PSO-based PID Speed Control of Traveling Wave Ultrasonic Motor under Temperature Disturbance

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Abstract. Traveling wave ultrasonic motors (TWUSMs) have a time varying dynamics characteristics. Temperature rise in TWUSMs remains a problem particularly in sustaining optimum speed performance. In this study, a PID controller is used to control the speed of TWUSM under temperature disturbance. Prior to developing the controller, a linear approximation model which relates the speed to the temperature is developed based on the experimental data. Two tuning methods are used to determine PID parameters: conventional Ziegler-Nichols (ZN) and particle swarm optimization (PSO). The comparison of speed control performance between PSO-PID and ZN-PID is presented. Modelling, simulation and experimental work is carried out utilizing Fukoku-Shinsei USR60 as the chosen TWUSM. The results of the analyses and experimental work reveal that PID tuning using PSO-based optimization has the advantage over the conventional Ziegler-Nichols method.

1. Introduction

Proportional Integral Derivative (PID) controller is still widely used in industrial applications even though many new advanced control algorithms have been proposed[1-2]. PID control has a simple structure and easy to be understood by engineers. In practical conditions, PID controller is more reliable compares to new advanced and complex control algorithms. Generally, PID controller consists of three gains: proportional, integral and derivative. The value of each gain needs to be tuned appropriately to get a good or optimal control of the system.

Ziegler-Nichols, Cohen-Coons, Astrom and Haggland tuning methods are some of the early developed tuning methods for PID control. However, tuning results of these methods is insufficient due to problems such as phase lag and high overshoot percentage. Particle Swarm Optimization (PSO) is an evolutionary computation technique approach introduced by Kennedy and Eberhart in 1995[3]. The PSO development is based on observations of animal social behaviour such as bird flocking and fish schooling. In PSO, each particle in swarm interacts in constructive cooperation and share information between them. By using the PSO method, high quality solution can be generated in a short calculation time. The detail of PSO technique is presented later in this paper.

In this study, the PSO tuning of PID controller is implemented to speed system of the ultrasonic motor (USM). An ultrasonic motor is an electric motor driven by piezoelectric vibrations[4,5]. Ultrasonic motors have been extensively studied in recent decades due to their key features such as high torque compare to the volume ratio, no demand on gear, fast dynamics, small electromagnetic interference and high stability [4]. However, they are drawbacks in ultrasonic motor such as short life time, low efficiency and temperature-dependence performance [6]. The temperature rise causes shift in resonant frequency
and subsequently results in decreasing the vibration amplitude of the stator. The low vibration amplitude degrades the performance of TWUSM, specifically the speed [7]. This clearly shows that the temperature variations significantly affect the dynamic characteristics of the motor.

The following sections are organized as follows: the model identification of speed system is described, followed by a brief discussion about performance estimation of PID controller. Next, the PSO method and its implementation into the PSO-PID controller are viewed in detail. Further, the simulation and physical experimental methods are explained. Finally, the discussion of the results followed by conclusion of the research is provided.

2. Model Identification of Speed System of TWUSM

The modelling approach in this study is based on the experimental results. The relation between speed and temperature is observed and studied. The mathematical model is developed by assuming the motor temperature as the only dependable variable to the speed performance[6–8]. Before the system model can be identified, experiments were performed to measure the system outputs. The system has one input which is the command voltage to the driver. The outputs of the system are shaft speed and temperature of TWUSM. Commercial ultrasonic motor Fukoku-Shinsei USR60-S2 with its driver circuit D2060 was used in our experiments. The command voltage to the driver is the only user control input. The speed of TWUSM is proportional to the command voltage value. The driver through its voltage-controlled oscillator in the circuitry adjusts the frequency of the applied sinusoidal drive voltage to the TWUSM. The frequency of the applied voltage determines the speed of TWUSM.

A temperature sensor LM35 was attached to the body of the motor, while an incremental rotary encoder (HENGSTLER Incremental Shaft Encoder) was used to measure the shaft rotation speed. The ambient temperature was set to be approximately at 25°C when the experiments were performed. Elvis II together with LabVIEW was used to transmit the speed and temperature readings to a personal computer. For each experiment, a constant command voltage was applied to the driver. The speed and temperature were simultaneously logged. The experiments were done for 900 seconds, which is sufficient for observing the temperature related performance of TWUSM. The experiments were repeated for several command voltage settings ranging from 0.4V to 1.4V.

Curve fitting toolbox in MATLAB software was used to get the model equation by fitting the experiments data. The following speed equation was fit to the obtained data

\[ s = (a_0u - a_0ue^{a_1t}) + (B(T) - B(T)e^{b_0t}) \]  

where \(s\) is the motor speed, \(t\) is the time, \(T\) is the temperature, \(u\) is the command voltage and \(B(T)\) is a function of temperature which can be described as the following equation

\[ B(T) = b_1(T - T_0) - b_2 \]  

The temperature \(T\) of the motor is described by the following equation

\[ T = T_0 + [(c_0u + c_1) - (c_0u + c_1)e^{c_2t}] \]  

where \(T_0\) is the initial temperature of the TWUSM. In equations above \(a_{0-2}, b_{0-2}\) and \(c_{0-2}\) are fitting parameters. The equations were chosen based on minimum root mean square error (RMSE) when compared with experimental data. The value of all fitting parameters is shown in Table 1.

| Fitting Parameter | Value  | Fitting Parameter | Value  |
|-------------------|--------|-------------------|--------|
| \(a_0\)           | 10.5   | \(b_2\)           | 0.6    |
| \(a_1\)           | -1000  | \(c_0\)           | 4      |
| \(b_0\)           | -0.04  | \(c_1\)           | 5      |
| \(b_1\)           | -0.1545| \(c_2\)           | -2.096e-3 |
The model simulation was performed using the equations above. The simulation results were compared with experimental results. The comparison was done to validate the identified model. Figure 1 shows the comparison of simulated and measured temperature with several different command input voltages. The results from experiments show that the temperature of TWUSM rises with time. The rate of temperature in TWUSM depends on the command voltage applied to the motor’s driver. The bigger the command voltage, the higher the temperature rise rate. Figure 2 shows the results for TWUSM speed with different command input voltages. The results clearly show that the speed decreases with time with temperature rise. The results also indicate that an increase in command voltage input results in an increase of the motor’s speed. The simulation results in both Figure 1 and Figure 2 clearly shows that the model is comparable with the actual experimental results.

**Figure 1.** Experimental and simulation results of temperature rise for different command input voltages input.

**Figure 2.** Experimental and simulation results of TWUSM speed for different command input voltages.
3. PSO-PID Algorithm
Gaing [10] proposed the new performance criterion for evaluation PID controller which is denoted as \( W(K) \). The criterion \( W(K) \) is the combination of several performance criteria. These performance criteria are maximum overshoot \( M_p \), rise time \( t_r \), settling time \( t_s \) and steady state error \( E_{ss} \). Therefore, \( W(K) \) is defined as

\[
W(K) = (1 - e^{-\beta t}) \cdot (M_p + E_{ss}) + e^{-\beta t} \cdot (t_s - t_r)
\]

where \( K = [k_p, k_i, k_d] \) and \( \beta \) is the weighting factor.

The evaluation function \( f \) is defined as the reciprocal of \( W(K) \). It implies that the smaller the value of \( W(K) \) the higher its evaluation value

\[
f = \frac{1}{W(K)}
\]

By using suitable weighting factor \( \beta \) value in performance criterion \( W(K) \) the control performance requirement can be satisfied. Weighting factor \( \beta \) can be set to be larger than 0.7 to reduce overshoot and steady state error. On the other hand, the rise time \( t_r \) and settling time \( t_s \) can be reduce by setting the value of weighting factor \( \beta \) smaller than 0.7. In this research, the value of \( \beta \) is set in the range of 0.8 to 1.5.

In PSO, individuals called as particles represent a potential solution of the problem. Each particle keeps track of its positions as it is treated as flying in \( g \)-dimensional search space. The positions are associated with the best solution (evaluating value) it has achieved so far. This value is called \( \text{pbest} \). The global version of particle swarm optimizer which tracks the overall best evaluating value, and its position obtained by any particle in the group is called \( \text{gbest} \). The particle size of 50 is used in this research. There are 3 members in each particle to represent three PID parameters.

In PSO concept, each particle changes its velocity toward its \( \text{pbest} \) and \( \text{gbest} \) positions at each time step. As example, the \( j^{th} \) particle is represented as \( x_j = (x_{j,1}, x_{j,2}, ..., x_{j,g}) \) in \( g \)-dimensional space. The best previous position of the \( j^{th} \) particle is recorded and represented as \( \text{pbest}_j = (\text{pbest}_{j,1}, \text{pbest}_{j,2}, ..., \text{pbest}_{j,g}) \). The index of best particle among all particles in the group is represented as \( \text{gbest} \). The rate of the position change (velocity) for \( j^{th} \) particle is represented as \( v_j = (v_{j,1}, v_{j,2}, ..., v_{j,g}) \). The modified velocity and position of each particle can be calculated using the current velocity and distance from \( \text{pbest}_{j,g} \) to \( \text{gbest}_g \) as shown in the following formulas:

\[
v_{j,g}^{(t+1)} = w \cdot v_{j,g}^{(t)} + c_1 \cdot \text{rand()} \cdot (\text{pbest}_{j,g} - x_{j,g}^{(t)}) + c_2 \cdot \text{rand()} \cdot (\text{gbest}_g - x_{j,g}^{(t)})
\]

\[
x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)}
\]

where

\[
\begin{align*}
n & \quad \text{number of particles in a group;} \\
m & \quad \text{number of members in a particle;} \\
t & \quad \text{pointer of iterations(generations);} \\
\end{align*}
\]
velocity of particle $j$ at iteration $t$,

$$v_{j,g}^{(t)} \leq v_{j,g}^{\text{min}} \leq v_{j,g}^{(t)} \leq v_{g}^{\text{max}};$$

$w$ inertia weight factor;

c1, c2 acceleration constant;

$\text{rand}(\ )$ random number between 0 and 1;

$x_{j,g}^{(t)}$ current position of particle $j$ at iteration $t$;

$\text{pbest}_{j,g}$ $\text{pbest}$ of particle $j$;

$\text{gbest}_g$ $\text{gbest}$ of the group

The parameter $v_g^{\text{max}}$ determines the resolution, or fitness, with which regions are searched between the present position and target position. If $v_g^{\text{max}}$ is too high, particles might fly past good solutions but if $v_g^{\text{max}}$ is too low, particles may not explore sufficiently beyond local solutions.

The constant $c_1$ and $c_2$ represent the weighting of the stochastic acceleration terms that pull the particles towards $\text{pbest}$ and $\text{gbest}$. The value of $c_1$ and $c_2$ are often set as 2.0 according to experience. The low values of $c_1$ and $c_2$ allow particle to fly far from target region before being tugged back while high values result in abrupt movement towards or past target regions [10].

Suitable selection for inertia weight $w$ provides a balance in local and global explorations, thus requiring less iterations on average to find a sufficiently optimal solution. Formula for determining the values of inertia weight $w$ is shown in Equation (8)

$$w = \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \times \text{iter} \tag{8}$$

where $\text{iter}_{\text{max}}$ is the maximum number of iterations or generations, $\text{iter}$ is the current iterations, $w_{\text{max}} = 0.9$ and $w_{\text{min}} = 0.4$

4. Simulation and Experimental Results

The PSO searching algorithms was done in MATLAB and the results for the three PID parameters was applied to PID controller in TWUSM speed system for simulation. The simulation was done using Simulink package in MATLAB. The simulation results with weighting factor $\beta = 1$ and is shown in Table 2.

| $\beta$ | 1.0 |
|---|---|
| Number of Iteration | 50 |
| $k_p$ | 0.0519 |
| $k_i$ | 0.3678 |
| $k_d$ | 0.0181 |
| $t_r$ | 0.7792 |
| $t_s$ | 1.1618 |
| $M_p$ | 0.0646 |
| $E_{ss}$ | 0.0053 |
| $f$ | 5.4088 |

Physical experiments were conducted to validate the simulation results. Additionally, to emphasize the advantage of PSO-PID controller, the Ziegler-Nichols-PID control was also implemented is TWUSM speed system. Closed-loop Ziegler-Nichols tuning method was used in determining the parameters for PID control. The experiment results for ZN-PID and PSO-PID are shown in Table 3. The results show that the PSO-PID is more superior method than ZN-PID. The comparison from rise time
show that the PSO-PID achieves less time that is 0.5724 seconds compared to ZN-PID that need 0.8991 seconds. Furthermore, the settling time was quicker by using PSO-PID compared to ZN-PID by more than 30%. The results also show that PSO-PID tuning performance is superior than ZN-PID in maximum overshoot and overall evaluation function.

### Table 3. Performance comparison between PSO-PID and ZN-PID

| Tuning Method | PSO-PID | ZN-PID |
|---------------|---------|--------|
| $k_p$         | 0.0519  | 0.0480 |
| $k_i$         | 0.3678  | 0.2400 |
| $k_d$         | 0.0181  | 0.0024 |
| $t_r$         | 0.5724  | 0.8991 |
| $t_s$         | 0.6671  | 0.9837 |
| $M_p$         | 1.5360  | 2.5420 |
| $E_{ss}$      | 0.1536  | 0.2542 |
| $f$           | 0.9067  | 0.5660 |

5. Conclusion

We analytically and experimentally compared the performance of speed control of TWUSM using ZN-PID and PSO-PID tuning methods. The modelling of TWUSM speed system was based on the temperature of the motor. The results of the analyses and experimental work reveal that PID tuning using PSO-based optimization has the advantage over the conventional Ziegler-Nichols method.

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