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Disturbance Observer Based Anti-slip Re-adhesion Control for Electric Motor Coach

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ABSTRACT

This paper proposes a new anti-slip re-adhesion control system for electric railway vehicle driven by inverter-fed induction motors. This paper introduces an instantaneous tangential force coefficient estimator between driving wheel and rail, which is based on disturbance observer. The torque command of proposed system regulates to exceed this estimated tangential force coefficient in order to avoid undesirable slip phenomenon of driving wheels.

We have already proposed the anti-slip re-adhesion control system based on disturbance observer for simplified one wheel equivalent model successfully. This paper extend to this system to the actual bogie system, which has four driving wheels driven by two induction motors fed by one inverter. In order to apply anti-slip re-adhesion control to the actual bogie system, a new anti-slip re-adhesion control based on both disturbance observer and speed sensor-less vector control of induction motor with quick response are combined. The experimental results and the numerical simulation results prove the validity of the proposed control system.

Key words: Re-adhesion Control, Disturbance Observer, Speed Sensor-less Vector Control

1. INTRODUCTION

Generally, the tangential force is defined by the function of both the weights of electric motor coach and the tangential force coefficient μ between rail and driving wheel. The characteristics of tangential force coefficient μ is strongly affected by the conditions between rails and driving wheels, such as moisture, dust, oil on the rails and so on [1]. When the tangential force coefficient μ decreases, the electric motor coach has a slip phenomenon. A slip phenomenon is uncomfortable for the passengers of electric motor coach, and consumes both the rails and the driving wheels. Therefore, the drive system of electric motor coach is requested to have a fine anti-slip & re-adhesion control system.

We have already proposed the anti-slip & re-adhesion control system based on disturbance observer [2][3][4][5]. This system has a fine torque response for one driving wheel driven by one inverter-fed induction motor. However, a bogie of electric motor coach has four driving wheels driven by two induction motors, which are driven by one inverter. Hence, an anti-slip & re-adhesion control system should consider both a resonant frequency of bogie system and two induction motors driven by one inverter [6].

The electric motor of ordinary electric motor coach has the speed sensor based on the ultra low-resolution rotary encoder, such as 60[*pulse/rev.*]. Using this speed sensor, the detection time of actual motor speed becomes about 25[*msec*] [4][5]. Therefore, it is difficult for a drive system of electric motor coach to realize a quick anti-slip & re-adhesion control by using this speed sensor. In order to overcome this problem, the recent research for drive system of electric motor coach has been carried out the implementation of sensor-less vector control [7][8][9].

This paper proposes a new anti-slip & re-adhesion control method based on both disturbance observer and sensor-less vector control [10]. The experimental results and the numerical simulation results point out that the proposed control method has the desired anti-slip & re-adhesion control response for the tested bogie system of electric motor coach on condition of two induction motors driven by one inverter.

2. SLIP PHENOMENON AND ESTIMATION OF TANGENTIAL FORCE COEFFICIENT

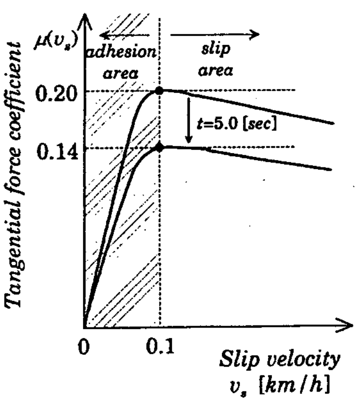

Fig. 1. Characteristics between tangential force coefficient and slip velocity (Numerical simulation condition)

Generally, the relation characteristics between the tangential force coefficient μ and the slip velocity v_s is summarized as shown in Fig.1. The tangential force coefficient μ is a function of slip velocity v_s. The peak value of tangential force is determined by the condition of maximum tangential force coefficient $\mu(v_s)_{max}$. When the driving torque τ of electric motor coach is exceed the maximum tangential force, the excess of torque generates a slip phenomenon.

Electric motor coach moves by this tangential force between its driving wheel and the rail, and has the bogie driven by four driving wheels and two induction motors as shown in Fig.2. It has some resonant frequencies.

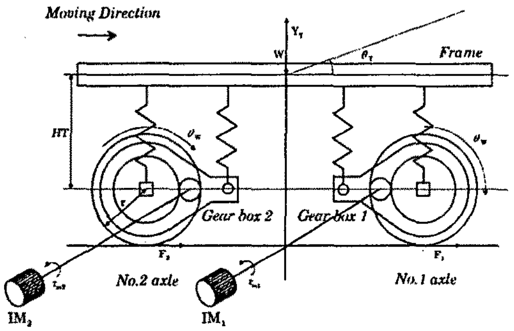

Fig. 2. Image of bogie of electric motor coach

At first, this paper makes a model for estimation of tangential force coefficient, and designs its anti-slip & re-adhesion control system. The motion equations of electric motor coach are governed by (1) and (2). (1) describes the motion of rolling stock of electric motor coach, and (2) describes the motion of driving wheel of electric motor coach. In equation (2), $\mu(v_s)\cdot W\cdot g\cdot r$ is the wheel torque corresponding to the tangential force between rail and driving wheel.

$$M\cdot\frac{d}{dt}v_t = \mu(v_s)\cdot W\cdot g\cdot - F_d(v_t) \quad (1)$$

$$J\cdot\frac{d}{dt}\omega_d = \tau - \mu(v_s)\cdot W\cdot g\cdot r \quad (2)$$

$$v_s = v_d - v_t \quad (3)$$

Here,

v_t: velocity of electric motor coach
v_d: velocity of wheel
ω_d: angular velocity of wheel
W: weight of electric motor coach
M: weight on wheel
J: total inertia moment of wheel
$F_d(v_t)$: resistance of electric motor coach
g: gravity acceleration
r: radius of wheel

A torque equation of electric motor is governed by (4). τ_c is the disturbance torque of electric motor. Using (2), this paper obtains the significant motion equation as shown in (5). $\mu(v_s)\cdot W\cdot g\cdot r/R_g$ is the motor torque corresponding to the tangential force between rail and driving wheel, which is a disturbance torque of electric motor. Since disturbance observer estimates the disturbance torque τ_c which is the tangential force as shown in (6), the tangential force coefficient $\mu(v_s)$ is estimated as shown in (7).

$$J_m\frac{d}{dt}\omega_m = \tau_m - \tau_c \quad (4)$$

$$J_m\frac{d}{dt}\omega_m = \tau_m - \frac{1}{R_g}\mu(v_s)\cdot W\cdot g\cdot r \quad (5)$$

$$\hat{\tau}_c = \frac{a}{s+a}\cdot(\tau_m - J_m\cdot s\cdot\omega_m) \quad (6)$$

$$\hat{\mu}(v_s) = \frac{R_g}{W\cdot g\cdot r}\cdot\hat{\tau}_c \quad (7)$$

$$\frac{d\mu}{dv_s} = \frac{d\mu/dt}{dv_s/dt} = \frac{d\mu}{dt}\cdot\frac{dt}{dv_s} \quad (8)$$

In an ordinary electric motor coach, since the slip velocity v_s cannot be detected, the re-adhesion control system cannot use the slip detection equation $d\mu/dt = 0$. When a electric motor coach is accelerated, both the driving torque τ and the velocity v_d of wheel varies. Therefore, the value of dv_s/dt does not become zero. Hence, using (8), the slip detection equation is treated as $d\mu/dt = 0$.

Table 1. Parameters of tested electric motor coach

Gear ration	R_g	5.5
Wheel radius	r	0.41 [m]
Weight	W	5950 [kg]
Total inertia moment	J	159.18 [kgm²]

Table 2. Parameters of tested induction motor

Pole pair number		2
Rated line voltage		1100 [V]
Rated current		80 [A]
Rated output		120 [kW]
Primary resistance	R_1	0.182 [Ω]
Secondary resistance	R_2	0.257 [Ω]
Mutual inductance	M	0.06341 [H]
Primary self inductance	L_1	0.001738 [H]
Secondary self inductance	L_1	0.001738 [H]

In order to confirm the validity of estimation of tangential force coefficient by using disturbance observer, this paper carries out the numerical simulation as shown in Fig.3. The bogie of electric motor coach has the four driving wheels driven by two induction motors as shown in Fig.2, which are driven by one inverter. This paper calls the two induction motors driven by one inverter 2M1C. The parameters of tested electric motor coach and tested induction motor are represented as shown in Table.1 and Table.2, respectively. The pole a of tested disturbance observer is 100[*rad/sec*].

Fig.3 point out that the zero point **P** of actual average $d\mu/dv_s$ coincides with the peak point of the estimated tangential force coefficient $\hat{\mu}$ of disturbance observer. The proposed estimation method of tangential force coefficient well estimates the average value of tangential force coefficient of two induction motors. However, the waveform of $d\hat{\mu}/dt$ is oscillatory due to the vibration of bogie system. Therefore, we think that the estimated tangential force τ_c is used for the torque command of anti-slip & re-adhesion control but $d\hat{\mu}/dt$ is not used for the detection of slip phenomenon.

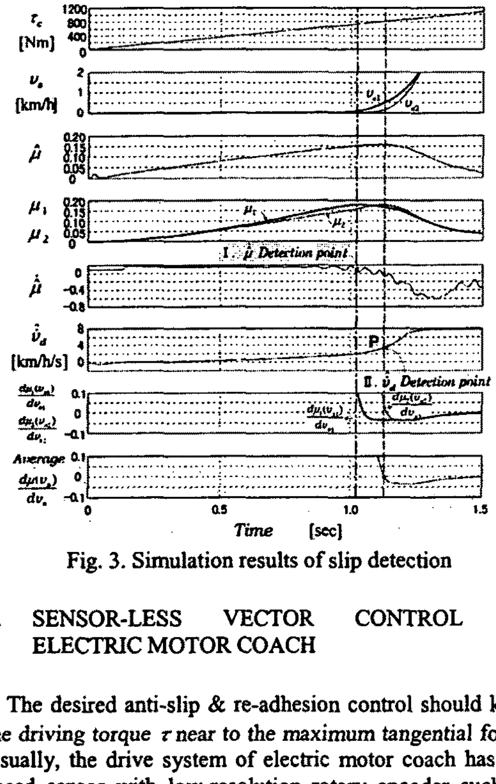

Fig. 3. Simulation results of slip detection

3. SENSOR-LESS VECTOR CONTROL OF ELECTRIC MOTOR COACH

The desired anti-slip & re-adhesion control should keep the driving torque τ near to the maximum tangential force. Usually, the drive system of electric motor coach has the speed sensor with low-resolution rotary encoder such as 60[*pulse/rev.*]. It is very difficult to control the motor torque to suppress the slip phenomenon quickly.

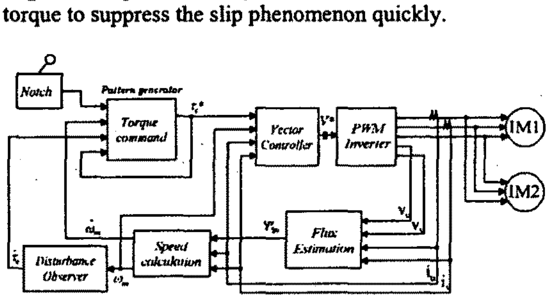

Fig. 4. Re-adhesion control system based on disturbance observer and sensor-less vector control

In order to realize a quick torque response, this paper proposes that the sensor-less vector control system drives the two induction motors of electric motor coach. Sensor-less vector control system estimates the instantaneous torque and magnetic flux inter-linkage of induction motor using the signals of current and voltage. Although sensor-less vector control system has many advantages comparing to ordinary vector control system with speed sensor, the major advantage for anti-slip control is that it is free from the delay of low-resolution encoder, especially in low or middle speed range.

The average angular speed $\hat{\omega}_m$ of the two induction motors of electric motor coach is quickly estimated by using from (9) to (12). [11]

$$\hat{\Psi}_{2v} = \int\left[\frac{L_2}{M}\left(\vec{v} + R_1\vec{i}\right)\right]dt - \left(\frac{L_1L_2}{M} - M\right)\vec{i} \tag{9}$$

$$\hat{\omega}_s = R_2\frac{M\left(\Psi_{2v\alpha}i_\beta - \Psi_{2v\beta}i_\alpha\right)}{L_2\left(\Psi_{2v\alpha}^2 - \Psi_{2v\beta}^2\right)} \tag{10}$$

$$\hat{\omega} = \frac{d}{dt}\left(\tan^{-1}\frac{\Psi_{2v\alpha}}{\Psi_{2v\beta}}\right) \tag{11}$$

$$\hat{\omega}_m = \hat{\omega} - \hat{\omega}_s \tag{12}$$

Here,

$\hat{\Psi}_2$: rotor flux in stationary (α,β) reference frame

$\Psi_{2\alpha}, \Psi_{2\beta}$: α,β-axis component of $\hat{\Psi}_2$

$\hat{\omega}_s$: estimated slip angular frequency

$\hat{\omega}$: estimated primary angular frequency

$\vec{v}$: stator voltage vector

$\vec{i}$: stator current vector

i_α, i_β : α,β-axis component of current vector $\vec{i}$

The velocity $\hat{v}_d$ of driving wheel is obtained by (13). Therefore, the proposed re-adhesion control system based on disturbance observer and sensor-less vector control is illustrated as shown in Fig.4.

$$\hat{v}_d = \frac{1}{R_g}\hat{\omega}_m \tag{13}$$

4. SLIP DETECTION AND TORQUE COMMAND

Fig.3 also shows the differential value $\dot{\hat{v}}_d$ of the estimated driving wheel velocity $\hat{v}_d$. The waveform of the differential value $\dot{\hat{v}}_d$ is smooth, and has little influence on the vibration of the resonant frequency of bogie system of electric motor coach. Moreover, Fig.3 points out that the zero point **P** of actual average $d\mu/dv_s$ coincides with $\dot{\hat{v}}_d$ =3.465[km/h/s]=(5[Hz/s]). Therefore, the proposed re-adhesion control system detects the slip phenomenon by using the condition equation $\hat{\upsilon}_d$=3.465[km/h/s]=(5[Hz/s]). The torque command pattern of the proposed anti-slip & re-adhesion control is shown in Fig.5. At the start, the driving torque command τ_c^* is a lamp function. When the proposed re-adhesion control system detects the first slip phenomenon by using $\hat{\upsilon}_d$ =3.465[km/h/s](= 5[Hz/s]), the torque command τ_c^* pulls down to τ_{c-lim} which is 88% of the tangential force estimated value $\hat{\tau}_c$ at the first slip-phenomenon point, and keeps this value τ_{c-lim} until T_1[sec]. After T_1[sec], the torque command τ_c^* pulls up to τ_{c-muc} which is nearly equal to $\hat{\tau}_c$, and keeps this value τ_{c-muc} until T_2[sec].

At the second slip-phenomenon point, the torque command τ_c^* pulls down to the other value τ_{c-lim} which is 93% of the tangential force estimated value $\hat{\tau}_c$ at the second slip-phenomenon point, and keeps the other value τ_{c-lim} until T_1[sec]. After T_1[sec], the torque command τ_c^* pulls up to the value τ_{c-muc} which is nearly equal to $\hat{\tau}_c$, and keeps the value τ_{c-muc} until T_2[sec]. After the third slip-phenomenon point, the same torque command pattern at the second slip-phenomenon point is repeated. In this paper, T_1 is 250[msec] and T_2 is 750[msec].

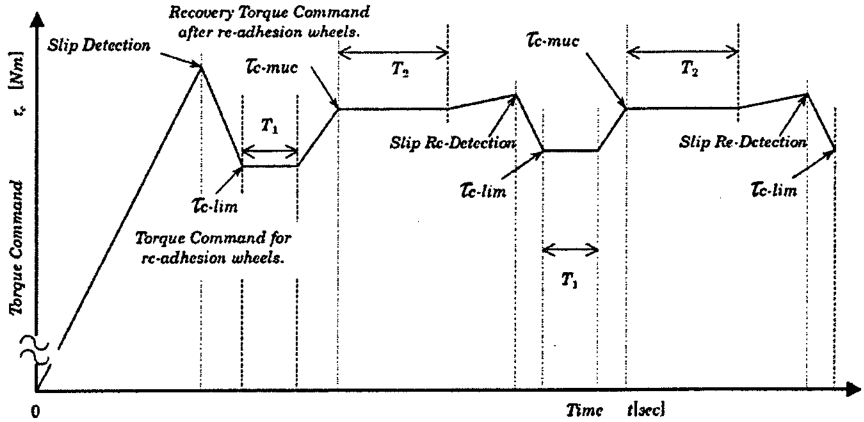

Fig. 5. Slip detection and torque command

5. NUMERICAL SIMULATION RESULTS

In order to confirm the validity of robust performance of the proposed re-adhesion control system, this paper shows the numerical simulation results on the condition of the variation of tangential force coefficient $\mu(\upsilon_s)$ and the impulsive disturbance torque. This chapter carries out the numerical simulation by using the two kinds of detection method on slip phenomenon. The first detection method is based on the signal of $d\hat{\mu}/dt$. The second detection method is based on the signal of $\hat{\upsilon}_d$.

The tangential force coefficient characteristic is illustrated as shown in Fig.1. Each of the maximum tangential force coefficient in Fig.1 is 0.20 and 0.14 at the same slip velocity point υ_s= 0.1[km/h], respectively. In these numerical simulations, at 5[sec], the maximum adhesion coefficient μ_{max} decreases from0.20 to 0.14 suddenly, and at 10[sec], the tested bogie system has the impulsive disturbance torque 5000[N] suddenly, which is equivalent to the phenomenon crossing the rail connection point.

At first, Fig.6 shows the re-adhesion response of the proposed re-adhesion control using the detection method based on the signal of $d\hat{\mu}/dt$. This re-adhesion control method well regulates the driving wheel, on condition that the maximum adhesion coefficient μ_{max} decreases from 0.20 to 0.14 suddenly at 5[sec]. Moreover, the utilization ratio of maximum adhesion coefficient μ_{max} is the more than 80[%]. However, at 10[sec], the detection method based on the signal of $d\hat{\mu}/dt$ has the misjudging on slip phenomenon. Hence, when the electric motor coach crosses the rail connection point, it is difficult for this re-adhesion control using the detection method based on $d\hat{\mu}/dt$ to maintain the desired anti-slip and re-adhesion control.

Next, Fig.7 shows the re-adhesion response of the proposed re-adhesion control using the detection method based on the signal of $\hat{\upsilon}_d$. Similarly, this re-adhesion control method well regulates the driving wheel on condition that the maximum adhesion coefficient μ_{max} decreases suddenly. The utilization ratio of maximum adhesion coefficient μ_{max} is the more than 80[%]. Moreover, at 10[sec], the detection method based on the signal of $\hat{\upsilon}_d$ has no misjudging on slip phenomenon in case of the impulsive disturbance torque 5000[N]. Hence, when the electric motor coach crosses the rail connection point, this re-adhesion control using the detection method based on $\hat{\upsilon}_d$ maintains the desired anti-slip and re-adhesion control.

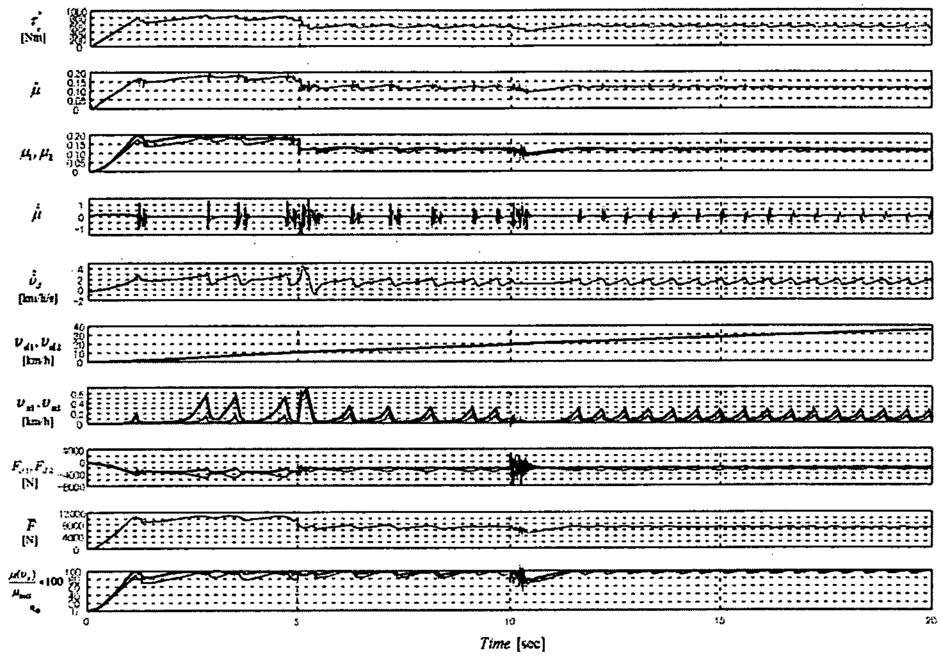

Fig.6. Simulation results of re-adhesion control using slip detection method based on $d\hat{\mu}/dt$, on condition of both tangential force coefficient variation and impulsive disturbance torque

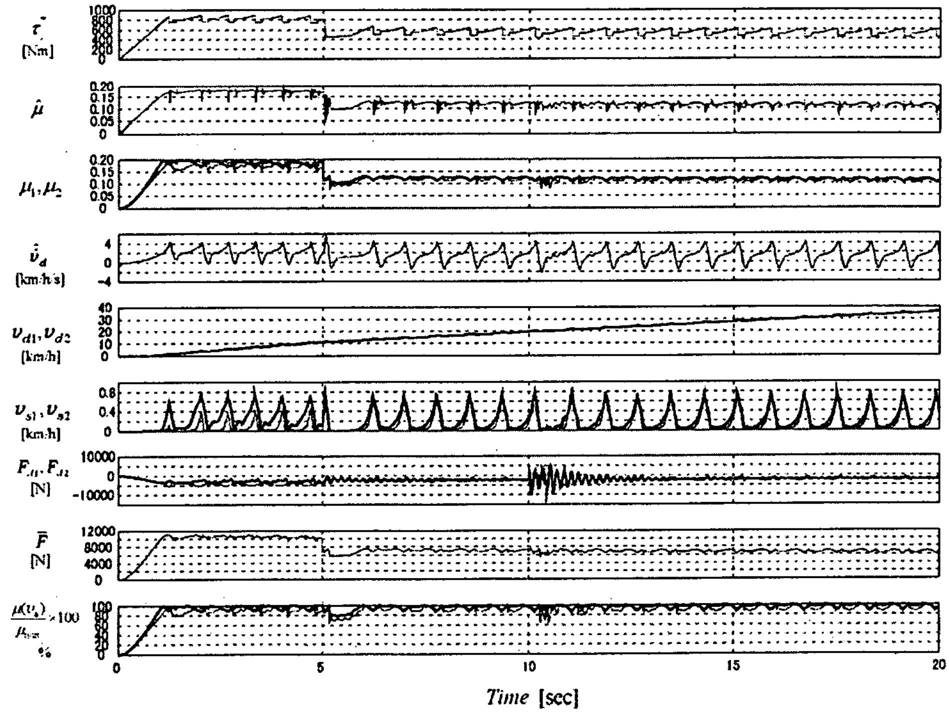

Fig.7. Simulation results of re-adhesion control using slip detection method based on $\hat{\dot{v}}_d$, on condition of both tangential force coefficient variation and impulsive disturbance torque

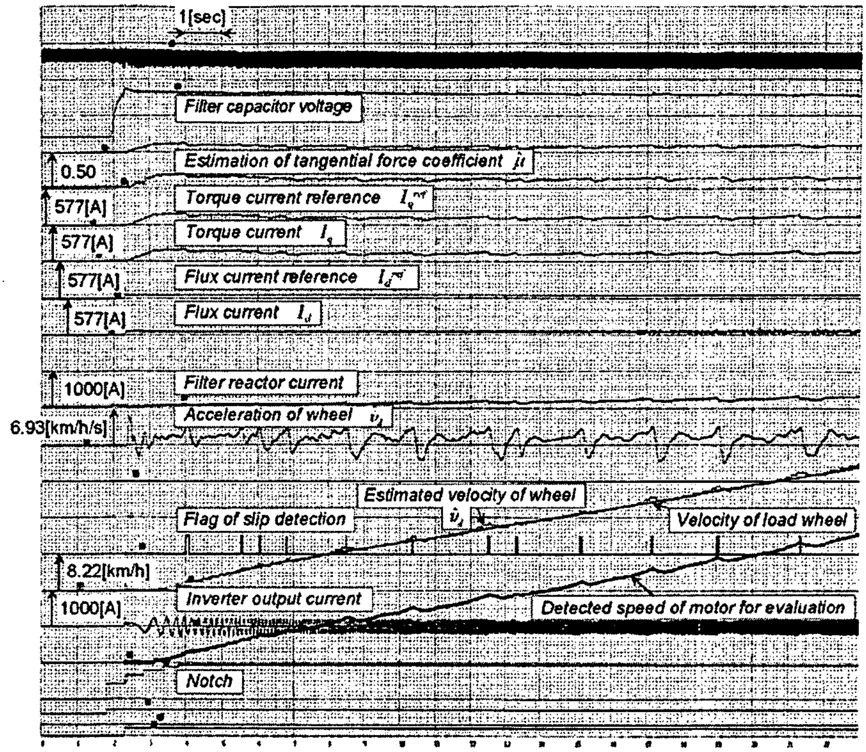

Fig. 8. Experimental results of re-adhesion control using tested bogie of electric motor coach

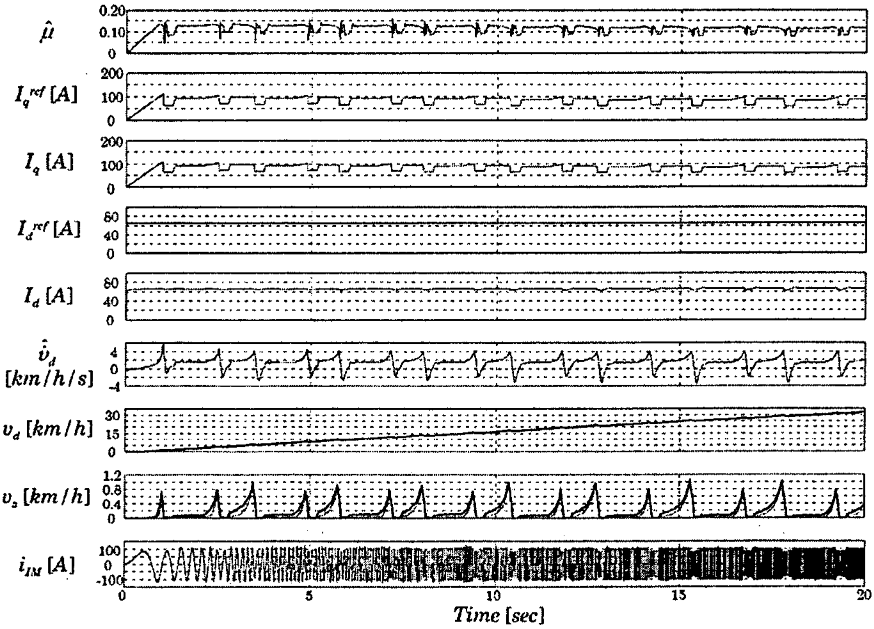

Fig. 9. Simulation results on the same condition of Fig.8

6. EXPERIMENTAL RESULTS

In order to confirm the actual validity of the proposed re-adhesion control system, this paper shows the experimental results using the tested system of actual bogie of electric motor coach, as shown in Fig.8. The parameters of tested electric motor coach and tested induction motor are represented as shown in Table.1 and Table.2, respectively. In the tested system, the driving wheel and rail wheel are sprayed with the soapsuds. The tested sensor-less vector control system regulates the two tested induction motors by one PWM inverter.

In Fig.8, the slip velocity v_s between the estimated driving wheel velocity $\hat{v}_d$ and the actual truck velocity v_t is always very small. The detected wheel velocity v_d well coincides with the estimated driving wheel velocity $\hat{v}_d$. Moreover, the numbers of the flag of slip detection is small. Therefore, these experimental results point out that the proposed re-adhesion control system using the detection method based on the signal of $\hat{\dot{v}}_d$ realizes the desired driving wheel torque response to the tested actual bogie system for anti-slip & re-adhesion control.

Next, this paper shows the numerical simulation results on the same condition of the tested bogie system, as shown in Fig.9. The tangential force coefficient characteristic of the numerical simulation is shown in Fig.1. The waveforms of estimated wheel acceleration value $\hat{\dot{v}}_d$ in Fig.9 coincide with them of Fig.8. The slip velocity v_s between v_d and v_t is always very small. Therefore, similarly, these numerical simulation results point out that the proposed re-adhesion control system realizes the desired anti-slip & re-adhesion control to the tested bogie system of electric motor coach.

Moreover, both Fig.8 and Fig.9 point out that the numerical simulation system in this paper has very useful confirmation characteristics on the anti-slip & re-adhesion control of bogie system of electric motor coach.

7. CONCLUSION

This paper proposes a new re-adhesion control system of electric motor coach, which is based on disturbance observer and sensor-less vector control. The experimental results and numerical simulation results point out that the proposed re-adhesion control system has the desired driving wheel torque response for the tested bogie system of electric motor coach on condition of the two induction motors driven by one PWM inverter.

Moreover, this paper confirms the validity of robust performance of the proposed re-adhesion control system on the condition of both the variation of tangential force coefficient $\mu(v_s)$ and the impulsive disturbance torque 5000[N] which is equivalent to the phenomenon crossing the rail connection point.

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