antenna is presented. Through the electric model, variation of inductance in the antenna is estimated by mutual inductance.
between the ATS and ATP antenna. The mutual inductance including the distance between the ATS and ATP antenna is calculated by using the Biot-Savart’s law. Moreover, variation of resonance frequency is estimated by the frequency response of the antennas according to the mutual inductance. As a result of the frequency response of the antennas, the mutual inductance met on operation range of resonance frequency is defined. Hence, the minimum distance between the ATS and ATP antenna is presented for accurate operation of the antennas.

2. Combined on-board Signal System

2.1 Composition

The combined on-board signal system was integrated with the ATS, ATP, and ATC systems in its design, as shown in Fig. 1, so that the trains could be operated through all the sections of the railroads in South Korea. The combined on-board system adopted dual-system control considering reliability and security [2].

In this study, two different interpretations were made for the analysis of the frequency response of the coupling coefficients between ATS and ATP in the combined on-board system diagram. One is the case when the combined on-board system passes over the ATS wayside antenna, and the other is the case when the system passes over the ATP wayside antenna. The ATC antenna was excluded in this study as it receives information through magnetic coupling.

2.2 Electrical model

2.2.1 When passing over the ATS wayside antenna

Fig. 2 shows the electric model between ATS inclusive of the ATS wayside antenna and ATP when the combined on-board system passes over the ATS wayside antenna [3-5].

Hence, $v_1(t)$ refers to the voltage of the ATS on-board antenna, and $v_2(t)$ to the voltage of the ATP on-board antenna; $R_1$ refers to the first car-side resistance of the ATS on-board antenna, and $L_1$ to the first car-side magnetic inductance; $R_2$ refers to the second car-side resistance of the ATS on-board antenna, and $L_2$ to the second car-side magnetic inductance; $L_3$ refers to the magnetic inductance of the ATS on-board antenna, and $C_1$ to the capacitance; $R_3$ refers to the resistance of the ATP on-board antenna, and $L_4$ to the magnetic inductance; $M_{12}$ refers to the mutual inductance of the first and second car-side ATS on-board antennas, and $M_{13}$ to the mutual inductance of the first car-side ATS on-board antenna and the wayside antenna; $M_{23}$ refers to the mutual inductance of the second car-side ATS on-board antenna and the wayside antenna, and $M_{14}$ to the mutual inductance of the first car-side ATS on-board antenna and the ATP on-board antenna; and $M_{24}$ refers to the mutual inductance of the second car-side ATS on-board antenna and the ATP on-board antenna, and $M_{34}$ to the mutual inductance of the ATS and ATP on-board antennas.

2.2.2 When passing over the ATP wayside antenna

Fig. 3 shows the electric model between ATS inclusive of the ATP on-board antenna and ATP when the combined on-board system passes over the ATP wayside antenna [3-5].
Hence, $L_4$ refers to the magnetic inductance of the ATP wayside antenna, and $C_3$ to the capacitance; $M_{43}$ refers to the mutual inductance of the first car-side ATS on-board antenna and the ATP wayside antenna, and $M_{45}$ to the mutual inductance of the second car-side ATS on-board antenna and the ATP wayside antenna; and $M_{45}$ refers to the mutual inductance of the ATP on-board antenna and the wayside antenna.

3. Analysis of the Mutual Inductance of Antennas And Frequency Response

3.1 Mutual inductance of the antennas
The magnetic flux density accrued from the on-board electricity was calculated as shown in equation (1), using the Biot-Savart rule for the calculation of the mutual inductance of antennas [3].

$$B_s = \mu_0 N A_s \frac{\partial \Phi}{\partial t}$$  \hspace{1cm} (1)

$$A_s = \pi R_v^2$$  \hspace{1cm} (2)

Hence, $\mu_0$ refers to the permeability in the free space, and $N_0$ to the number of antenna turns of the antenna at one side; $A_s$ refers to the sectional area of the antenna on that side, and $R_v$ to the radius of the sectional area of the antenna; and $d_{sw}$ refers to the separation distance between the antennas.

The counter-electromotive force induced to the antenna on the other side using equation (1) was calculated as shown in equation (3).

$$V_s(t) = -N_0 \pi \frac{d\Phi}{dt} = -N_0 A_s \frac{dB}{dt} = \frac{\mu_0 N N_0 A_s A_s d_s(t)}{2 \pi d_{sw}}$$ \hspace{1cm} (3)

$$A_s = \pi R_v^2$$ \hspace{1cm} (4)

Hence, $N_0$ refers to the number of antenna turns of the antenna at the other side, and $A_s$ to the sectional area of the antenna antenna; and $R_v$ refers to the radius of the sectional area of the antenna antenna on that side. The mutual inductance of the antennas induced from equation (3) is shown in equation (5).

$$M_{13} = M_{23} = \frac{\mu_0 N_0 N A_s A_s}{2 \pi d_{sw}}$$ \hspace{1cm} (5)

Equation (6) shows the separation distance between the antennas calculated using equation (5).

$$d_{sw} = 3 \sqrt[3]{\frac{\mu_0 N N_0 A_s A_s}{2 \pi M_{13} = M_{23}}}$$ \hspace{1cm} (6)

Equation (6) shows that the separation distance between the antennas becomes bigger as the number of antenna turns and the sectional area increase, and becomes shorter as the mutual inductance becomes larger.

3.2 Frequency response

3.2.1 When passing over the ATS wayside antenna
The case when the combined on-board system approaches the ATS wayside antenna can be applied using Fig. 2 as a reference, and the Euler method, as shown in equations (7) to (10) [6].

$$V_i = (R + j\omega L_i)I_i - j\omega M_{13} I_1 - j\omega M_{14} I_4$$ \hspace{1cm} (7)

$$0 = -j\omega M_{13} I_3 + (R + j\omega L_3)I_3 - j\omega M_{14} I_4$$ \hspace{1cm} (8)

$$0 = -j\omega M_{13} I_1 - j\omega M_{14} I_4 + \left(\frac{1}{j\omega C_1} + j\omega I_3\right)I_3 - j\omega M_{14} I_4$$ \hspace{1cm} (9)

$$0 = -j\omega M_{13} I_3 - j\omega M_{14} I_4 + (R + j\omega L_4)I_4$$ \hspace{1cm} (10)

The circuit equations of formulas (7) to (10) above can be expressed in matrix form, as shown in equation (11).

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_1 \\ 0 \\ 0 \\ V_4 \end{bmatrix}$$ \hspace{1cm} (11)

$$H = \begin{bmatrix} R_1 + j\omega L_1 - j\omega M_{13} - j\omega M_{14} \\ -j\omega M_{13} + R_2 + j\omega L_2 - j\omega M_{13} - j\omega M_{14} \\ -j\omega M_{13} - j\omega M_{14} + \frac{1}{j\omega C_1} + j\omega L_4 - j\omega M_{14} \\ -j\omega M_{13} - j\omega M_{14} + R_4 + j\omega L_4 \end{bmatrix}$$ \hspace{1cm} (12)

Equation (13) shows the interpreted frequency response against the electricity using the inverse matrix of $H$ in equation (11), and equations (14) and (15) show the frequency response against the electricity of the ATS wayside antenna and the on-board antenna.

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = H^{-1} \begin{bmatrix} V_1 \\ 0 \\ 0 \\ V_4 \end{bmatrix}$$ \hspace{1cm} (13)

$$I_2 = h_2 V_1 + h_4 V_4$$ \hspace{1cm} (14)

$$I_3 = h_3 V_1 + h_4 V_4$$ \hspace{1cm} (15)

$M_{14}$ and $M_{24}$ can be expressed as equations (16) and (17) to calculate the frequency responses against the coupling coefficients in equations (14) and (15), respectively.

$$M_{si} = K_{si} \times \sqrt{I_i L_i}$$ \hspace{1cm} (16)
be expressed in matrix form, as shown in equation (22).

\[
G = \begin{bmatrix}
R_1 + j\omega L_1 - j\omega M_{14} - j\omega M_{15} \\
-j\omega M_{12} + R_2 + j\omega L_2 - j\omega M_{13} \\
-j\omega M_{13} - j\omega M_{23} + R_2 - j\omega L_2 - j\omega M_{13} \\
-j\omega M_{15} - j\omega M_{25} - j\omega M_{26} + j\omega C_2 + j\omega I_2
\end{bmatrix}
\]

Equation (24) shows the interpreted frequency response against the electricity using the inverse matrix of G in equation (22), and equations (25) and (26) show the frequency response against the electricity of the ATP wayside antenna and the on-board antenna.

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4
\end{bmatrix} = G^{-1}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]

\[I_1 = g_o V_1 + g_o V_2 \]  
\[I_2 = h_o V_1 + h_o V_2 \]

As with the case when the combined on-board system approaches the ATS wayside antenna, the frequency response of the ATP on-board antenna and the ATP wayside antenna against the coupling coefficient between the ATS and ATP on-board antennas can be calculated by substituting equations (25) and (26) with equations (16) and (17), respectively.

### 4. Simulation

#### 4.1 Simulation conditions

Table 1 shows the simulation conditions for the analysis of the frequency response [7,8].

In other conditions, except for the simulation conditions described in Table 1, the voltage of the ATS on-board antenna was 10[V], and that of the ATP on-board antenna was 5[V]. The resistance in Table 1 is the pure resistance of the antenna itself, exclusive of the cable resistance, and the capacitance of the ATS wayside antenna was interpreted as 130[kHz], which is the resonance frequency of the stop position signal. The ERTMS/ETCS system was adopted as the basis for the ATP system, and the standard-type value was applied for the size of the on-board antenna while 4.5[MHz] was applied as the receiving frequency of the ATP on-board antenna [8]. Moreover, the mutual inductance of the first car-side ATS on-board antenna and the wayside antenna, and that of the second car-side on-board antenna and the wayside antenna, are equal as the distance between the first car-side on-board antenna and the wayside antenna and that between the second car-side antenna and the wayside antenna are similar, and as the

### Table 1. Simulation conditions

<table>
<thead>
<tr>
<th>Signal System</th>
<th>Desc.</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-board antenna</td>
<td>Magnetic inductance</td>
<td>1st</td>
<td>510[μH]</td>
</tr>
<tr>
<td>Wireside antenna</td>
<td>Magnetic inductance</td>
<td>2nd</td>
<td>510[μH]</td>
</tr>
<tr>
<td>On-board antenna</td>
<td>Magnetic inductance</td>
<td>1st resistance</td>
<td>1[Ω]</td>
</tr>
<tr>
<td>Wireside antenna</td>
<td>Magnetic inductance</td>
<td>2nd resistance</td>
<td>1[Ω]</td>
</tr>
<tr>
<td>On-board antenna</td>
<td>Mutual inductance</td>
<td>1st and 2nd</td>
<td>122[μH]</td>
</tr>
</tbody>
</table>

\[ M_i = K_a \times \sqrt{I_i L_i} \]  

The frequency response of the second car-side ATS on-board antenna and the ATS wayside antenna against the coupling coefficient between the ATS and ATP on-board antennas can be calculated by substituting equations (16) and (17) with equations (14) and (15), respectively.

3.2.2 When passing over the ATP wayside antenna

The case when the combined on-board system approaches the ATP wayside antenna can be applied using Fig. 3 as a reference, and the Euler method, as shown in equations (18) to (21)[6].

\[ V_i = (R_1 + j\omega L_1)I_i - j\omega M_{1i}I_i - j\omega M_{2i}I_i - j\omega M_{3i}I_i \]  

\[ 0 = -j\omega M_{1i}I_i + (R_2 + j\omega L_2)I_i - j\omega M_{12}I_i - j\omega M_{13}I_i \]  

\[ V_i = -j\omega M_{1i}I_i - j\omega M_{2i}I_i + (R_2 + j\omega L_2)I_i - j\omega M_{12}I_i \]  

\[ 0 = -j\omega M_{1i}I_i - j\omega M_{2i}I_i - j\omega M_{3i}I_i + \left( \frac{1}{j\omega C_1} + j\omega L_2 \right)I_i \]  

The circuit equations of formulas (18) to (21) above can be expressed in matrix form, as shown in equation (22).

\[ \begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix} = \begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} \]  

\[ G \]  

\[ I_1 = g_o V_1 + g_o V_2 \]  

\[ I_2 = h_o V_1 + h_o V_2 \]
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The numbers of antenna turns of the first and second car-side on-board antennas are the same. As the coupling coefficient was set at 0.02, which is the value at which the two do not affect each other, the mutual inductance that was applied was 10.2\(\mu\text{H}\) [5]. The mutual inductance of the ATS wayside antenna and the ATP on-board antenna and that of the ATS on-board antenna and the ATP wayside antenna was 1.88\(\mu\text{H}\), which value was obtained by calculating the proportions of the numbers of antenna turns of the ATS and ATP on-board antennas as the distance between the ATS wayside antenna and the on-board antenna and that between the ATP on-board antenna and the ATS wayside antenna are equal [4]. Further, the mutual inductance of the ATP on-board antenna and the ATP wayside antenna was set at 2.74[nH], which is the value that was considered to satisfy the bit error rate based on ATP at the train speed of 300[km/h].

4.2 Frequency response

Table 1 shows the simulation conditions for the analysis of the frequency

4.2.1 When passing over the ATS wayside antenna

When the combined on-board signal system approached the ATS wayside antenna, the frequency response of the ATS wayside antenna and the on-board antenna were analyzed by changing the coupling coefficient of the ATS and ATP on-board antennas to 0.2, 0.4, and 0.6 separately. The mathematical and simulation results are shown in Fig. 4~8, and the frequency response is considered the characteristic of the electric-current frequency induced to the ATS on-board antenna and the wayside antenna against the variations of the coupling coefficients between the ATS and ATP on-board antennas. Table 2 shows the variations of the resonance frequency of the ATS on-board antenna against the coupling coefficient.

The interpretations of the results of the Matlab and PSpice programs differ within about 5\[%\], proving that the foregoing calculations are mathematical equations. The resistance of the antenna was considered only in the amplitude of the electric current; therefore, the electric current can be interpreted as much bigger than the actual amplitude. The greater the increase in the coupling coefficient and the higher the resonance frequency were, the smaller the reduction of the amplitude of the wayside antenna's electric current. This is understood as the result in which the counter-emf was largely produced because the value of the mutual inductance was significantly increased by the enlarged coupling coefficient. Further, the range of the dynamic characters of the ATS on-board antenna and the wayside antenna were set at \(\pm 2\text{kHz}\). Therefore, when this value is applied to Table 2, the coupling coefficient of the ATS and ATP on-board antennas should remain lower than 0.4. In this case, the separation distance between the antennas appeared to be more than 233 [mm].

4.2.2 When passing over the ATP wayside antenna

When the combined on-board signal system approached
the ATP wayside antenna, the frequency response of the ATS wayside antenna and the on-board antenna were analyzed by changing the coupling coefficient of the ATS and ATP on-board antennas to 0.2, 0.4, and 0.6 separately. The mathematical and simulation results are shown in Fig. 7~9, and the frequency response is considered the characteristic of the electric-current frequency induced to the ATS on-board antenna and the wayside antenna against the variations of the coupling coefficients between the ATS and ATP on-board antennas. Table 3 shows the variations of the resonance frequency of the ATS on-board antenna against the coupling coefficient.

The interpretations of the results of the Matlab and PSpice programs differ within about 5[\%], proving that the foregoing calculations are mathematical equations. The resistance of the antenna was considered only in the amplitude of the electric current; therefore, the electric current can be interpreted as much bigger than the actual amplitude. As in the ATS case, the greater the increase in the coupling coefficient and the higher the resonance frequency were, the smaller the reduction of the amplitude of the wayside antenna’s electric current. Further, the range of the dynamic characters of the ATP and wayside antennas were set at ±50[kHz]. Therefore, when this value is applied to Table 3, the coupling coefficients of the ATS and ATP on-board antennas should remain lower than 0.2. In this case, the separation distance between the antennas appeared to be more than 419[mm].

### Table 3. Variation of the resonance frequency against the coupling coefficient in the ATP antenna

<table>
<thead>
<tr>
<th>Coupling Coefficient</th>
<th>Resonance Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>4.55[MHz]</td>
</tr>
<tr>
<td>0.4</td>
<td>4.58[MHz]</td>
</tr>
<tr>
<td>0.6</td>
<td>5.66[MHz]</td>
</tr>
</tbody>
</table>

### 5. Conclusion

In this paper, an electric model between the ATS and ATP antennas in the combined on-board signal system was proposed, and the frequency induced to the on-board and wayside antennas was mathematically estimated through the coupling coefficient between the ATS and ATP on-board antennas.

When the coupling coefficient is lower than 0.4, the combined on-board signal system is act dynamically within the dynamic-frequency range ±2[kHz] when the system passes over the ATS wayside antenna. When the coupling coefficient exceeds 0.4 and breaks away from the dynamic-frequency range, the system may malfunction. The band-pass filter had to be used to remove the possible interruptions of the signals on the same audible frequency band with the ATC between 10[Hz] and 1[kHz]. To keep the coupling coefficient lower than 0.4, the mutual inductance of the ATS and ATP on-board antennas should be kept lower than about 8.85[\mu H], and the separation distance should be kept more than 233[mm].

The combined on-board signal system acts dynamically within the dynamic-frequency range ±50[kHz] when the system passes over the ATP wayside antenna. Likewise, in the case when the system passed over the ATS wayside antenna, the band-pass filter had to be used to remove the possible interruptions of the signals on the same audible frequency band with the ATC between 10[Hz] and
100[kHz]. To keep the coupling coefficient lower than 0.2, the mutual inductance of the ATS and ATP on-board antennas should be kept lower than about 4.5[μH], and the separation distance should be kept more than 419[mm]. Therefore, it is necessary to keep the separation distance between the two antennas more than 419 [mm], and to install a band-pass filter to make the system active within the dynamic-frequency range, when the system passes over both the ATS and ATP wayside antennas.

The study is applied for frequency interference between antennas and a study on measuring the separation distance between the antennas in the real site is required.

References


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