A MICROSCOPIC OPERATING POINT ANALYSIS OF A NON-LINEAR MACROSCOPIC ADHESION CONTROL

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ABSTRACT

It is important to avoid the slip and to use adhesion phenomenon effectively for acceleration and deceleration in railways. A re-adhesion control system model based on a static, non-linear table is studied for investigating fundamental behavior of single motored axis electric rolling stock. It is assumed that characteristic of tractive coefficient decided by microscopic relative velocity between rim of wheel and rail. The dynamic re-adhesion operation is numerically under these conditions. In addition, we make sensitivity analysis from the two parameters change of non-linear torque reductive table.

1 INTRODUCTION

Friction force, called adhesive force between rail and wheel, plays significant role in driving rolling stocks. Effective use of the adhesion force is important to improve for good performance of an EMU. The adhesive force has the following two problems.

I. The absolute amount of the adhesive force of railway is small: it is much less than one of automobiles. The maximal coefficient is only 0.3 p.u.[1].
II. Whether conditions substantially affect the adhesive coefficient. The effect would be a significant disturbance for the control.

Recent inverter drive technology enabled sophisticated the re-adhesion control. It respond to the wheel angular velocity and angular acceleration and reduce motor torque when driving wheels become slip state. Their re-adhesion controller have a possibility of failing re-adhesion and have an improvement because the control respond to not slip state but the wheel angular velocity and angular acceleration[2]. In this paper, the coefficient of tractive force characteristic is assumed as a function responding the slip velocity subtracted body velocity from wheel rim velocity. Regarding the tractive force characteristic and re-adhesion controller as important, We construct a numerical analysing model that has single drive axis. Based on this model, it aims to obtain the finding of the behavior of the coefficient of tractive force characteristic and the re-adhesion possibility under the re-adhesion control.

2 NUMERICAL ANALYSIS MODEL

2.1 Characteristic of tractive force

Details of coefficient of tractive force-slip velocity characteristic has two areas shown as follows. One is the microslip area which is under the limit of adhesion and stable area of slip velocity from torque input. The other is macroslip area which is over the limit of adhesion and unstable area of slip velocity from torque input. When the slip velocity is positive, the coefficient of tractive force characteristic has two area and one peak at certain one slip velocity: v1. It is showed in Fig.1.

In this paper, tractive coefficient characteristic decided by slip velocity is constructed by several parameters which are shown as follows in positive slip velocity area.

The coefficient of adhesion: \( \mu_{\text{MAX}} \) is set out as the maximum coefficient of the tractive force characteristic. The microslip area of it is set out as a straight line whose gradient is \( g_1 \) (\( g_1 > 0 \)). The macroslip area of it is approximated exponential function which has the minimum gradient \( -g_2 \) (\( g_2 > 0 \)) and converge \( \mu_{\text{af}} \) (\( \mu_{\text{af}} > 0 \)) at huge slip velocity. The two areas are connected by parabolic function whose second order differential coefficient is \( -C_{\text{top}} \) (\( C_{\text{top}} > 0 \)). This math function is shown in equation(1). The characteristic in negative slip velocity
area is formulated by its odd function property.

\[
\mu(v_s) = \begin{cases} 
\frac{g_1 v_s}{\mu_{\text{MAX}}} - \frac{g_1}{4C_{\text{top}}} (v_s \leq v_1) \\
\frac{g_1 v_s}{\mu_{\text{inf}}} + B \exp\left(\frac{(v_2 - v_3)^2}{g_2^2}\right) (v_1 < v_s < v_2) \\
\frac{g_1 v_s}{v_2} (v_2 \leq v_s)
\end{cases} \quad (1)
\]

\(C_{\text{top}}\) is limited by continuity on the origin point as equation (2).

\[
v_1 = \frac{\mu_{\text{MAX}}}{g_1} - \frac{g_1}{4C_{\text{top}}} \geq 0
\]

\[
C_{\text{top}} \geq \frac{g_1^2}{4} \quad (2)
\]

Assistance parameters: \(v_1, v_{\text{top}}, v_2, B\) which used in equation (1). They are shown in equations (3) to (6).

\[
v_1 = \frac{\mu_{\text{MAX}}}{g_1} - \frac{g_1}{4C_{\text{top}}} \quad (3)
\]

\[
v_{\text{top}} = \frac{\mu_{\text{MAX}}}{g_1} + \frac{g_1}{4C_{\text{top}}} \quad (4)
\]

\[
v_2 = \frac{\mu_{\text{MAX}}}{g_1} + \frac{g_1}{4C_{\text{top}}} + \frac{g_2}{2C_{\text{top}}} \quad (5)
\]

\[B = \mu_{\text{MAX}} - C_{\text{top}}\left(\frac{g_2}{2C_{\text{top}}}\right)^2 - \mu_{\text{inf}} \quad (6)
\]

In follows case studies, The parameters are fixed as \(g_1 = 5, C_{\text{top}} = 40, g_2 = 0.05\) based on a measurement precedent of tractive coefficient characteristic[3].

### 2.2 Model of rolling stock

We construct a rolling stock model for numerical analysis which is single axis model. It is brought the model concept into focus tractive coefficient characteristic and re-adhesion control system. The model composition is shown in Fig.2. The model block diagram is shown in Fig.3. The dynamics of drive axis is shown in Equation (7). The dynamics of car body is shown in Equation (8). The relation of among slip velocity: \(v_s\), drive axis angular velocity: \(\omega_v\), and body velocity: \(v_b\) is shown in Equation (9). The constants which is used for numerical analysis, are shown in Table.1.

\[
J \omega_v = T_{\text{m}} R_g - W g r p(v_s) \quad (7)
\]

\[
M v_b = W g d(v_s) - F_d \quad (8)
\]

\[
v_s = r \omega_v - v_b \quad (9)
\]

\(T_{\text{m}}:\) motor torque, \(F_d: \) disturbance force, \( \mu(v_s): \) tractive coefficient. The system of motor torque response is set first order delay system whose delay time is 5ms.

### 2.3 Re-adhesion controller

In a present electric rolling stock, various re-adhesion control methods are proposed and applied. In this paper, We apply a re-adhesion method [4] which is one of them and is based on static torque reduction table, to the single drive axis electric rolling stock model.

![Fig.2 Single axis rolling stock model](image)

![Fig.3 Block diagram of the single drive axis rolling stock model](image)

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<th>Comment</th>
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<td>Mass per axis</td>
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<tr>
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<td>Mass on drive axis</td>
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<td>Equivalent inertia of drive axis</td>
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<tr>
<td>(R_g)</td>
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<td>Gear rate</td>
</tr>
<tr>
<td>(g)</td>
<td>9.0855[m/s^2]</td>
<td>acceleration of free fall</td>
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At first, it is assumed that it is rare that all of two or more axes cause this the idling at the same time. Under the assumption, detection of slip state and controller inputed value is deflections of velocity and acceleration on drive wheels rim. The torque reductive concept is described in follows. If deflections are near zero or less than zero, then controller assume adhesive state as microslip and do not reduce motor torque. Else, if one of them is big positive value, adhesive state is assumed as macroslip state and motor torque is reduced. Because velocitive deflection can not calculate in single drive axis model, input value of single drive axis model is only accelerative deflection. It set subtracted driver commanded acceleration from approximative differentiated rim of wheel velocity to the rim accelerative deflection of single drive axis model.

The block diagram of re-adhesion controller is shown in Fig.4. The shown non linear function has input that the accelerative deflection and the output that \(Adl\) shown in below. If input is less than \(\alpha_0\):Accelerative deflection room of torque reduction, output is 1. Else if input is more than \(\alpha_0 + \alpha_v\), output is 0. \(\alpha_v\) is accelerative deflection width of torque reduction. Else if it is between \(\alpha_0\) and \(\alpha_0 + \alpha_v\), output is applied linear supplement. their characteristic is shown in Fig.5. The non linear function output \(Adl\) which is torque multiplicative factor to torque command from driver: \(T_{\text{ref}}\) and the multiplied value is defined as \(T_{\text{adi}}\). Their relation is shown in Equation (10).

\[
T_{\text{adi}} = Adl \cdot T_{\text{ref}} \quad (10)
\]

Therefore the value of controller output: \(T_{\text{msl ref}}\) is applied LPF from \(T_{\text{adi}}\), the re-adhesion controller has four parameters shown in below.

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3.1 Adhesive condition and non linear table setting

We construct two case studies that one is succeed in re-adhesion and the other is fail in re-adhesion. The adhesive coefficient is decreased from 0.18 to 0.12 on both cases. The parameters of the non linear table of re-adhesion controller setting are shown in table 3. This setting means that case A has more torque reduction than case B.

3.2 Simulation results

The time-line trace of the slip velocity of case A is shown in Fig.7 by the solid line and boundary between microslip area and macroslip area is shown by the short dashed line. The coefficient of adhesion decrease less than Expected tractive coefficient and occurred slip at 6 second. But the slip being prevented being large slip by repeating the operation returned from the macroslip area to the microslip area by the re-adhesion control. Fig. 8 shows the result of case B. The first slip occurred at 6 second returns to the state of the microslip (grip) area. But, the slip of the second occurrence in the vicinity of time 7sec cannot be returned and the slip velocity emanates finally. This is shown in Fig.9.

The motor commanded torque converted into tractive coefficient scale is shown in the solid line and the tractive coefficient is shown in the short dashed line on Fig.10 of case A and on Fig.11 of case B. The convert factor is shown in equation (11).

\[ k_{T_\mu} = \frac{R_f}{W_gr} \frac{M}{M + \frac{1}{\tau}} \]  

The torque reduction when the secondarily occurred skip about 6.7s in case B is insufficient, and it can be confirmed that the slip velocity emanates though an enough torque reduction seeing is done until. In case A, the differentiation value of the slip velocity becomes negative value when the tractive coefficient decreases by the secondarily occurred skip.

In addition, time-line trace of the motor commanded torque value converted into the tractive coefficient and slip
velocity are shown in Fig.14 about case A. The tractive coefficient is decreased and it settles at the limit cycle after the slip occurrence and the skip settling are repeated twice momentarily. Fig.15 shows the case of condition B failing in the re-adhesion.

The re-adhesion possibility indicates whether the emanation of the slip velocity is suppressed and the re-adhesion is possible at long time. And the judgment of the re-adhesion possibility is used characteristic of the system which draw the limit cycle on the motor commanded torque - slip velocity space when succeeding in re-adhesion. If limit cycle which includes 14s moment comes and goes between macroslip state and microslip state during one cy-
cle which begin at the minimum motor commanded torque moment, it is defined that the controller has possibility of re-adhesion.

The minimum re-adhesive coefficient is a minimum coefficient of adhesion that can return to microslip state at long time under a certain controller. This is based on assumption that succeeding in the re-adhesion becomes difficult as hanging on the decrease of the coefficient of adhesion.

The re-adhesive availability is shown in equation (12). It is a time average of the momentary tractive coefficient per adhesive coefficient of the indication in the expression at 14 sec from 6 sec that decrease the adhesive coefficient and makes the slip.

\[
\mu_a = \frac{1}{14 - 6} \int_6^{14} \frac{\mu(t)}{\mu_{MAX}(t)} dt
\]

4.2 Condition of parameter analysis on the re-adhesion control system

In this subsection, We make clear that relations among three induces and non linear table setting of the controller described in the former subsection. Accelerative deflection room of torque reduction is set as below.

\[
\alpha_0 = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
\]

Accelerative deflection width of torque reduction is set as below.

\[
\alpha_w = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
\]

The limited adhesive coefficients (\(\mu_{lim}\)) are decreased from 0.16 up to 0.02 at intervals of 0.01. To request the minimum re-adhesive coefficient more in detail, intervals of the dropped adhesive coefficients is set 0.002 at near the minimum re-adhesive coefficient.

4.3 Results of numerical analysis

Figure 16 shows the possibility of re-adhesion on \(\alpha_0 - \mu_{lim}\) space. The marker ‘o’ shows the point has the possibility of re-adhesion and the marker ‘x’ shows the point does not have the possibility of re-adhesion. The minimum re-adhesive coefficient is between marker ‘o’ and marker ‘x’ in same the \(\alpha_0\) points. Therefore to become the \(\alpha_0\) small make minimum re-adhesive coefficient small. We need set the \(\alpha_0\) small to make minimum re-adhesive coefficient less value that means succeed re-adhesion in worse condition.
Moreover, the characteristic of the re-adhesive availability from the $\mu_{\text{lim}}$ is shown in Fig.17. In the area that fails in the re-adhesion, the re-adhesive availability decreases steeply against the $\mu_{\text{lim}}$ at near minimum re-adhesive coefficient. In the area that succeeds in re-adhesion, their re-adhesive availability is over 90% and have their difference of the re-adhesive availability in % order. Figure 18 shows the possibility of re-adhesion $\alpha_{v0} - \mu_{\text{lim}}$ space. To become the $\alpha_{v0}$ small make minimum re-adhesive coefficient small and in the area of $\alpha_{v0} \geq 0.6$, it is not possible to re-adhesion at all. We need set the $\alpha_{v0}$ small to make minimum re-adhesive coefficient less value that means succeed re-adhesion in worse condition. In addition, the characteristic of re-adhesive availability from the $\mu_{\text{lim}}$ is shown in figure 17. In the area that succeeds in re-adhesion, their re-adhesive availability is over 90% and have their difference of the re-adhesive availability in % order. If the limited adhesive coefficient is about 0.16 and $\alpha_{v0} \approx 0.3$, the re-adhesive availability becomes smaller than a case of more less limitation adhesive coefficient. Fig.20 and Fig.21 show to continue a halfway slipping for a long time from lack of torque reduction.

5 CONCLUSION

A re-adhesion control system model based on a static and nonlinear table is applied to single drive axis electric rolling stock model. It was assumed that it had the characteristic of tractive coefficient decided by microscopic relative velocity between rim of wheel and rail. The dynamic re-adhesion operation was numerically analysed under these conditions. When succeeding in the re-adhesion, slip state repeats macroslip state and microslip state and slip state is kept microslip state in terms of time average and the model and controller system has near 90% re-adhesive availability. In addition, we make sensitivity analysis from the two parameters change of non-linear torque reductive table. The minimum re-adhesive coefficient has large sensitivity from the table setting on re-adhesion controller and it have large improvable room for good re-adhesion control. To make minimum re-adhesive coefficient small, we have to make the table which has more torque reduce from a same input. The re-adhesive availability has small sensitivity from the table setting on re-adhesion controller. To make improvement of re-adhesive availability, it is important to reduce grow of slip velocity when slip break out. In the future, it is considered the bogie-body system vibration and multi axis drive of the rolling stock.

REFERENCES

Transactions, Proceedings or Journal Articles:

Doctorial thesis: