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Power Steering System for Electrically Assisted Bicycles Riding with Toddlers -Experimental Implementation and Verification-

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***Abstract*— A bicycle riding with toddlers becomes convenient and indispensable transportation for parents in Japan. On the other hand, the bicycle with toddlers tends to be less-stable when start moving, low-speed biking and abrupt steering because it is hard to steer due to increasing the moment of inertia of the handlebars. Hence this study proposes a power steering system for electrically-assisted bicycles riding with a toddler. The power steering system is designed to allow a rider to steer the handlebars with a toddler as if steer the handlebars without him. The power steering system is mounted on a real bicycle, and its effectiveness is verified through experiments.**

I. INTRODUCTION

A bicycle is useful and indispensable transportation for parents with toddlers in Japan. Since the road traffic law concerned with bicycles has been changed 2009 in Japan, people can ride a bicycle with up to two toddlers as long as the bicycle fulfills the conditions for safety, maneuverability, braking performance, and rigidity of a body frame and handlebars. Bicycle manufacturer are developing bicycles for riding with toddlers fulfilling the conditions [1].

A safety standards require several safe conditions, for example, the strength of a bicycle frame when people rides a bike with toddlers, and stability of the bicycle starting, running and stopping. These requirements mainly focuses on the bicycle structure. However, we claimed that it is not enough and the dynamics of a bicycle should be paid attention to in [2]. The stability of the bicycle, in the case that a toddler sits on the rear seat, becomes worse rather than other situations that a toddler sits on the front seat or toddlers sit on both front and rear seats. As a result, it is better for keeping the stability that a toddler should sit on a front seat. But, the moment of inertia of the handlebars increases when a toddler sits on the front seat, and it causes to deteriorate the maneuverability of the handlebars.

This study aims to develop an electrical assist system for bicycles riding with toddlers to improve safety and maneuverability paying attention to the dynamics variations due to toddlers sitting on seats. The assist system consists of a power steering system and a pedaling assist system. So-called pedaling assist system has been implemented in commercial electrically-assisted bicycles. The system generates auxiliary driving torque according to a rider's pedaling force, and, as a result, assists the rider to bike. The number of commercial electrically-assisted bicycles increases, and is about 200,000 in 2010 which is ten times of the number in 2005. Hence electrically-assisted bicycles are actually popular in Japan. As our previous work concerned with the pedaling assist system, an interesting assist control has been proposed based on a repetitive control, and reduces the driving torque ripple by generating auxiliary torque adequately by a motor [3].

This paper focuses on a power steering system to recover the maneuverability of the bicycle handlebars with a front seat on which a toddler sit. The mechanism is simple, and a motor is mounted to generate auxiliary torque assisting the handlebar operation. Some studies such as [4], [5] modifies the handlebar to which control input is applied. These studies try to control a bicycle autonomously for stabilizing and tracking desired paths. However, this study focuses on support of rider operations. Matsuzawa and Sato design a control system of the power steering system to recover the handlebars dynamics without a toddler even though a toddler sits on the front seat mounted the handlebars. The effectiveness of the proposed control system has been verified through numerical simulations and experiments using a prototype power steering system. As a next step, a power steering system will be mounted to a real bicycle, and will be evaluated practically. However, the power steering system has some points to be fixed for practical experiments.

This paper reports redesign of the power steering system to fix the problems, and demonstrates the effectiveness of the modified one practically. The control implemented to the power steering system is based on a disturbance observer, and recovers the non-mass handlebar dynamics even though some mass instead of a toddler is practically put on the front seat. Frequency response analysis and numerical simulations are performed to evaluate the modified power steering system, and its effectiveness is verified though experiments by an electrically-assisted bicycle with the proposed power steering system.

II. EXPERIMENTAL SYSTEM OF ELECTRICALLY-ASSISTED STEERING FOR BICYCLE

This research begins with a simple and experimental steering simulator shown in Fig. 1, which has the same structure with the real one. In this paper, under the situation, the dynamics is analyzed with the steering simulator, a control law based on a disturbance observer designed.

A. Prototype of power steering system

A schematic figure in Fig. 2 depicts the structure of the steering system. This steering system consists of a motor,

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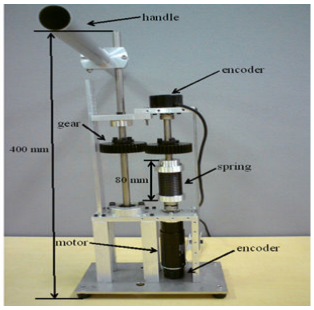


Fig. 1. The photo shows the simple and experimental steering simulator which has the same structure with the real electrically-assisted steering system.

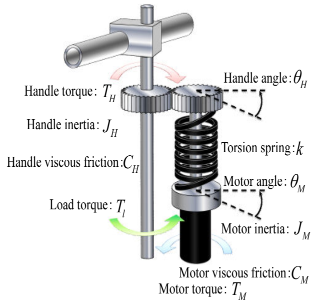


Fig. 2. The schematic figure shows the structure of the simple steering simulator. This system consists of a motor, a torsional spring, gears, and encoders.

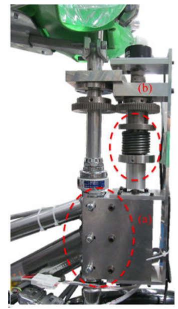


Fig. 3. The photo shows the early-type power steering system.

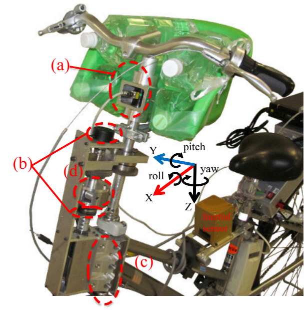


Fig. 4. The photo shows the modified power steering system.

a spring, two gears and two encoders. Each encoder can measure the handlebars and the motor rotational angle, respectively. The torsional spring is attached between the motor output axis and the gear connected to the handlebars axis. Hence the spring plays two important roles. The first role implies if the difference between those angles is measured, the torque applied to the spring can be estimated without any other sensors. The second is that the elasticity permits a driver to control the handlebars manually if the actuator was broken and locked.

The set of equations of motion of the steering simulator is derived by the physical modeling procedure. It follows that

$$J_M \ddot{\theta}_M = T_M - k(\theta_M - \theta_H) - C_M \dot{\theta}_M, \quad (1)$$
$$J_H \ddot{\theta}_H = T_H - k(\theta_M - \theta_H) - C_H \dot{\theta}_H - T_\ell, \quad (2)$$

where θ_M and θ_H is the motor and the handlebars rotational angle, respectively. T_M is the torque generated by the motor, and T_H is the torque applied by the rider. J_M and C_M is the moment of the inertia, and the viscous friction coefficient around the motor rod. J_H and C_H is around the handlebars rod. k is the spring constant of the torsional spring, and T_ℓ shows the ground reaction torque.

B. Early-type power steering system

An early-type power steering system has been developed based on the prototype system. The early-type system is shown in Fig. 3. It had two problems considered. One of the problems was concerned with its mount parts at Fig. 3 (a). The mount parts were loose, and could not to rivet the power steering system to the bicycle body. The other was concerned with the torsional spring at Fig. 3 (b). A pair of the spring holder was difficult to be realized because the length of the torsional spring deformed when the spring was twisted. Moreover, the elastic modulus of the spring influenced the control system performance, and therefore it was necessary that several springs with different elastic modulus were prepared to choose an adequate spring from the control viewpoint. However it was difficult to change a spring due to the pair of the holder. These issues drove us to make a new and improved power steering system.

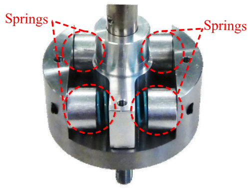
C. Modified power steering system

An improved power steering system is redesigned by modifying the early-type one. The system is shown in Fig. 4. The main modification is to redesign a spring system. The details of the spring mechanism is explained in the next subsection. As other modifications, two high-resolution rotary encoders are attached to both side of the spring system as shown in Fig. 4 (b). These encoders improve the measurement accuracy of the torsional angle of the spring system. A torque sensor is installed in the shaft of the handlebars additionally as shown in Fig. 4 (a). This sensor is used to measure the torque applied by the rider for verification of the proposed power steering system. The applied torque with the power steering system will be less than one without the power steering system if a toddler sits on the front seat fixed at the handlebar shaft. The parts to mount the power steering system on the bicycle is remanufactured, and the system is mounted rigidly as in Fig. 4 (c).

D. Modified Spring mechanism

The spring used in the early-type power steering is just a torsional spring. There are two problems; it is hard to hold and grasp the spring due to deformation of the length of the spring twisted, and is difficult to change a spring with a different elastic modulus due to the holder structure. A modified spring system is redesigned as shown in Fig. 5 to overcome these problems. This spring mechanism has four small springs arranged in the horizontal space as Fig. 5. It has a good advantage that the deformation of the spring length is not necessary to be considered.

These small springs can be detached, and changed easily. Hence we can make an experiment used springs with different elastic modulus readily. We prepare two types of springs; type A with the elastic modulus, 2.9 N·mm, and type B with 7.0 N·mm. The elastic modules of the entire spring system with the type B springs is identified through a preliminary experiment. The identification result is demonstrated in Fig. 7. It shows that the spring mechanism plays a role as a torsional linear spring. The identified elastic modulus with the type A spring is 16.0711 N·m/rad, and one with the type B is 33.6805 N·m/rad.



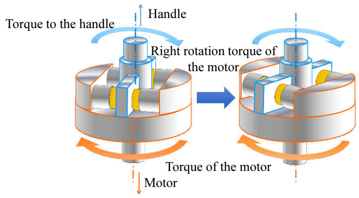


Fig. 5. The photo shows the modified spring mechanism. It has four small springs arranged in the horizontal plane.

Fig. 6. The schematic figure depicts the spring mechanism. The motor torque is transmitted through the mechanism with elastic deformation of the small springs.

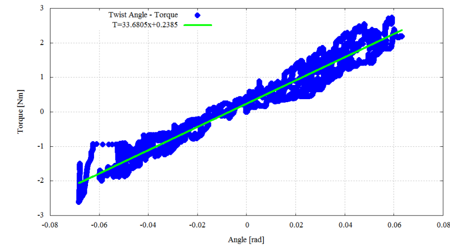


Fig. 7. The graph shows the spring effect between twist angle and torque of the modified spring mechanism. As the result, the spring mechanism can be regarded as a linear spring.

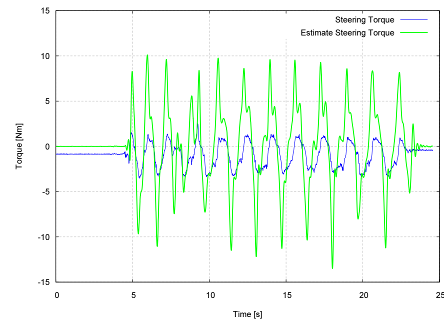


Fig. 8. The graph shows the estimated steering torque and the measured one for comparison. The green line is the estimated torque, and the blue one is the measured one.

E. Evaluation of estimated steering torque

The power steering system requires the information on steering torque applied by a rider for generating auxiliary assistant torque. A torque sensor can measure the steering torque easily, however it cannot be practically retrofitted from the cost, complexity and intensity viewpoints. Hence, an estimation method of the steering torque has been proposed in [6] as the previous work. In [6], the prototype power steering system was used for evaluation. On the other hand, this study uses a real power steering mounted on a bicycle. The proposed measurement method is evaluated to compare the estimation torque and the measured one by the torque sensor installed in the handlebar shaft.

The steering torque estimator is given by (3)

$$\hat{T}_H(s) = Q(s)G_H{}^{-1}(s)(-G_M(s)T_M(s) + \theta_H(s)) \qquad (3)$$

where $G_H(s)$ is the transfer function with a mass instead of a toddler from the input torque applied by the rider, T_H, to the handlebars angle, $\theta_H(s)$. $G_M(s)$ is the transfer function from the motor torque $T_M(s)$ to the handlebars angle. $Q(s)$ is a low-pass filter with adequate relative degree to let $Q(s)G_H^{-1}(s)$ and $Q(s)G_R^{-1}(s)$ proper.

The estimated steering torque by (3) is evaluated compared with the steering torque measured by the retrofitted sensor. The evaluation is performed using the profile of the steering angle and the steering torque when the handlebars is steered counterclockwise and clockwise. The profiles of the estimated steering torque and the measured one are depicted by Fig. 8. Fig. 8 illustrates that the steering torque can be effectively estimated by (3). However, we can see some phase shift between the estimated value and measured one, and the peak of the estimated torque is larger than the real one. We suppose that the reason is due to the static friction when the steering direction changes. The estimation error will be corrected as a future study.

III. Preliminary Experiment of Power Steering System under Proportional Control

A preliminary experiment is conducted to verify the possibility that the power steering system assists the rider's operation of the heavy steering handlebars. The power steering method is based on a proportional control to the steering torque applied by the rider. The steering torque applied by the rider cannot be measured in the practical case because we suppose no torque sensor is retrofitted to the handlebars. Therefore the proportional control cannot be used in the practical case. On the other hand, the current power steering system has a torque sensor for evaluation of the proposed assist system. Hence the preliminary experiment uses the torque sensor just for verification of the possibility. In the practical situation, the estimated steering torque is used instead of the measured torque.

The possibility of the power steering system is verified though slalom biking experiments as shown in Fig. 9. The steering torque applied by the rider, the roll angle of the bicycle body and its angular velocity are measured. The torque, angle and angular velocity in the case of slalom biking under a proportional control is compared with ones under no proportional control. The profiles under the proportional control are shown in Fig. 10, and ones under no control are shown in Fig. 11. The steering torque under the proportional control tends to be smaller than the one under no control because the power steering system generates the auxiliary torque adequately. The body roll angle and the angular velocity under the control are in the same tendency. Hence the preliminary experiments illustrates the power steering system can assist the steering of the heavy handlebars, and can reduce the bicycle wobbling caused by the heavy handlebars. In the following section, we will derive a control system based on a disturbance observer, which doesn't require the steering torque information of the rider, instead of the proportional control.

IV. Control System Design

A control law is proposed for the power steering system. The control law is designed to recover the dynamics of

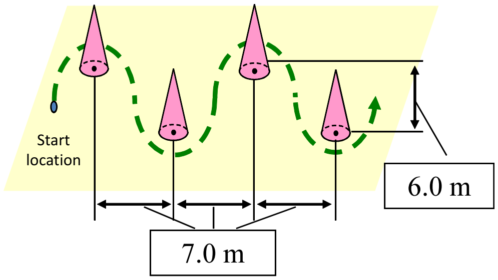


Fig. 9. The schematic figure illustrates slalom biking conditions.

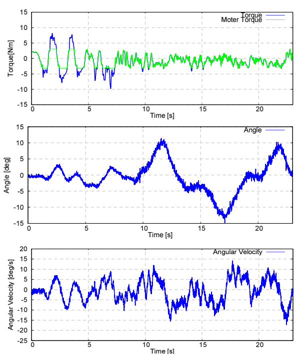


Fig. 10. The upper graph shows the estimated steering torque and the measured torque. The middle and lower graph shows the roll angle and angular velocity of the bicycle body, respectively. All graphs are in slalom biking experiment under assist control.

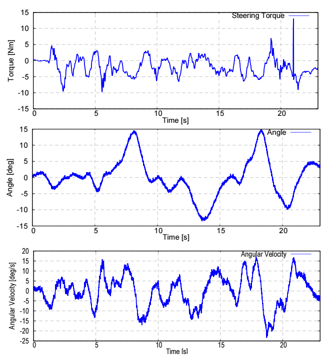


Fig. 11. The upper graph shows the estimated steering torque and the measured torque. The middle and lower graph shows the roll angle and angular velocity of the bicycle body, respectively. All graphs are in slalom biking experiment under no assist control.

the handlebars when a toddler doesn't sit on the front seat even though a toddler actually sits on the front seat. The control law is realized by utilizing a disturbance observer. Its block diagram is illustrated in Fig. 12. In Fig. 12, a controller, $G_c(s)$, is derived so that the closed-loop transfer function from $T_H(s)$ to $\theta_H(s)$ is equivalent to the ideal transfer function $G_R(s)$. $G_R(s)$ shows the dynamics of the handlebars when a toddler doesn't sit on the front seat. $G_H(s)$ is the transfer function from the steering torque $T'_H = T_H - T_l$ to $\theta_H(s)$, and $G_M(s)$ is the transfer function from the motor torque $T_M(s)$ to $\theta_M(s)$. The low-pass filter $Q(s)$ is given by (4) with the cut-off frequency ω_c

$$Q(s) = \frac{1}{\left(\left(\frac{s}{\omega_c}\right)^2 + 0.7654\left(\frac{s}{\omega_c}\right) + 1\right)\left(\left(\frac{s}{\omega_c}\right)^2 + 1.8748\left(\frac{s}{\omega_c}\right) + 1\right)} \tag{4}$$

This control system supposes that air resistance, gyro moment, road friction and load torque are included as disturbances, T_ℓ. On that basis, the control system controls the motor torque $T_M(s)$ to let the steering torque $T'_H(s)$ equivalent to the steering torque which should be applied to the handlebars with no toddler. Moreover the torque sensor for measuring the steering torque is not available in the practical case. Hence the estimated steering torque, $\hat{T}_H(s)$, is used in the control system.

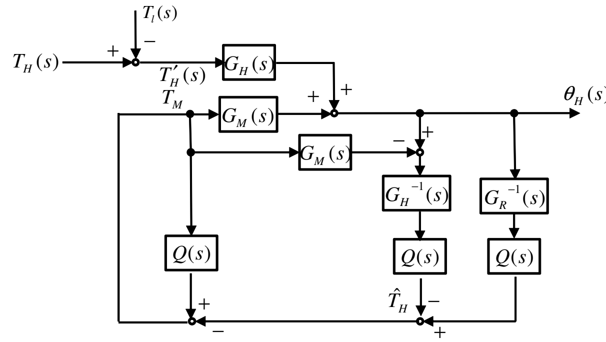


Fig. 12. The block diagram shows the assist control system based on the DOB.

The closed-loop transfer function is derived. The steering angle is given by (5),

$$\theta_H(s) = G_H(s)T'_H(s) + G_M(s)T_M(s) \tag{5}$$

The estimated steering torque, $\hat{T}_H(s)$, is given by (6)

$$\hat{T}_H(s) = Q(s){G_H}^{-1}(s)\left(\theta_H(s) - G_M(s)T_M(s)\right) \tag{6}$$

The motor torque, $T_M(s)$, is represented using $\hat{T}_H(s)$ as

$$T_M(s) = (1 - Q(s))^{-1}\left(\hat{T}_H(s) - {G_R}^{-1}(s)\theta_H(s)\right) \tag{7}$$

The estimated torque, $\hat{T}_H(s)$, is substituted into (5) instead of the true torque, $T'_H(s)$.

$$\theta_H(s) = \frac{G_H(s) - Q(s)G_H(s) + Q(s)G_M(s)}{1 - Q(s) + Q(s)G_M(s){G_R}^{-1}(s)} T'_H(s) \tag{8}$$

When the gain of the low-pass filter Q over the frequency range where a rider manipulates the handlebars is equal to 1, (8) is reduced to (9),

$$\theta_H(s) = G_R(s)T'_H(s) \tag{9}$$

(9) demonstrates the proposed control system realizes the closed-loop transfer function equivalent to the ideal transfer function, $G_R(s)$ from the steering torque to the handlebars angle when no toddler sits on the front seat.

V. Evaluation for Control System

The control system designed in the previous section is evaluated by frequency response and numerical simulation.

A. Frequency response analysis

The frequency analysis of the closed-loop system in (8) is performed to confirm the ideal transfer function should be recovered by the proposed controller. To conduct the evaluation, the cut-off frequency of $Q(s)$, ω_c has to be decided. Hence ω_c is set 25 Hz. Other physical parameters are set values in Table I.

The bode plot of the transfer function from the steering torque, (8), to the steering angle is shown in Fig. 13. The solid line depicts $G_R(s)$, the dotted line $G_H(s)$, and the dashed line illustrates the frequency response of (8). The upper graph shows the gain diagram, and the lower shows the phase diagram. As shown in Fig. 13, the closed-loop

TABLE I
PHYSICAL PARAMETERS USED IN THE SIMULATION

J_H	0.783815	J_M	0.002975
C_H	0.340948	C_M	0.002530
f_H	0.269411	f_M	0.095591
J_R	0.022394	C_R	0.006992
f_R	0.009039	k	33.6805

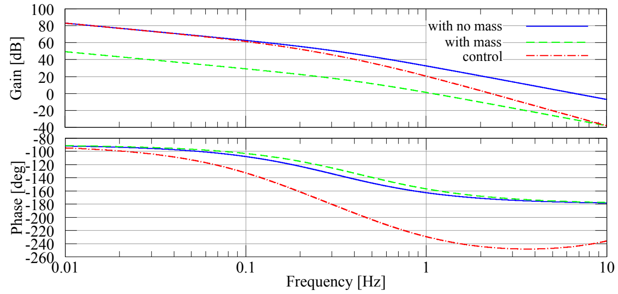


Fig. 13. The graph shows the bode diagram of the transfer function of (8). The blue line is with no mass. The green line is with mass. The red line is of the closed-loop.

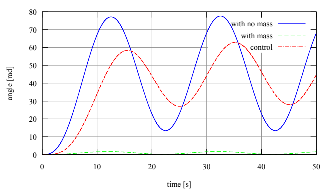


Fig. 14. The graph shows the simulation results of the steering angle. The blue line is with no follow toddler. The green line is with a toddler. The red line is of the closed-loop.

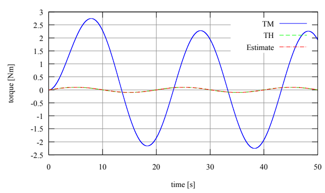


Fig. 15. The graph shows the simulation results of the steering torque. The blue line is the assist-motor torque. The green is steering torque. The red is a estimated torque.

frequency response recovers the response in the case of non-toddler. Especially the gain of the closed-loop is almost same with the ideal one until 0.2 Hz. The phase is delayed slightly compared with the ideal one. However, when the rider slowly steers the handlebars as normal, the closed-loop system behaves in the almost same way as the ideal case.

B. Numerical Simulation

Some numerical simulations are conducted to verify the effectiveness of the control system for the power steering assist. The profile of the handlebars angle with a follow toddler should be different from the one with no follow toddler even though the same steering torque is applied by the rider. However the proposed controller for the power steering system can realize the profile of the handlebars with no follow toddler. Additionally (6) should estimate the applied steering torque. To verify those points, the following simulations are conducted. The simulation period is set 50 sec, the sampling interval is 1 msec, and the all initial state is 0. The simulation results are shown in Figs. 14 and 15.

The line style in Fig. 14 is in the same way as Fig. 13. In Fig. 15, the solid line is of the motor-assist torque, the doted line is of the rider's steering torque, and the dash line is of the estimated steering torque. These results demonstrates the dynamics of the closed-loop can be recovered.

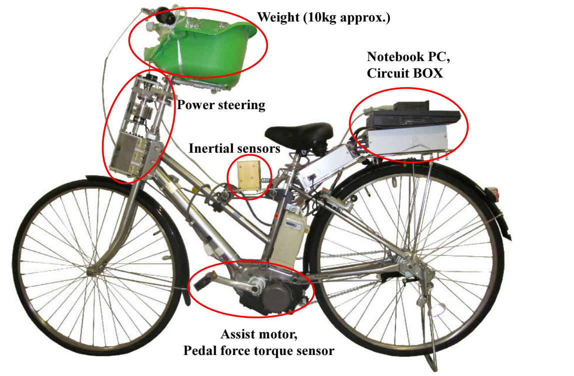


Fig. 16. The photo shows the power-assist bicycle equipped with the power steering system.

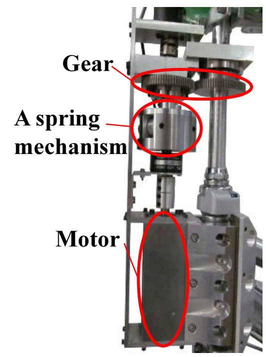


Fig. 17. The photo shows the power steering system including the developed spring mechanism.

VI. EXPERIMENTS AND VERIFICATION USING PRACTICAL BICYCLE WITH POWER STEERING SYSTEM

The control system for the power steering system proposed in the previous section is implemented to a practical bicycle experiment apparatus. The bicycle apparatus equips the power steering system, various sensors, electrical circuits and computers as shown in Fig. 16. Some mass is mounted to the front seat instead of a toddler. An inertial sensor can measure the posture of the bicycle in 6 DOF. The body roll angle and angular velocity in the posture are used for evaluation of the wobbling. The power steering system developed in this study is presented in Fig. 17. The spring mechanism is installed to the power steering system.

The effectiveness of the proposed power steering system is verified though the following experiments. The steering angle, steering torque applied by the rider, and the auxiliary torque generated by the power steering system are measured. Those measurements are used for comparison and evaluation. A rider steers the handlebars 30 degrees counterclockwise, clockwise alternately under different three conditions:

- Condition 1: Put no mass and assist-off.
- Condition 2: Put 10 kg mass and assist-off.
- Condition 3: Put 10 kg mass and assist-on.

Experimental results in each condition are shown in Figs. 18-21, respectively. In Fig. 18 and 19, the upper graphs indicates the measured steering angle. The lower graphs

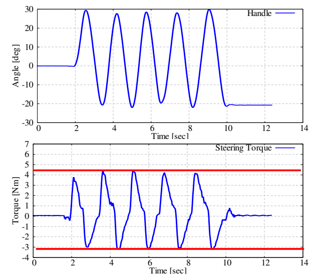


Fig. 18. The graph shows the steering angle and steering torque in the condition 1.

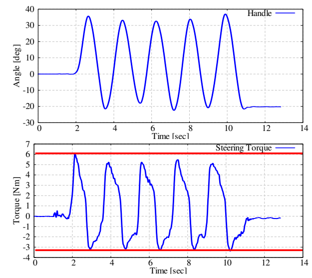


Fig. 19. The graph shows the steering angle and steering torque in the condition 2.

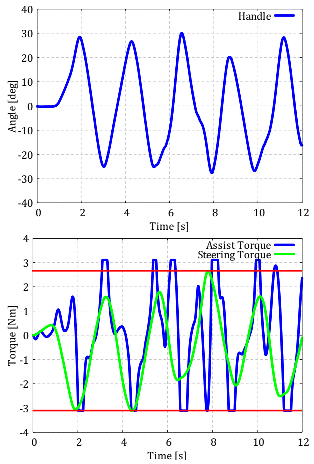


Fig. 20. The graph shows the steering angle, steering torque and assist-torque in the condition 3.

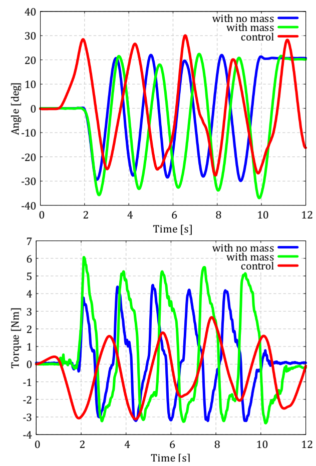


Fig. 21. The graph shows the steering angle and steering torque in the conditions 1 to 3.

indicates the measured steering torque. The steering torque in the condition 2 is within -3 to 6 Nm, and the torque in the condition 1 is within -3 to 4 Nm. Comparing the torque in the condition 2, Fig. 19 with the one in the condition 1, Fig. 18 obviously leads that the steering torque in the condition 2 is larger than the torque in the condition 1.

Fig. 20 in the condition 3 demonstrates the steering torque is reduced to the same range of the condition 1 even though 10 kg mass is mounted to the front seat. Fig. 21 illustrates the comparison among the condition 1, 2, and 3. The graph obviously the steering torque in the case of the assist-on is reduced. These experimental results demonstrates the proposed power steering system based on the disturbance observer works effectively, and the steering torque is reduced even though a mass is mounted to the front seat.

VII. Conclusion

The power steering system for electrically assisted bicycles with toddlers has been proposed in this study. The power steering system is useful for assisting a rider to steer the handlebars whose moment of inertia is increased. A control law based on the disturbance observer technique can recover the dynamics of the handlebars without toddlers. This advantage has been illustrated by numerical simulations and frequency response analysis. The power steering system with the control law has been mounted on a real electrically assisted bicycle. The effectiveness has been shown by experiments in that some weights instead of toddlers are put on the seat of the handlebars. As a result, the steering torque with the power steering system is less than that without the steering system. As future works, more practical cases should be considered. For example, a toddler is usually moving on the seat. Hence the wobble of COG of the mass on the seat should be taken into account. Because of the fact, some parameter variations of the bicycle model are observed. The power steering system should assist a rider adequately even if those parameter variations occur. Finally the power steering system should cooperate with an assist system for pedaling. A total assist system will be designed to provide a more safety bicycle with toddlers.

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