Journal of the Korean Institute of Illuminating and Electrical Installation Engineers Vol. 23, No.11, pp. 94~101 November 2009 (23-11-12)

Tracking Control Method of a Step Motor for a Bilateral Symmetric Trainer

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Abstract

This paper poses tracking control and torque control methods to reduce torque ripple for bilateral symmetric trainers. As opposed to the conventional method, the torque control method for active joint movement is proposed. Using a step motor (PK296-03b, step angle: 1.8°), a simulator for a bilateral symmetric trainer is created, and the effectiveness of the proposed control method is verified through experiment results.

Key Words : Tracking Control Method, Torque Control Method, Step Motor, Bilateral Symmetric Trainer

1. Introduction

Recently, with the “graying of the nation”, health problems among the elderly have emerged as an issue. Severe disorders include movement disorders caused by a decline or loss of brain functions because of a stroke, one of the most frequent cerebrovascular diseases among the aged. In addition, the number of handicaps caused by industrial or car accidents has continuously increased. With these kinds of physical handicaps, different constraints are encountered in daily physical activities and the demand for adequate therapy to help manage handicaps has increased. In terms of medical treatment of the handicapped, rehabilitation and disease treatment are important in helping individuals continue social duties and activities. Therefore, studies of exercise therapy has been active. To date, studies of exercise device-based rehabilitation therapy have focused on the legs but recently, the upper part of the body has also undergone active study based on bilateral symmetric trainer-based therapy. The bilateral symmetric trainer is a rehabilitation therapy device which trains paretic limbs that have not been used for a long time due to stroke-caused hemiplegia or an accident.

The bilateral symmetric trainer mode can be divided into the passive and the active mode. The passive mode is available for a patient with a paretic arm. Two methods are available in the passive mode. The first method operates the bilateral symmetric trainer according to a pre-designed program. The patient exercises depending on the operation of the bilateral symmetric trainer. The second method helps the

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Date of submit : 2009. 10. 27
First assessment : 2009. 10. 29
Completion of assessment : 2009. 11. 18

patient exercise his/her arm using the healthy, unaffected arm as the paretic arm is fixed to the bilateral symmetric trainer. Exercise of the paretic arm is symmetrical to that of the unaffected arm. This method allows the patient to perform exercises customized to his/her handicap. Under the passive mode, even though the paretic arm can improve in terms of flexibility, no improvement is expected in muscular strength. On the contrary, the active mode can be used when the patient can somewhat move his/her paretic arm under his/her own power. In this mode, the paretic arm alone is used without the use of the unaffected arm. If one side of the bilateral symmetric trainer is moved using the paretic arm, the trainer will operate in the opposite direction and therefore the bilateral symmetric trainer can disturb the movement of the paretic arm. The active mode can improve the flexibility and muscular strength of the paretic arm, making it very useful in rehabilitation therapy. Most conventional bilateral symmetric trainers operated in the passive mode [1].

Studies that have shown the usefulness of bilateral training on hemiplegic status have been released in Korea [2] and many studies on the use of robots for bilateral training have been conducted internationally [3-4]. The robot-based apparatus is complicated and expensive and it will be necessary to develop an efficient bilateral symmetric trainer that is more cost effective than that at present.

Most bilateral symmetric trainers are powered by a motor. A step motor is a high-torque, high-response and high-resolution motor which rotates at an angle set by pulse signals. The step motor operated by pulse signals with its own holding power is extremely suitable as the power source for the bilateral symmetric trainer [5].

This paper has proposed a bilateral symmetric trainer which can be operated in either active or passive mode using the tracking control of a step motor. A torque control method through which the torque ripple can be reduced with the characteristics of stiffness generated from the step motor is examined in this paper. Using a PK296-03B step motor with a step angle of 1.8°, an experimental setup is prepared. Then, the feasibility of the step motor-based bilateral symmetric trainer is proven using the test results.

2. System configuration

2.1 Configuration

Fig. 1 below shows the block diagram of a step motor-based bilateral symmetric trainer.

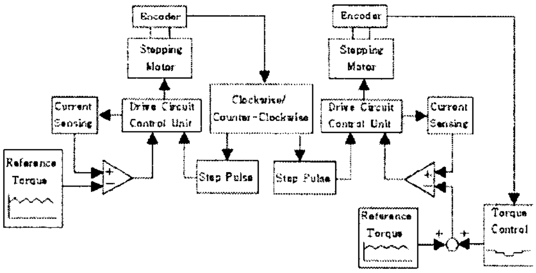


Fig. 1. Block diagram of bilateral symmetric trainer

The left and right sides on Fig. 1 above represent the unaffected arm and paretic arm respectively. After the user selects the arm that will be used, the step motor on the unaffected and paretic sides can be operated using a pre-designed program in the passive mode. If the user moves the step motor on the unaffected side, the direction of movement and the position of the step motor are sensed through the unaffected arm encoder. Then, the control system generates the operating pulse of the step motor on the paretic side for tracking of the unaffected arm using the sensed information. The user sets the reference torque depending on the patient's condition to generate a certain level of torque, which is necessary for the step motor to move the paretic arm. Then, the step motor on the paretic side is operated by the torque and pulse. In other words, the passive mode is made possible by the unaffected arm. Once the step motor on the paretic side moves, positions of movement are detected through the paretic arm encoder. To decrease torque ripple, the new reference torque is set after adding the change to the reference torque. The reference torque is set in the step motor on the unaffected side, the step motor is set to generate torque in the opposite direction of the step motor on the unaffected side, and muscle exercise for the unaffected arm is made possible.

Using the active mode, the step motor on the paretic side alone is used. The user is forced to move the step motor on the unaffected side using the paretic arm. The motor on the unaffected side is then controlled in the same way in which the muscle exercise on the unaffected side is controlled in the passive mode. The step motor on the unaffected side therefore helps exercise the paretic side as it acts as a load. Because the muscular strength on the paretic side is used under the active mode, the muscle on the paretic side can be made more flexible and stronger.

For accurate torque control of a step motor, in this study the actual current (actual torque) of the step motor was sensed to make current control possible under both passive and active modes. It was then compared to the reference torque.

2.2 Current control circuit

Fig. 2 below demonstrates the current control circuit of a step motor.

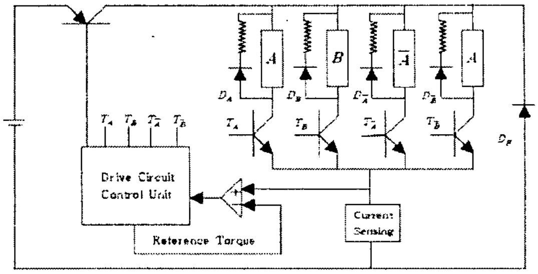


Fig. 2. Current control circuit

A current control circuit controls the transistor (T_A T_B, $T_{\bar{A}}$, $T_{\bar{B}}$) connected to each phase of the step motor after receiving pulse signals from the control unit. After sensing the actual current (actual torque) for torque control, it is compared to the reference torque. Then, current is controlled by turning the current control transistor (T_C) on and off. A free-wheeling diode (D_F) consists of a loop that emits energy stored in the step motor winding when the transistor (T_C) is off. The free-wheeling diode (D_A, D_B, $D_{\bar{A}}$, $D_{\bar{B}}$) connected to each phase consists of a loop that emits energy stored in each phase winding when each phase is off.

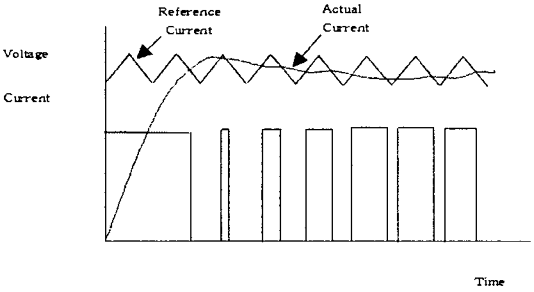


Fig. 3. Pulse Width Modulation Drive

In general, current control adopts a hysteresis current control system. However, the hysteresis current control system can raise switching frequency and burden the transistor with a large power consumption. This paper used a pulse width control method which controls pulse width from the transistor by using the reference torque to which oscillation signals 32[kHz] are added in order to reduce the burden of transistor. Fig. 3 shows the pulse width control method.

3. System control

3.1 Tracking control

The relation between the step angle of the step motor (θ_s) and resolution can be stated as follows:

$$\text{Resolution} = \frac{360}{\theta_s} \tag{1}$$

The step angle of the step motor used in this paper is 1.8° with resolution of 200. An encoder with a resolution of 400 has been used. Therefore, two encoder pulses occur per step. The position of the step motor on the unaffected side can be detected at one-fourth position of the step. The free-wheeling step motor is controlled for tracking after moving the step motor on the unaffected side by 0.45[°]. Fig. 4 demonstrates the reference pulse waveform for the tracking control.0.45°

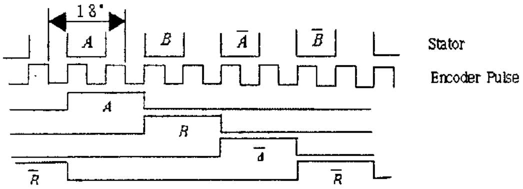


Fig. 4. Reference pulse waveform for the tracking control

3.2 Torque control

If the winding current in each phase in the step motor is constant, the step motor has stiffness of torque. With Z_R of rotor dimension and T_H of maximum torque, the torque of each phase can be stated as follows:

$$\begin{aligned} T_A &= -T_H \sin(Z_R\theta) \\ T_B &= -T_H \sin\left(Z_R\theta - \frac{\pi}{2}\right) \\ T_{\bar{A}} &= -T_H \sin(Z_R\theta - \pi) \\ T_{\bar{B}} &= -T_H \sin\left(Z_R\theta - \frac{3\pi}{2}\right) \end{aligned} \tag{2}$$

The phase difference of the m-phase step motor is $\frac{\pi}{m}$ [rad]. Therefore, the torque on the 'i'th exciting phase can be stated as follows:

$$T_i = -T_H \sin\left(Z_R\theta \frac{(i-1)}{m}\right)\pi \tag{3}$$

Fig. 5 shows the stiffness of each phase:

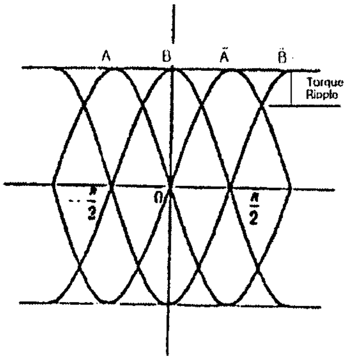


Fig. 5. Stiffness characteristic curve

In the case of excitation at a constant current as shown in Fig. 5, torque ripple occurs. Under a 2-phase unipolar system, 8[%] torque ripple has been reported. Therefore, torque with a range of 0 to 8[%] can occur depending on the position of movement of the step motor. The change of reference torque to compensate for torque change depending on the moving position is allowable and under this kind of reference torque control, the position of the step motor can be sensed at four positions per step using A- and B-phase encoder pulses. Based on the sensed position, the current control circuit is controlled to make reference torque greater than the current value at the position where step motor torque decreases. Fig. 6 shows the current control waveforms that reduce torque ripple. As shown in the figure, the waveforms have the opposite form of the stiffness curve. As encoder resolution becomes greater, torque ripple can be further reduced.

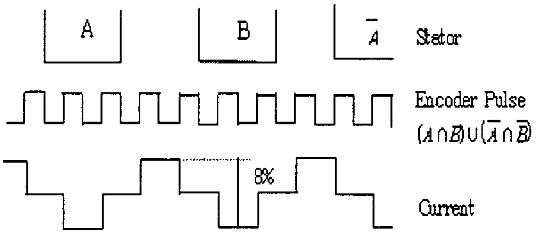


Fig. 6. Current waveform to reduce the torque ripple

Fig. 7 shows the reference pulse waveform for the active mode. As shown in this figure, A-phase excitation is observed until the step motor on the unaffected side reaches the B-phase after passing through the A-phase. This kind of movement represents the occurrence of torque in the opposite direction of the step motor. In other words, the step motor will keep moving when the torque greater than the step motor torque using muscle. The active mode used for the treatment of a paretic arm is therefore effective in improving flexibility and muscular strength. As mentioned above, this kind of control is applied to the exercise of muscle on the unaffected side while in the passive mode.

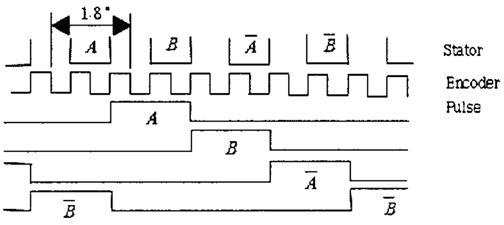


Fig. 7. Reference pulse waveform for the active mode

4. Test results

To test the tracking and torque control methods in the proposed step motor, the experimental setup for a bilateral symmetric trainer has been made using a PK296-03B step motor with a (1.8°) of step angle. Table 1 shows the step motor used in the experimental setup and encoder parameters while Fig. 8 demonstrates the experimental setup.

Table 1 Parameters of step motor and encoder

Rotor Inertia [10^{-7}kg·m^2]	2.2
Rated Current [A/Phase]	4.5
Rated Voltage [V]	2
Coil Impedance [Ω/Phase]	0.48
Step Angle [°]	1.8
Encoder Resolution	400

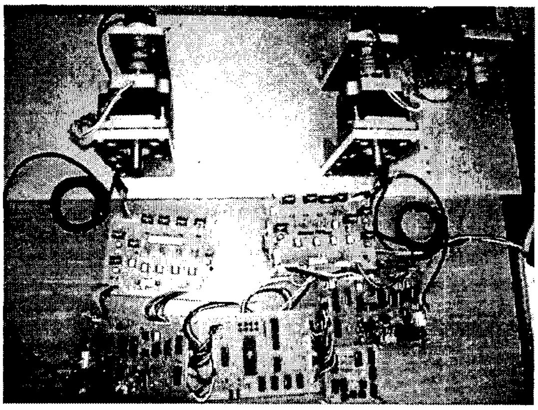


Fig. 8. Experimental setup

Fig. 9 shows the reference and actual current waveforms of the current control circuit which uses the pulse width control method. Using the pulse width control method, it is operated with a fixed switching frequency (32[kHz]).

Fig. 10 represents A-phase reference pulses on both the unaffected and paretic sides. The upper waveform demonstrates the encoder pulse waveform on the unaffected side while the waveform in the middle shows the A-phase pulse waveform on the paretic side. The lower waveform demonstrates the A-phase pulse waveform on the unaffected side.

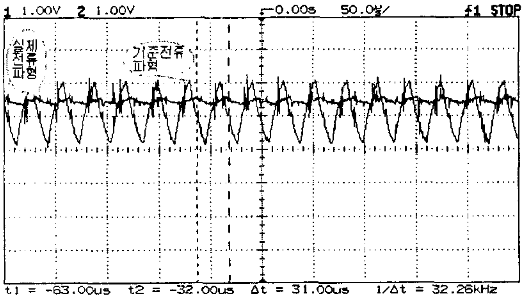


Fig. 9. Reference current and actual current waveform

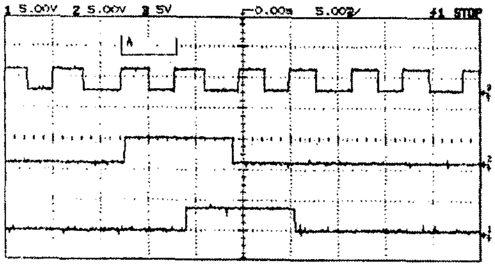


Fig. 10. Reference pulse waveform of A-phase

According to the A-phase pulse waveform on the paretic side, the motor on the unaffected side senses the movement of the unaffected arm after passing one-fourth of a step (Fig. 4). Then, the A-phase pulse waveform on the paretic side takes place. That is to say, after the step motor on the unaffected side moves by 0.45[°], the step motor on the paretic side moves along the motor on the unaffected side. According to the A-phase pulse waveform on the unaffected side, the A-phase pulse waveform is maintained until the step motor on the unaffected side reaches the B-phase. Therefore, muscle exercise on the unaffected side is controlled in the passive mode. Also , this kind of control uses in the active mode

Fig. 11 shows the pulse waveforms that use encoder the A-phase and B-phase and current waveforms for reduction of torque ripple. The first waveform represents the B-phase pulse waveform on the unaffected side while the second waveform shows the A-phase pulse waveform on the unaffected side. The 3rd waveform represents the pulse waveforms that use A-phase and B-phase on the unaffected side. Lastly, the fourth waveform shows the current control waveform for reduction of torque ripple.

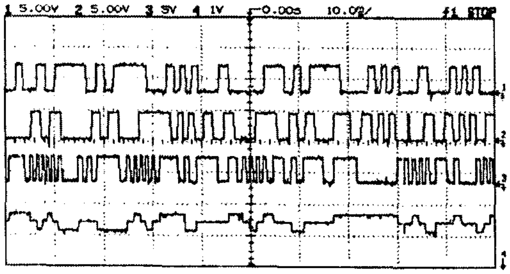


Fig. 11. Current waveform to reduce the torque ripple

As shown in Fig. 11, the current control waveform with the opposite shape of the stiffness curve shape were observed. Using this current control waveform, torque ripple can be reduced through torque control (Fig. 6).

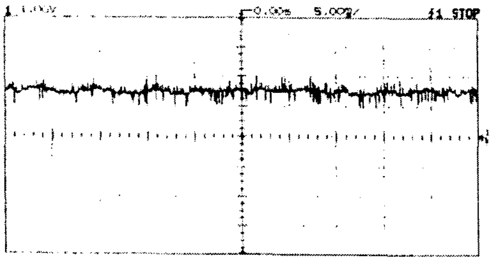


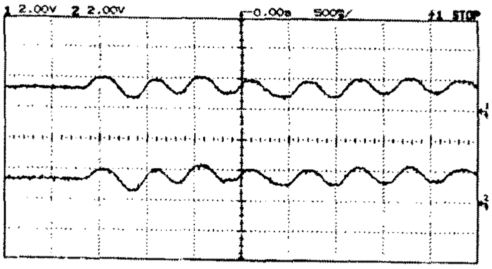
Fig. 12. Actual current waveform

Fig. 12 represents the actual current waveforms when the current wave form which was acquired by adding the torque change to the reference torque was imposed upon the step motor for the reduction of torque ripple.

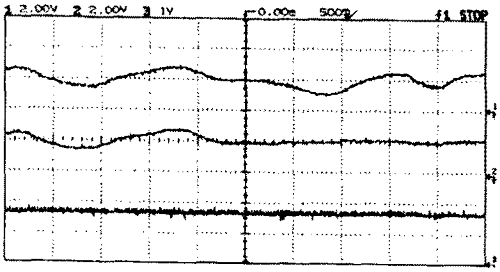
As shown in this figure, the actual current can show the opposite shape of the stiffness curve shape by the compensation current for the reduction of torque ripple caused by the position of a step motor even though the current (1.5A) remains constant. Therefore, it can be said that torque control has been adequate for the reduction of torque ripple.

Fig. 13 demonstrates waveforms by the moving position of step motors on both the unaffected and paretic sides. The moving position shows the waveforms in which the maximum value of the counter with 255 resolution is expressed at 5V. Furthermore, 2V is set as the reference point of rotational direction and therefore, voltage lower than 2V represents a reverse rotation while voltage higher than 2V shows forward rotation.

Fig, 13 (a) represents the waveform on the unaffected side and the waveform on the moving position of the step motor on the paretic side. The step motor on the paretic side on the bottom shows that the movement of the step on the upper unaffected side is properly tracked. With excellent tracking control functions, it is suitable as a bilateral symmetric trainer. Fig. 13 (b) shows the waveform when torque greater than the reference torque (1.7A) is imposed on the step motor on the paretic side. That is to say, the preset reference torque is not adequate to support exercise on the paretic side. As shown in the figure, no increase in current value has been observed in the motor on the paretic side. This confirms that the step motor on the paretic side maintains current position through slip without tracking the step motor on the unaffected side because of a constant current, which differs from a general motor which tries to increase speed by increasing current when speed decreases. In general motor, the increase in current represents compulsory tracking and user safety is not guaranteed. If a step motor is used, on the other hand, the system is controlled under constant current regardless of speed, ensuring user safety.



(a) normal load



(b) overload

Fig. 13. Tracking waveform

5. Conclusion

An experimental setup for a bilateral symmetric trainer has been made using a PK296-03B step motor with a step angle of 1.8°. The following results have been obtained:

1) Because the step motor on the paretic side follows the step motor on the unaffected side once the step motor on the unaffected side moves, excellent tracking control performance is observed.

2) The step motor-based bilateral symmetric trainer is available in two methods under the passive mode.
3) The active mode, which is not available in conventional bilateral symmetric trainers, is available as well. Therefore, the new unit is effective both in improving flexibility on the paretic side and in increasing muscular strength as well.
4) Torque can be completely controlled through a current control circuit. User safety is guaranteed even in an overload.
5) With torque control, which changes reference torque depending on the step motor's position, torque ripple can be reduced.
6) A step motor-based bilateral symmetric trainer is simple and efficient.

Based on these results, the feasibility of the step motor-based bilateral symmetric trainer has been proven. It would appear that step motor-based tracking and torque control could also be used in wrist/finger rehabilitation exercises and leg therapy.

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Biography

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Mr. Kim received B.S., M.S., and Ph. D., degrees in electrical engineering from Hanyang University, Seoul, Korea, in 1984, 1989, and 1996, respectively. Since 1997, he has been with Gangneung-Wonju National University, Wonju, Korea, where he is currently a professor in the Department of Electrical Engineering. His research interests include switching techniques of power converters and motor control applications.