Aircraft Yaw-rate Control by Electrically Driven Wheel for Crosswind Landing

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Demand for aircraft transportation has doubled in the past ten years and is expected to increase. Therefore, aircrafts must become more safer. Most business jets accidents occur while landing; in many times, the accidents are caused by strong cross winds and tail winds. In this paper, we propose motion control for aircraft landing, taking advantage of electric motorization of aircraft in recent years and the characteristics of electric motor. By utilizing the advantages such as fast torque response, easy distributed arrangement, and independent control, electric motors for driving the wheels, we propose a method to suppress the yaw-rate generated in crosswind landing. In this paper, we demonstrate the effectiveness of the proposed method by the simulation and basic experiments. Simulation was also performed when the velocity control was incomplete due to measurement error, and showed the robustness of the proposed method.

Keywords: Electric Aircraft, Crosswind Landing, Electrically Driven Wheel, More Electric Aircraft

1. Introduction

1.1 Recent demand for aircraft transportation Demand for aircraft transportation has nearly doubled in the past 10 years and is expected to increase further by 2035 (1). In recent years, the equipment of aircraft is gradually improving, i.e. the Boeing 787. Although the internal combustion engine is still used for the propulsion power, the electricization of the aircraft's equipment has been further carried out. The main motivation in aircraft electrification is reducing the fuel cost due to high efficiency, and growing concern environmental problems. For example, in the case of the Boeing 787, the use of a large-sized generator and high voltage distribution, reduction of fuel consumption by adopting electric compressor and electrification the anti-icing system have been achieved.

Mounting electrically driven wheels on aircraft has also been proposed. At the time of takeoff, the conventional jet engine is used to move from the runway to the terminal. Recently, Airbus is developing such electrically driven wheel to suppress the exhaust gas generated by the towing vehicle and the jet engine. Also, at the Japan Aerospace Exploration Agency (JAXA), has been developing electrically driven wheels during takeoff. As a result, they succeeded in reducing the running distance during takeoff.

The electric motors have been increasing employed in such applications because they have the following advantages,

- Torque response is much faster than internal combustion engines and hydraulic systems.

Fig. 1. Electrically driven wheel of Airbus A320 (2)

- The torque can be calculated with high accuracy by the motor current.
- Distributed arrangement and independent control, which are impossible with internal combustion engines, can be achieved and consequently the freedom of aircraft design is high.

One example of application taking advantage of these characteristics is slip control (3) of an electric vehicle and yaw-rate control (4). Therefore, this paper proposes a the method to control yaw-rate at landing by appropriately regulating the driving wheels. In this paper, we show effectiveness mainly focusing on suppression of yaw-rate occurring during crosswind landing, especially sideslip landing. The motivation is to improve the safety at landing, to reduce the accidents and to increase the navigation efficiency.

1.2 Proposed method : yaw-rate control in crosswind landing Accidents in aircraft still remain a problem, especially in the case of business jet accidents account for

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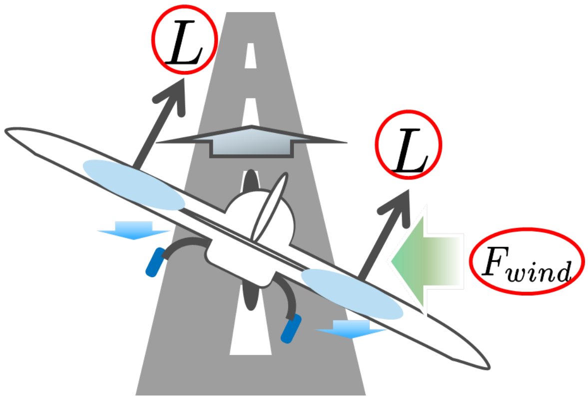


Fig. 2. Overview of sideslip landing

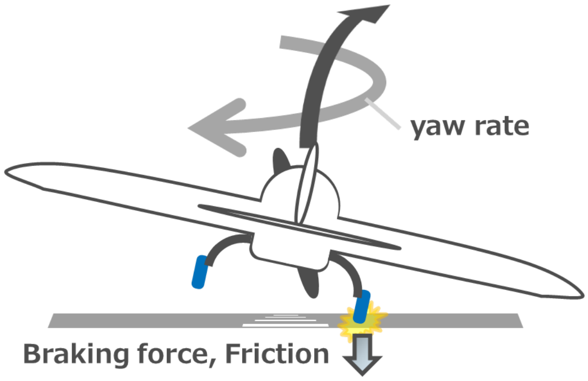


Fig. 3. Problem of sideslip landing

56.5% of the total at the time of landing [6] [7]. Therefore, improvement of safety at landing is very important. In addition, some of takeoff and landing accidents are caused by the influence of wind such as strong crosswinds and tailwinds.

The case of sideslip landing is described as following: when the aircraft lands and strong crosswinds blows, the aircraft is detached from the runway. As a countermeasure, a method of balancing horizontal wind force and lift is actuated by tilting the aircraft in the roll direction. This technique is called sideslip landing. A reference diagram is shown in Fig.2.

However, with this method, there is a moment when only one wheel lands; at that time, a yaw-rate proportional to the distance to the ground plane of the tire is generated. Also, even after landing, a strong crosswind causes a lift difference between the left and right, changing the load balance on the left and right of the landing wheel. Due to these yaw-rates, the traveling direction of the aircraft deviates, potentially coming off the runway and thus risking an accident as shown in Fig.3. Currently, countermeasures such as pilots returning the aircraft horizontally just before landing are taken. However, if the timing of returning in the horizontal direction is too early, it will be flowed into the side wind. Therefore, the landing success depends greatly on pilot skills.

The proposed method consists in controlling the electrically driven wheel before the landing. Then, the braking force generated from the difference between the wheel velocity and the aircraft velocity is suppressed, and the yaw-rate is still suppressed at the time of crosswind landing by increasing or decreasing the driving force according to the generated yaw-rate.

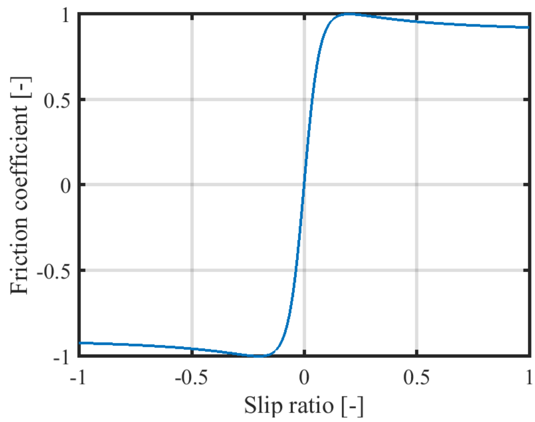


Fig. 4. μ - λ curve

2. Aircraft model

This section describes the motion model of the aircraft. in this section, we describe the plant model of the driving wheel and the plant model on the yaw-rate generated by it.

2.1 Wheel model and yaw moment model The rotational motion of each wheel model can described as [12] [13]

$$J_w \dot{\omega}_w = T_w - rF_d \qquad (1)$$

$$F_d = \mu(\lambda) N \qquad (2)$$

$$V_w = r\omega_w, \qquad (3)$$

where J_w is the moment of inertia of driving wheel, ω_w is the wheel angular velocity, T_w is the motor torque, r is the wheel radius, F_d is the driving force, N is the normal force, $\mu(\lambda)$ is the friction coefficient, V_w is the wheel velocity, respectively.

The wheel velocity V_w and aircraft velocity V are related with slip ratio, and respectively calculated as

$$\lambda = \frac{V_w - V}{\max(V_w, V, \epsilon)}, \qquad (4)$$

where ϵ is a small constant to avoid division by zero. It is known that the slip ratio λ is related with the friction coefficient μ as shown in Fig.4 [15].

Also, aircraft dynamics in the direction of travel are given as

$$M\dot{V} = F_d - \mu_0 N \qquad (5)$$

where M is the mass of aircraft, $\mu_0 N$ is the rolling friction coefficient. Hence, a block diagram about driving wheel is given in Fig.5.

Airplane dynamics of vertical direction are given as (6),

$$Mg = L + N \qquad (6)$$

where g is the acceleration of gravity, L is the lift that caused by wings.

Yaw dynamics of aircraft are given as (7), and a block diagram is shown in Fig.6.

$$I_{yaw}\dot{\gamma} = l(F_{dl} - F_{dr}) \qquad (7)$$

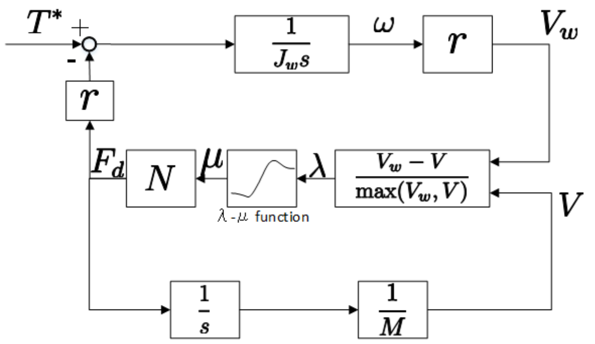


Fig. 5. Block diagram of driving wheel model

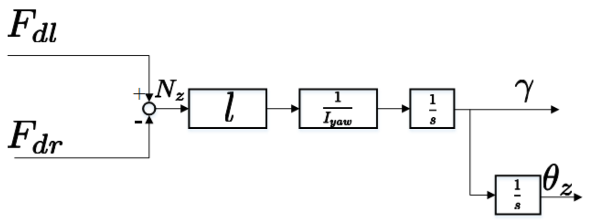


Fig. 6. Block diagram of yaw moment model

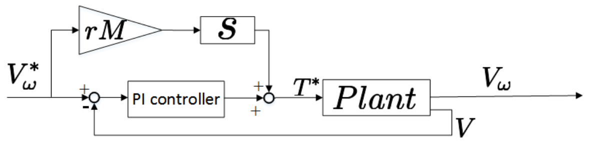


Fig. 7. Block diagram of velocity feedforward controller

3. Simulation with no difference between measured and true velocity

3.1 Overview in this section, we propose a compensation method of yaw-rate by arranging driving wheels on aircraft by making easy use of distributed arrangement.

As a proposed method of yaw-control, we use two controllers:

- One applies velocity control for electrically driven wheel, and make it rotate at as ground velocity just before landing(velocity feedforward controller).
- The other is feedback control based on yaw-rate sensor after landing(yaw feedback controller).

Velocity feedforward controller is derived from (1), (5), and wheel velocity sensor. Then, the transfer function from V^*_w to T^* is shown as

$$T^* = rMsV^*_w \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (8)$$

and is set as PI control, and the pole was set to -5 [rad/s] by the pole placement method. This block diagram is shown in Fig.7. Yaw feedback controller is consisted from(1), (7), and is set as PI control, and the pole was set to -30 [rad/s] by the pole placement method. This block diagram is shown in Fig.8.

in this section, we will simulate Cessna 172 Skyhawk. The landing velocity considered is 100 [km/h]; it is approximately 20% faster than the stall velocity (83 [km/h]). The performance of Skyhawk is shown in Table.1.

In the simulation, it is assumed that the landing happens on the right wheel, one second after the start of the simulation and the other wheel touches ground after 2 seconds. The velocity control system acts on the right wheel 0.5 seconds after the start of the simulation and on both wheels 1.5 seconds later, assuming that the ground velocity can be measured with pitot tube or GPS without error. The wheels' velocity at the moment of landing are identical.

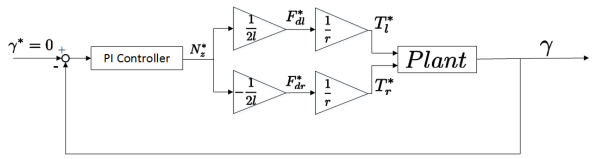


Fig. 8. Block diagram of yaw feedback controller

Table 1. Performance of cessna 172 skyhawk

Definition	Value	Unit
Total Mass M	1000	kg
Yaw Inertia I_{yaw}	2667	kg m^2
Stall Velocity	83.00	km/h
Landing Velocity V	100.0	km/h
Wheel Radius r	0.1520	m
Wheel Mass	7.790	kg
Torque Limit of Wheel	±100.0	N
Wheel Inertia J_w	0.1810	kg m^2
The Rolling Friction Coefficient μ_0	1.000×10^{-4}	-

In the simulation, comparison was made between no control case, and the proposed control case.

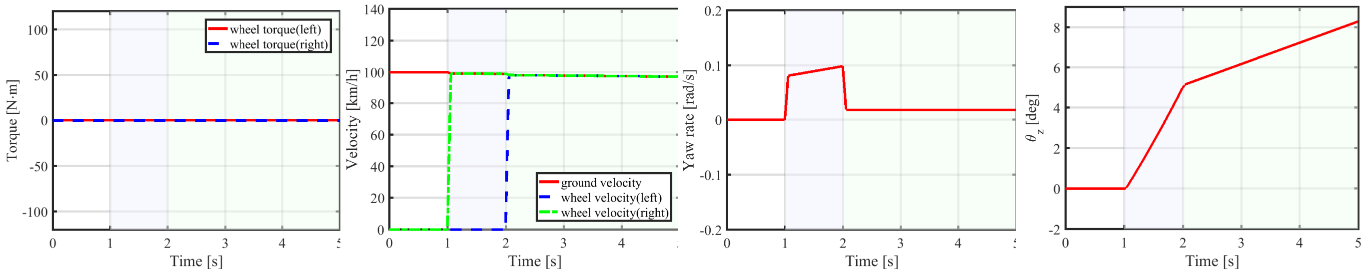
3.2 Results Simulation results are shown in Fig.9, and 10. Fig.9, and 10 from the left shows the velocity, the yaw-rate, and the angle with respect to the runway. Comparing the graph of yaw-rate, up to 0.1 [rad/s] is generated in the case of no control. On the other hand, by applying this method, the yaw-rate can be suppressed to almost zero. Also, the angle with respect to the runway is shifted by eight degrees with respect to the traveling direction after ten seconds in the case of no control. On the other hand with the proposed, then it can be suppressed to almost zero. The aircraft can land without being displaced with respect to the runway.

4. Experiment

This paper has conducted basic experiments to verify whether the yaw-rate is actually suppressed when velocity feed forward controller is performed. The experimental machine is shown in Fig.11, and the performance is shown in Table 2.

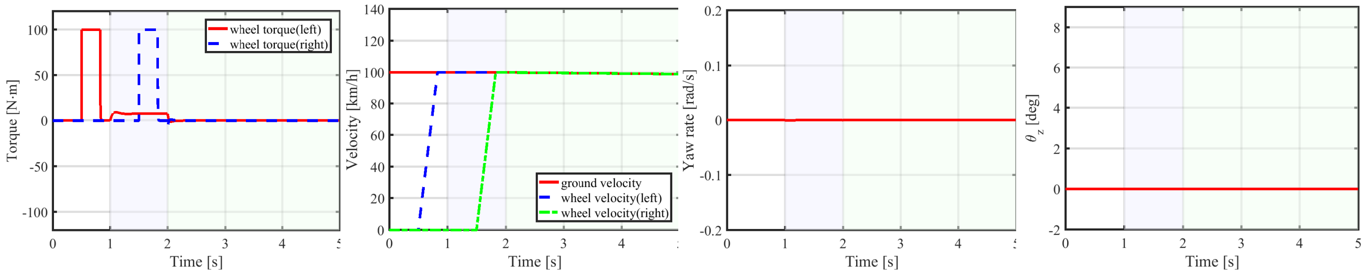
in this section, we use a treadmill to reproduce ground velocity. In order to simulate the landing on one wheel, ropes of different lengths are tied to the wheels and to one higher spot. Then, using the rope, the experiment machine is lifted and positioned it so that only one wheel is in contact with the treadmill. An overview of the experiment is shown in Fig.12.

in this section, the wheel velocity and the aircraft velocity are both set to 0.5 [km/h]. The rotation velocity of the treadmill to 0.5 [km/h]. Experimental results are shown in Fig.13, and Fig.14. In the experiment, the yaw-rate is suppressed when only one wheel is landing, and the landing is started from the time of the shaded part of the figure. Comparing the case without control and the case with control as shown in the figure, the yaw-rate is about 0.8 [rad/s] when there is no control, while the yaw-rate is suppressed when there is control.



(a) Torque (b) Ground and wheel velocity (c) Yaw rate (d) Yaw angle

Fig. 9. Simulation result in case 1 (there is no difference between measured and true value



(a) Torque (b) Ground and wheel velocity (c) Yaw rate (d) Yaw angle

Fig. 10. Simulation result in case 1 (there is no difference between measured and true value) : with control

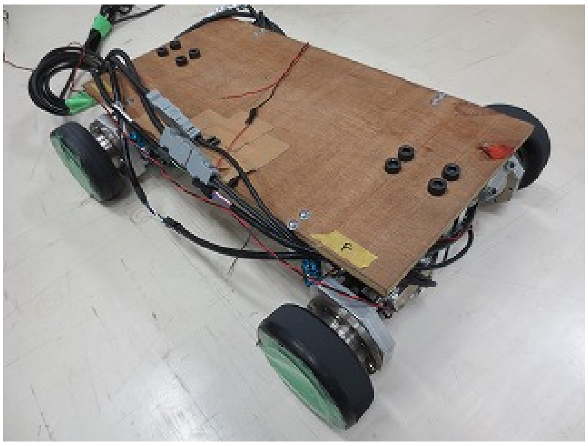


Fig. 11. Experimental device

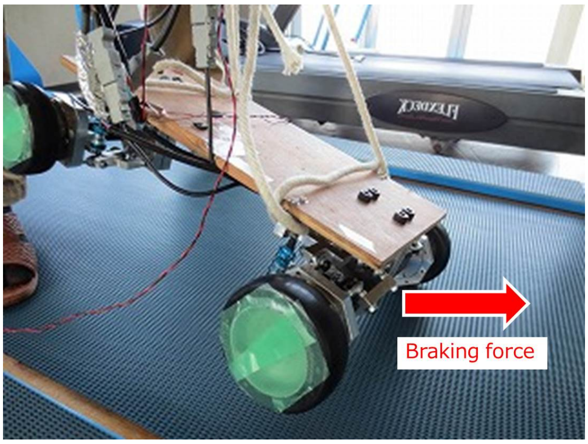


Fig. 12. Overview of experiment

Table 2. Performance of experimental device

Definition	Value	Unit
Total Mass M	7.8	kg
Wheel Radius r	5.0×10^{-2}	m
Maximum Wheel Velocity	1.0	km/h
Wheel Inertia J_w	0.23	kg m^2
Gear Ratio	1:100	-

5. Simulation with difference between measured and true velocity

In this section, the effectiveness of the proposed system in the case where the wheel velocity does not match the measured velocity is shown with a simulation.

Usually, the aircraft uses some measurement to obtain ground velocity, i.e. the pitot tube and GPS [17]. However, the measured velocity and the true value are different because of some causes. Therefore, in this section, we show the effectiveness when applying both the velocity feed forward and the yaw feedback control at the same time when the measured velocity and the true ground velocity do not coincide.

In this simulation, it was assumed that the ground velocity was 95 [km/h], and the electrically driven wheel was operated so that the wheel velocity was 100 [km/h] beforehand using Fig.7. At the moment of landing, which is 1 second after the start of the simulation, the error is corrected by using the yaw feedback represented by Fig.8. The simulation results are shown in Fig.15, and Fig.16.

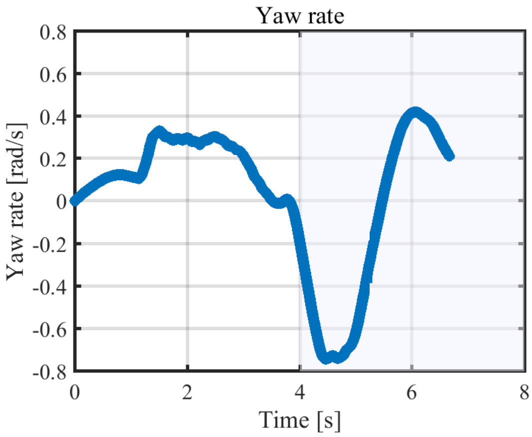


Fig. 13. Experiment result : w/o control

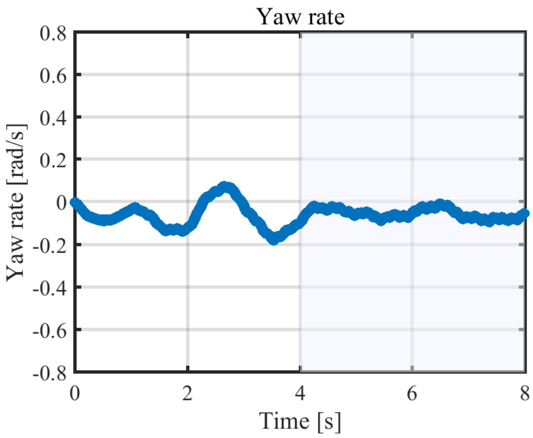


Fig. 14. Experiment result : with control

The case of no control is presented in Fig.15. However, even if the ground velocity can not be obtained accurately due to errors, the simulation result in Fig.16 indicate that the proposed control is effective.

6. Discussion

The experiment conducted in this section was made with the wheel velocity and the aircraft velocity set to 0.5 km/h due to limitations of the experimental machine. However, when compared with the actual aircraft, the velocity difference is large. Therefore, in order to show the effectiveness, it is necessary to carry out the experiment with faster wheel velocity and ground velocity. Therefore, it is necessary to construct the experimental machine corresponding to the faster wheel velocity and to suppress the yaw-rate even under such circumstances.

7. Conclusion

When there are crosswinds during the landing and the aircraft performs a sideslip landing, yaw-rate is generated when only one wheel lands because of lift difference due to crosswind. Therefore, the direction of travel of the aircraft deviates due to the yaw-rate and this can potentially end in an accident. In this paper, we suppress the yaw-rate by adopting electrically driven wheels as landing legs. This method is to make it rotate at as ground velocity before landing. And when landing, feedback control based on yaw-rate sensor is applied. Based on the simulation results, the proposed method showed that the yaw-rate can be suppressed even when there is a difference between the true ground velocity and the measured. We also conducted basic experiments, however we were able to conduct experiments only at slower vehicle velocities than the landing velocity of the aircraft due to the circumstances of the experimental aircraft. For this reason, it is necessary to improve the experimental machine and to make experiments with a higher wheel velocity.

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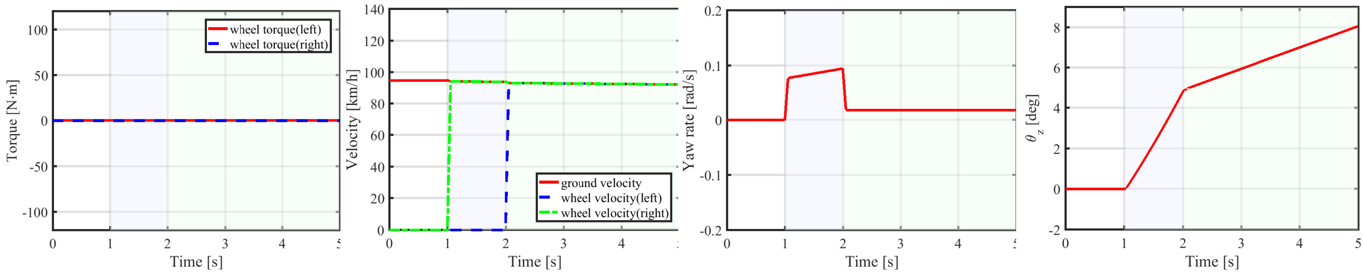
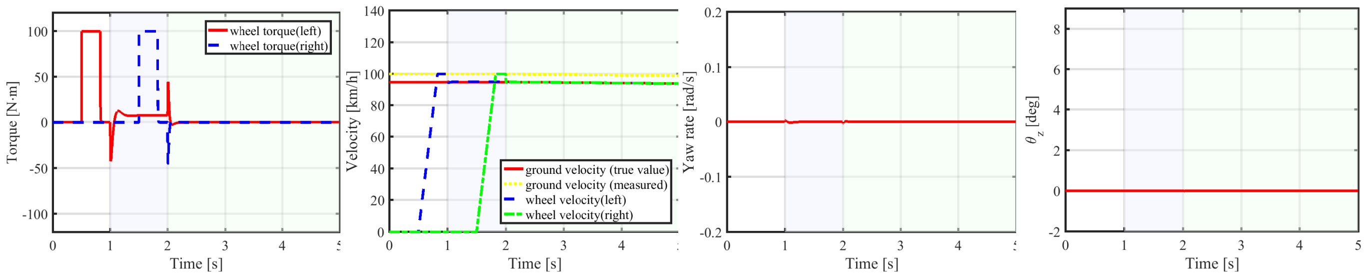


(a) Torque (b) Ground and wheel velocity (c) Yaw rate (d) Yaw angle

Fig. 15. Simulation result in case 2 (there is difference between measured and true value) : w/o control



(a) Torque (b) Ground and wheel velocity (c) Yaw rate (d) Yaw angle

Fig. 16. Simulation result in case 2 (there is difference between measured and true value) : with control

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