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Capacitor Regenerative Braking System of Electric Wheelchair for Senior Citizen based on Variable Frequency Chopper Control

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***Abstract*— This paper proposes a novel regenerative braking control system of electric wheelchairs for senior citizen. "Electric powered wheelchair", which generates the driving force by electric motors according to the human operation, is expected to be widely used as a mobility support system for elderly people. This study focuses on the braking control to realize the safety and smooth stopping motion using the regenerative braking control technique based on fuzzy algorithm. The ride quality improvement and energy recycling can be expected by the proposed control system with stopping distance estimation and variable frequency control on the step-up/down chopper type of capacitor regenerative circuit. Some driving experiments confirm the effectiveness of the proposed control system.**

I. Introduction

ELDERLY people and disabled people who have difficulty in walking are increasing. As one of mobility support for them, the significance of "electric powered wheelchair" and "electric power assisted wheelchair" which assist driving force using electric motors on both wheels and spreads their areas of life has been recently enhanced [1].

Advanced motion control for electric powered wheelchairs and electric power assisted wheelchairs can be one of the important elements for supporting elderly people and physically handicapped people and has great possibilities to contribute in various cases. In such control systems, toward the practical use, the user-friendly operation and driving quality should be further improved considering the human's sense and driving environments.

Some types of wheelchairs can be defined according to the human interface devices and using forms. One is the joystick driving type of wheelchairs and the human operators can give the driving command such as the direction and velocity through the joystick [2][3]. The other is the caregiver operation type of electric wheelchairs and it can be controlled by measuring or estimating the caregiver's operation force from the rear side of the wheelchair [4][5][6]. The rider type of electric power assisted wheelchair is also the remarkable vehicle for elderly people and physically handicapped people and some advanced driving control schemes have been presented [7]-[15] such as the driving trajectory design and the stable and well-balanced straight and circular road driving control.

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This paper focuses on the rider operation type of electric powered wheelchair for senior citizen and its advanced motion control system. The rider operates the handlebar and acceleration lever for himself/herself and the driving torque is generated according to the human operation. Fig.1 shows the photograph of electric powered wheelchair for senior citizen developed by Suzuki Motor Corporation.

Fig. 1. Photograph of an electric wheelchair for senior citizen.

The idea of the regenerative braking is one of the important factors for the advanced motion control of mobility systems and has been applied mainly to trains and electric vehicles in order to obtain the braking power and to realize the efficient energy management (ECO vehicle) [16][17][18]. The regenerative braking can be also applied to electric wheelchairs and the authors verified the effectiveness of the regenerative braking control system with variable duty ratio as the first step to realize the safety driving on downhill roads [19]. The priority is to suppress the excessive velocity for the safety driving with the good ride quality and it is better if much energy saving also can be realized.

This paper proposes a novel variable frequency chopper control based capacitor regenerative braking system of electric wheelchairs for senior citizen to realize the safety and smooth stopping motion on flat roads. The proposed control system applies the fuzzy algorithm and it will be effectively applied to both the stopping distance estimation and the variable frequency control. Some basic driving experiments will be conducted using the experimental wheelchair to verify the effectiveness of the proposed system.

II. Braking Control of Electric Wheelchair for Senior Citizen

This type of electric wheelchairs for senior citizen shown in Fig.1 has only one human interface device for acceleration and deceleration. It is the acceleration lever shown in Fig.2. If the acceleration lever is pushed down, the electric wheelchair will be accelerated according to the degree of pushing the lever. If the acceleration lever is released, the electric wheelchair will be decelerated. Fig.3 shows the linear relationship between acceleration lever output voltage and angle. Acceleration lever output is calculated from Eqn.(1).

$$L(a) = (L_{max} / A_{max}) \times a \tag{1}$$

$L(a)$ is the acceleration lever output voltage, A_{max} is the maximum angle, L_{max} is the acceleration lever output when pushed down perfectly, a is angle of acceleration lever. The lever angle can be measured. Fig.4 shows an example of acceleration lever operation. As voltage output human intent can be read out by integration of acceleration lever operation shown Fig.4. Integration of acceleration lever output value is calculated from Eqn.(2).

$$I = \int_{T-1}^{T} L(t)dt \tag{2}$$

I is integration value. T is the time when the lever is released perfectly. The large integration value from $T-1$ to T means sudden braking and the small value means slow braking.

Fig. 2. Acceleration lever.

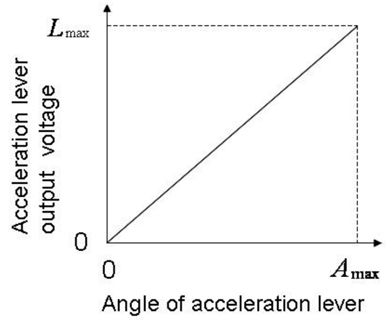


Fig. 3. Relationship between acceleration lever angle and output voltage.

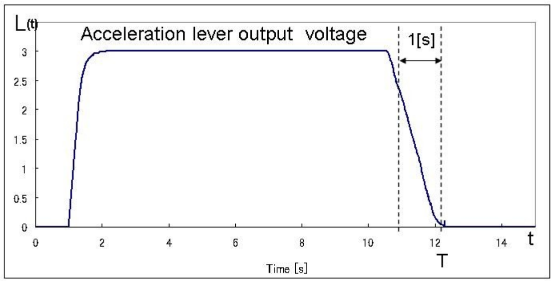


Fig. 4. Example of acceleration lever operation.

Fig.5 shows the acceleration data when the human operator released the lever at time t=8[s]. The deceleration value during stopping motion is too large due to the large braking power and it definitely gives discomfort to the operator. Therefore, more stable and smooth stopping motion should be realized to improve the ride quality.

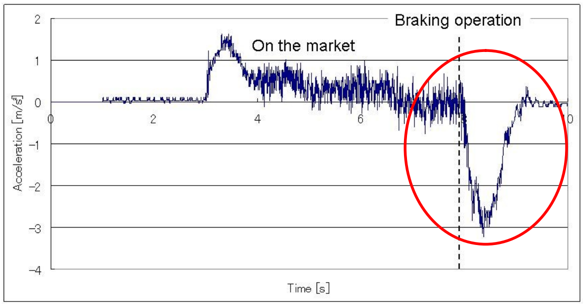


Fig. 5. Acceleration data of the stopping motion using the electric wheelchair on the market.

In the braking control of electric wheelchairs, mechanical braking systems have been generally used, however, some electrical braking systems are also expected to be applied for the purpose of the continuous braking power control. This study aims at realizing the stable and smooth stopping motion considering the acceleration lever operation and also improving the electrical energy efficiency. Thus the capacitor regenerative braking technique will be applied to the stopping motion control. It is expected to realize the continuous control of braking power and also to improve the energy efficiency. Fig.6 shows the ultra capacitor applied to the chopper control system. Recently, ultra capacitors are expected as new batteries and often applied to electric vehicles. Capacitors have many advantages such as long life time and friendliness to the environment.

Fig. 6. Ultra capacitor.

III. Regenerative Braking Control Using Step-up /Down Chopper Circuit

It is true that the proper velocity control or torque control system can be applied to the velocity adjustment for the safety and smooth stopping motion, but the regenerative braking system is comparatively expected to surely and efficiently decrease the wheelchair's velocity. The energy saving function is also very important because the wheelchair is driven only by the battery power. Therefore, this paper proposes a stopping motion control scheme based on the capacitor regenerative braking system.

When driving by inertia, the electric motor externally receives the rotating force and it can be regarded as the power generator, therefore, the braking force can be obtained and also energy. Then the step-up/down circuit shown in Fig.7 is required to realize the capacitor regenerative braking because the regenerative voltage should be adjusted according to the capacitor's state-of-charge. The step-up/down chopper can be designed by the reactance L, diode and switching device like FET. The device is switched by the gate signal with duty ratio d and switching frequency f. The determination of the reactance L and the gate signal with duty ratio d is generally quite difficult. Then the size and weight of the regenerative braking system are necessarily limited in case of compact wheelchairs because it has to be carried on wheelchairs, therefore in this study, the reactance L is designed as a small value, L = 550[μH], and the gate signal with duty ratio d is adjusted as a large value, $d = 0.9$. In addition, the braking power can be obtained due to the capacitor current and motor current and this study confirmed that the braking power can be controlled by frequency and the larger braking power can be obtained by smaller frequency. Fig.8 shows the examples of the motor current and gate signal when f = 0.5[kHz]. Fig.9 shows the examples of the motor current and gate signal when f = 10[kHz]. These figures clearly show that the small frequency brings the larger motor current, therefore, the braking power can be changed by adjusting the gate signal frequency.

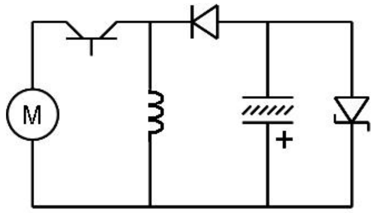


Fig. 7. Configuration of step-up/down chopper circuit.

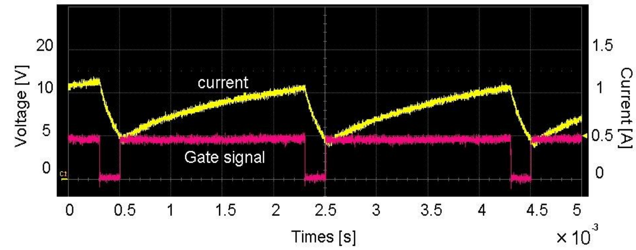


Fig. 8. Motor current and gate signal when f = 0.5 [kHz].

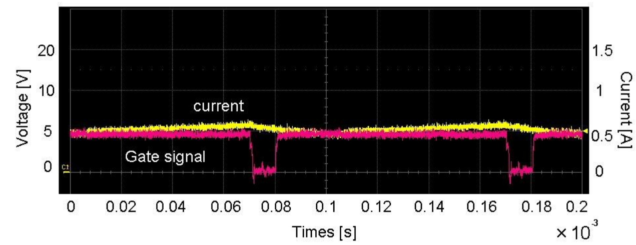
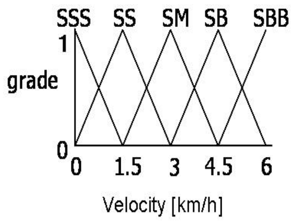


Fig. 9. Motor current and gate signal when f = 10 [kHz].

IV. Stopping Distance Estimation Based on Fuzzy Algorithm

The human operator's input signal to the acceleration lever, for example, quick braking or slow braking, should be considered for the stopping motion control. Therefore this study estimates the stopping distance of the wheelchair using the human input information to the lever.

It is difficult to model the characteristics from lever operation and velocity to the stopping distance, therefore, this study applies fuzzy algorithm which never needs the characteristics modeling and can be easily designed by human's sense and experience. The proposed fuzzy control system applies "Min-Max" method. Fig.10 shows the triangular fuzzy variable for the fuzzy variables of wheelchair's velocity which is expressed by the symbols SSS, SS, SM, SB and SBB. The vertical axis shows the grade value from 0 to 1. The horizontal axis shows the velocity. Fig.11 shows the triangular fuzzy variable for the integration value of the lever output voltage which is expressed by the symbols ASS, AS, AM, AB and ABB. The horizontal axis shows the normalized integration value of the lever output voltage. In this variable, SSS is very small and SBB is very large. Table.1 shows the proposed fuzzy rules and the grade values of twenty five variables are determined by "Min" method. Thus, those grade values of five grade values DSS, DS, DM, DB and DBB are determined by "Max" method. Then the stopping distance is estimated by calculating the center of math in Fig.12. In this study, the stopping distance is estimated from 1.8[m] to 2.5[m].



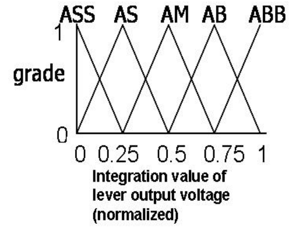


Fig. 10. Triangular fuzzy variable for wheelchair's velocity.

Fig. 11. Triangular fuzzy variable for integration value of lever output voltage.

	SSS	SS	SM	SB	SBB
ASS	DS	DS	DSS	DSS	DSS
AS	DM	DM	DS	DS	DS
AM	DB	DM	DM	DM	DM
AB	DBB	DB	DB	DB	DB
ABB	DBB	DBB	DB	DBB	DBB

Table. 1. Proposed fuzzy rules to infer stopping distance.

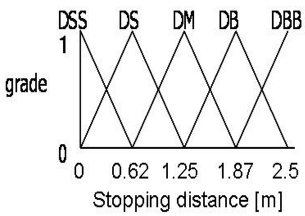


Fig. 12. Triangular fuzzy variable for stopping distance.

Once the stopping distance is estimated, the braking power will be suitably adjusted so that the wheelchair stops at the estimated position. The next chapter will describe the braking power adjustment control scheme based on fuzzy algorithm.

V. Fuzzy Algorithm Based Braking Control With Variable Frequency

The capacitor regenerative braking control can be realized by the step-up/down chopper circuit shown in Fig.7, and the braking power can be adjusted by the frequency of the gate signal. The frequency of the gate signal is also determined by fuzzy algorithm. It is difficult to model the characteristics from the variable frequency to the remainder of driving distance and wheelchair's velocity, therefore, this study applies fuzzy algorithm which never needs the characteristics modeling and can be designed by human's sense. Fig13 shows triangular fuzzy variable for the remainder of driving distance. The remainder of driving distance can be obtained by subtracting the driving distance from the estimated distance. This chapter's fuzzy algorithm uses two fuzzy variables, wheelchair's velocity and the remainder of driving distance, shown in Fig.10 and Fig.13. Table.2 shows the proposed fuzzy rules to infer the frequency. As well as the last chapter, the fuzzy control system applies "Min-Max" method. Fig.14 shows the triangular fuzzy variable for frequency.

Fig.15 shows the configuration of the proposed whole control system.

The enclosed part by dotted line as shown in Fig.15 expresses the fuzzy algorithm in last chapter. The stopping distance is estimated by using this fuzzy algorithm at the braking operation only once. The fuzzy algorithm for determining the frequency is used in the feedback control system as shown in Fig.15.

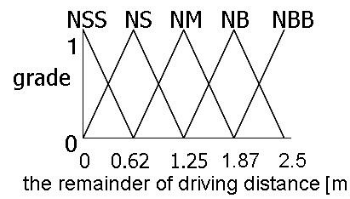


Fig. 13. Triangular fuzzy variable for the remainder of driving distance.

	SSS	SS	SM	SB	SBB
NSS	PB	PBB	PBB	PBB	PBB
NS	PM	PM	PB	PBB	PBB
NM	PS	PM	PM	PB	PBB
NB	PSS	PS	PM	PB	PB
NBB	PSS	PSS	PS	PM	PM

Table. 2. Proposed fuzzy rules to infer the frequency.

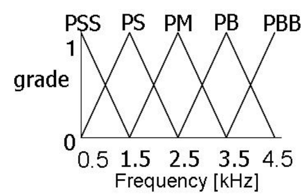


Fig. 14. Triangular fuzzy variable for frequency.

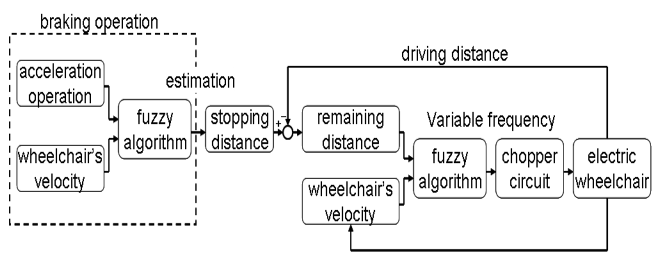


Fig. 15. Configuration of the proposed whole control system.

VI. Driving Experiments

The effectiveness of the proposed capacitor regenerative braking system of electric wheelchair based on variable frequency chopper circuit will be verified through some basic driving experiments on the practical flat road. Fig.16 shows the experimental setup of electric wheelchair for senior citizen and Fig.17 shows the configuration of the experimental setup. H8 is microcomputer, and the variable frequency is outputted by H8 as shown in Fig.17. Fig.18 shows a scene of the driving experiment. Rotary encoder and acceleration sensor are installed in the electric wheelchair to measure the electric wheelchair's velocity and acceleration. The electric wheelchair is controlled by the PC with advanced-real-time OS, called ART-Linux as shown in Fig.17.

In this experiment, as the first step in the driving experiment, the driving course is made by the straight on flat loads, and electric wheelchair for senior citizen is operated by a young able-bodied subject.

Fig. 16. Experimental setup.

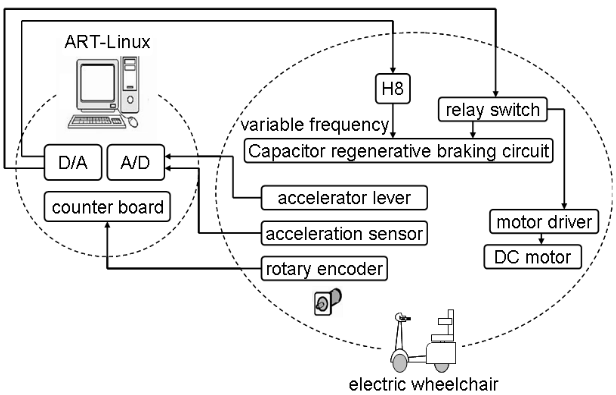


Fig. 17. Configuration of the experimental setup.

Fig. 18. Overview of the driving experiment.

Fig.19 shows the driving experimental results when the acceleration lever is operated slowly. The vertical axis shows the wheelchair's velocity, acceleration and driving distance. The horizontal axis shows the driving time. The vertical line at t=12[s] in Fig.19 indicates the braking timing by the operator, and the horizontal line at t=12[s] indicates the estimated stopping position. This figure clearly shows the regenerative braking control performance is better than the driving characteristics on the market because the acceleration value is smaller than that of electric wheelchair on the market shown in Fig.5. In addition, the stopping distance is determined as 2.25[m], therefore, the estimated distance is 12.72[m]. The electric wheelchair could be surely and smoothly stopped to the estimated position.

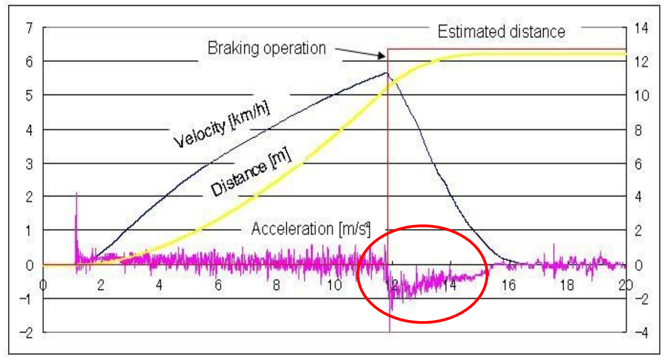


Fig. 19. Driving experimental results when the acceleration lever is operated slowly.

Fig.20 shows the driving experimental results when the acceleration lever is operated quickly. The stopping distance is determined as 1.8[m] by fuzzy algorithm, therefore, the estimated distance is 11.1[m]. As well as Fig.19, Fig.20 indicates the improvement of acceleration and sure braking control to the stopping position.

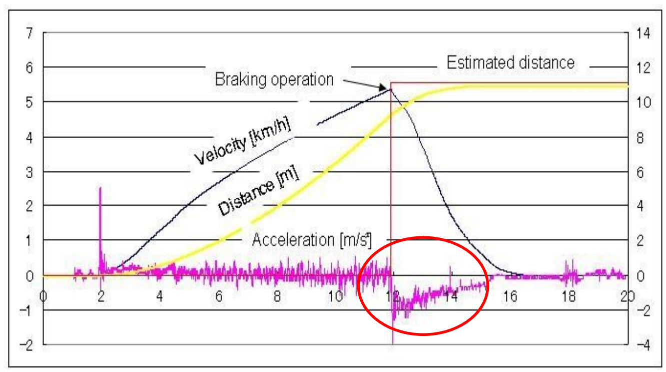


Fig. 20. Driving experimental results when the acceleration lever is operated quickly.

These experimental results show the effectiveness of the proposed capacitor regenerative braking control based on fuzzy algorithm.

VII. Discussion

This study realized the safety and smooth stopping motion of electric wheelchairs using the fuzzy algorithm based capacitor regenerative braking control system with the stopping distance estimation but still has the following important future problems.

- The stopping distance should be estimated more accurately and flexibly according to the human operator's characteristics using the regression analysis based on lots of driving data.
- The ride quality and safeness of the proposed control system will have to be further improved considering "jerk" value and to be evaluated using many trial subjects on various roads.
- The subjective evaluation by real elderly people will have to be needed in order to confirm the effectiveness of the proposed control system.
- This study verified only the effectiveness of the regenerative braking control and didn't focus on the energy efficiency. Therefore the long distance driving test will have to be conducted in order to analyze how much energy efficiency can be realized using the proposed regenerative braking system. The improvement of the regenerative braking circuit and battery characteristics also will have to be considered.

VIII. Conclusion

This paper proposed a novel safety and smooth stopping motion control scheme for electric wheelchairs based on the capacitor regenerative braking system with fuzzy algorithm based stopping distance estimation. The smooth deceleration during the stopping motion and the efficient energy management can be realized the proposed system. Some basic driving experiments verified the effectiveness of the proposed control system. Our future work will solve some important problems described in the last chapter.

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