LETTER

Design of Closed-Loop Fuzzy FES Controller and Tests in Controlling Knee Extension Movements

Takashi WATANABE††, Member and Takumi TADANO††, Nonmember

SUMMARY Fuzzy controller can be useful to realize a practical closed-loop FES controller, because it is possible to make it easy to design FES controller and to determine its parameter values, especially for controlling multi-joint movements by stimulating many muscles including antagonistic muscle pairs. This study focused on using fuzzy controller for the closed-loop control of cycling speed during FES cycling with pedaling wheelchair. However, a designed fuzzy controller has to be tested experimentally in control performance. In this paper, a closed-loop fuzzy FES controller was designed and tested in knee extension movements comparing to a PID controller with healthy subjects before applying to FES cycling. The developed fuzzy controller showed good control performance as a whole in comparing to PID controller and its parameter values were determined through simple control tests of the target movement.

key words: FES, closed-loop control, fuzzy, PID, knee

1. Introduction

Rehabilitation of lower limb motor functions is important for subjects with motor paralysis in order to improve activities of daily living. Functional electrical stimulation (FES) is a technique for assisting or restoring paralyzed motor functions caused by spinal cord injury or cerebrovascular disease, which has been recently applied to rehabilitation training [1], [2]. We have studied on rehabilitation system with a pedaling wheelchair using FES [3], which makes it possible to carry out safely rehabilitation training of lower limbs of paraplegic subjects. In that FES cycling system, electrical stimulation pulses with constant stimulation intensities were applied to lower limb muscles switching between the right and the left sides, and the maximum stimulation intensity was used in order to achieve high cycling speed. However, such open-loop controller has a difficulty in determination of parameter values for controlling cycling speed during FES cycling because electrical stimulation regulates joint movements or muscle force. Fuzzy controller makes it easy to design FES controller and to determine its parameter values for adjusting stimulation intensity to control cycling speed through simple FES control test of propelling the pedaling wheelchair.

The purpose of this paper was to develop a continuous time closed-loop fuzzy FES controller. First, a fuzzy FES controller was designed based on the previous fuzzy FES controller [6], [7] that was for a kind of repetitive control. Then, the controller was examined in controlling knee extension movements by comparing to a PID controller with healthy subjects in order to evaluate control performance.

2. Design of Fuzzy Controller

Figure 1 shows the block diagram of closed-loop fuzzy FES controller designed in this study. The fuzzy controller has inputs of angle error and its derivative and output of the fuzzy controller is change of stimulation pulse amplitude. Output of the fuzzy controller is adjusted by error-based output adjustment factor (E-OAF). The E-OAF is determined by the angle error, which increases the output value of the controller if the error is large [7].

Input and output fuzzy sets of the fuzzy controller are shown in Figs. 2 and 3. Input membership functions were expressed by triangular and trapezoidal functions, and the output variable ΔV∗ was expressed by fuzzy singleton. Fuzzy rules are summarized in Table 1. The rules were configured based on that stimulation intensity is increased if error is negative, and decreased if error is positive, in which error is defined by

\[ \text{Error} = (\text{measured angle}) - (\text{target angle}) \]  

Fig. 1 Fuzzy controller used in this study.

Copyright © 2017 The Institute of Electronics, Information and Communication Engineers
Fig. 2 Input and output membership functions of fuzzy FES controller. The fuzzy linguistic terms are shown by NL (negative large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium) and PL (positive large).

Fig. 3 Input and output membership functions of E-OAF in the fuzzy controller.

Table 1 Fuzzy rule sets of the designed fuzzy controller.

<table>
<thead>
<tr>
<th>Error</th>
<th>NL</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>PS or NS</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
</tr>
<tr>
<td>NM</td>
<td>PL</td>
<td>PM</td>
<td>Z</td>
<td>Z</td>
<td>NM</td>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td>PL</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>NL</td>
</tr>
<tr>
<td>Z</td>
<td>PL</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>PL</td>
</tr>
<tr>
<td>PS</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>NS or PS</td>
<td>NM</td>
<td>PL</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>NS or PS</td>
<td>NM</td>
<td>NL</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>NS or PS</td>
<td>NM</td>
<td>NL</td>
<td></td>
</tr>
</tbody>
</table>

For example, a fuzzy rule is expressed by the following:

IF Error is NL (Negative Large) and \( \frac{d}{dt} \) Error is PS (Positive Small) THEN \( \Delta V^* \) is Positive Large (PL)

For the fuzzy set “Zero (Z)” of Error, output \( \Delta V^* \) depends on signs of the error and its derivative. That is, if Error is positive, negative value of the derivative of error (NL) produces PS for \( \Delta V^* \) and positive value of the derivative (PM and PL) produces NS for \( \Delta V^* \). If Error is negative, negative derivative of the error (NL) produces NS and positive derivative (PM and PL) produces PS for \( \Delta V^* \), respectively.

The fuzzy inference was accomplished by using the Mamdani method. Defuzzification process converted the fuzzy inference output \( \Delta V^* \) into a crisp value \( \Delta V \). Center of gravity (COG) shown in the following equation was used in the defuzzification process,

\[
\Delta V = \frac{\sum \mu(\Delta V^*) \Delta V^*}{\sum \mu(\Delta V^*)}
\]

where \( k = 1, 2, \ldots, K \). \( K \) is the number of the fuzzy linguistic term of \( \Delta V^* \). \( \mu(\Delta V^*_k) \) is membership value of \( \Delta V^*_k \).

3. Experimental Tests in Knee Extension Control

3.1 Experimental Methods

The fuzzy controller and a PID controller were compared in knee extension control with 3 healthy subjects (22-23 years old). Knee extension movements were controlled by applying electrical stimulation to the rectus femoris and the vastus lateralis through surface electrodes. Electrical stimulation pulses were negative unipolar pulses with a frequency of 30Hz and a pulse width of 300\( \mu \)s. The minimum and the maximum stimulation amplitudes were determined before control tests for each subject. Subjects seated in the chair (GT-30, OG Giken), by which their knee joint could be moved without foot contact to the floor. Initial knee joint angle was measured at the beginning of each control trial and set to 0deg. Knee extension angle was measured with an inertial sensor attached on the shank [8].

The PID controller used in this study was velocity-type PID controller shown by the following:

\[
\Delta V_n = K_P(e_n - e_{n-1}) + K_Ie_n + K_D(e_n - 2e_{n-1} + e_{n-2})
\]
Δ\(V_n\) and \(e_n\) show change of stimulation intensity and error at time \(n\Delta T\). \(\Delta T\) is the sampling period. \(K_P, K_I\) and \(K_D\) show parameters of the PID controller, which were determined by the CHR method under the condition of no overshoot for changing target value as follows:

\[
K_P = \frac{0.6T}{KL}, \quad K_I = \frac{0.6\Delta T}{KL}, \quad K_D = \frac{0.3T}{K\Delta T} \quad (4)
\]

\(K\) is the gain that were determined by input-output characteristics because of its nonlinear characteristics [5]. \(T\) and \(L\) were time constant and delay determined by step response.

Parameter values of the output membership function of the fuzzy controller (\(\Delta V^*\) in Fig. 2) and those of the PID controller determined by measurements of step response and input-output characteristics were adjusted before the control tests in order to produce no oscillation in the constant value control, and they were fixed for all control tests.

3.2 Results

In order to evaluate control results, mean absolute steady state error (\(MAE_{ss}\)), rise time and settling time were calculated in the constant value control test, and mean absolute error (\(MAE\)) and correlation coefficient (\(CC\)) were calculated in the tracking control test. Here, \(MAE_{ss}\) was calculated for the last 1s and \(MAE\) was for all control period. The rise time was defined as the difference between times that the controlled angle reached 10% and 90% of the target value. The settling time was defined as the time when the controlled angle reached and remained within the error of \(\pm 1\)deg.

Evaluation results are shown in Fig. 4. There were no significant differences in the constant value control between the fuzzy and the PID controllers. However, the fuzzy controller showed good control performance as a whole in comparing to PID controller. For the tracking control, \(MAE\) values were smaller and \(CC\) values were larger with the fuzzy controller than the PID controller (\(P < 0.05\)). Control performance for fast tracking controls (5s) was not good with both controllers. This was because the control performance was remarkably poor with one subject for the fast tracking control.

4. Discussions

The designed fuzzy controller showed good control performance in comparing to the PID controller. The parameter values were determined in the preliminary test of constant value control in order to produce no overshoot. Therefore, if PID parameter values are determined in a tracking control, the control performance of the PID controller may be improved for the tracking control. However, PID controller requires measurements of step responses and input-output characteristics for parameter determination. This causes a difficulty in practical application of closed-loop control of cycling speed in FES cycling.

The control performance of the developed fuzzy controller is considered to be good in comparison to results of a computer simulation study [9]. However, values of rise time and settling time in the constant value control were not so small. \(MAE\) values were increased and \(CC\) values were decreased by the delay in the tracking control with shorter
time period. Including feedforward control would improve the delay as shown in the previous study [10], while time-lag errors were large in closed-loop control only. If the delay in muscle response causes any problems, feedforward control has to be implemented with the closed-loop control. Although another study showed good tracking control performance [11], it used total knee-joint dynamics model at the sitting position and the disturbance included in the model is considered to significantly affect on practical application such as FES cycling.

For cycling speed control of FES cycling, fuzzy controller is considered to be useful, because the fuzzy controller can be designed by using cycling speed error as the input and stimulation intensity as the output. Therefore, parameter values of the output membership function can be adjusted by using the data of cycling speed errors and applied stimulation intensities obtained by preliminary cycling tests. On the other hand, PID controller can also be used after the determination of parameter values through measurements of step responses and input-output characteristics of electrically stimulated muscles such as stimulation intensity-angle characteristics. However, if the number of muscles increases or antagonistic muscle pairs are stimulated, the parameter determination process becomes complicated. For example, posture for the measurements has to be changed for each muscle and motor disabled subjects may not be able to make some of postures for the measurements. In addition, PID parameters have to be related to the cycling speed, because the parameter values have to be adjusted finally by using cycling speed.

5. Conclusion

In this paper, a closed-loop fuzzy FES controller was designed and tested in controlling knee extension movements comparing to a PID controller. The developed fuzzy controller showed good control performance in comparing to the PID controller in constant value control and tracking control tests. Parameter values of the fuzzy controller were determined through simple control tests of the target movement. The fuzzy controller is expected to be applied to cycling speed control in FES cycling with a pedaling wheelchair.

Acknowledgments

This work was partly supported by JSPS KAKENHI Grant Number 15H03050.