Speed Sensorless Control of Ultrasonic Motors Using Neural Network

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ABSTRACT

In this paper, a speed sensorless control for an ultrasonic motor (USM) using a neural network (NN) is presented. In the proposed method, rotor speed is estimated by a three-layer NN which adapts nonlinearities associated with load torque and motor temperature into control. The intrinsic properties of a USM, such as high torque for low speeds, high static torque, compact size, etc., offer great advantages for industrial applications. However, the speed property of a USM has strong nonlinear properties associated with motor temperature and load torque, which make accurate speed control difficult. These properties are considered in designing a control method through the application of mathematical models. In these strategies, a detailed speed model of the USM is required which makes actual applications impractical. In the proposed method, a three-layer NN estimates the speed of the USM from the drive frequency, the root mean square value of input voltage and the surface temperature of the USM, where no mechanical speed sensor is needed. The NN speed based estimator enables inclusion of variations in driving conditions due to input signals of the NN involved during the driving state of the USM. The disuse of sensors offers many advantages on both the cost and maintenance front. Moreover, the model free sensorless control method offers practical controller construction within a small number of parameters. To validate the proposed speed sensorless control method for a USM, experiments have been executed under several conditions.

Keywords: Speed sensorless control, ultrasonic motor, neural network

1. Introduction

The USM is a special type of motor, which is driven by the ultrasonic vibration force of piezoelectric elements. It has excellent performance and many other useful features\textsuperscript{1}, which are not present in other electromagnetic type motors, e.g., high torque, low speed operation, compact in size, no electromagnetic interferences, high holding torque without supply, high response characteristics, and so on. In actual applications, a USM has been used as actuators of cameras, in medical equipment and in high magnetic field uses. The speed characteristics of a USM have a strong nonlinear property. A number of researchers have studied an analytical model of a USM\textsuperscript{2-5}, which was proposed to evaluate performance. Therefore, the analytical model has a lot of variable parameters which makes applications of the speed model highly impractical\textsuperscript{6-9}. On the other hand, accurate speed control is necessary for applications, and we
generally require the detailed mathematical model for adapted speed control. To realize high performance and high-precision speed control, accurate speed information is necessary to generate the control input. Generally, the rotor speed is measured by using mechanical sensors such as resolvers or rotary encoders. However, these sensors are usually expensive and bulky, and which increases the cost and size of the drive system [9].

In the proposed method, a three-layer NN is used with off-line training. The drive frequency, the rms of input voltage, and the surface temperature of the USM are used as the input for the NN to estimate the rotor speed. It is well known that the nonlinear identification ability of NNs [10] enable fewer parameters to be used. The validity of the proposed method is confirmed by experimental results.

2. Drive System for USM

The drive system for the proposed speed control of a USM is shown in Fig. 1 and the design specifications of the experimental USM are given in Table 1. A typical traveling-wave type USM has been applied and consists of a stator and rotor made with an elastic body and piezoelectric elements. The load and rotary encoder are connected with the motor via coupling, the actual motor speed is measured by a 10,000 pulse/revolution rotary encoder to compare the estimated speed with the measured speed. The personal computer implements the controller which calculates the control signal in the proposed method. The control signal is transmitted to the oscillator via a GPIB (General Purpose Interface Bus). Then the inverter generates a two-phase alternating voltage $V_A$ and $V_B$ as shown in Fig. 2. There have been reported many drive systems for USMs based on this two-phase half-bridge inverter [11]. The drive system has three controllable parameters of the two-phase alternating voltage to control the rotor speed, i.e., rms voltage of the sine-wave, drive frequency and phase difference of a two-phase alternating voltage. Advantages of this system include a fast response and a wide controllable range. We applied the drive frequency $f$ to control the rotation speed where the phase difference maintains at $\phi = 90\,\text{deg}$.

Table 1 Motor specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Drive voltage</td>
<td>100 Vrms</td>
</tr>
<tr>
<td>Rated current</td>
<td>53mA/2phase</td>
</tr>
<tr>
<td>Rated torque</td>
<td>0.314 Nm</td>
</tr>
<tr>
<td>Rated output power</td>
<td>3 W</td>
</tr>
<tr>
<td>Rated speed</td>
<td>9.0 rad/s</td>
</tr>
<tr>
<td>Mass</td>
<td>0.240 kg</td>
</tr>
</tbody>
</table>

3. Characteristics of USM

The USM has nonlinear speed characteristics as shown in Figs. 3 and 4. Maximum rotational speed is at resonance frequency $f_r$ for the USM. Variations in the surface temperature and motor load torque cause variations in the resonance frequency $f_r$. As a result, motor speed drops if the motor is driven at a fixed frequency. From Fig. 3(a), it indicates that a motor speed control is necessary and a USM has an unstable control area lower than resonance frequency $f_r$. We used the
control input as a drive frequency, ranging from 40.4kHz to 41.8kHz, because the commanded and actual motor speed needs to be operated with a drive frequency value higher than resonance frequency \( f_r \). Fig. 3(b) shows the characteristics of the input voltage and rotor speed for driving frequency. Using a low drive frequency enables acceleration of the rotor speed. While impedance variations of the USM, related to drive frequency, causes a decreased input voltage. The input voltage \( V_{rms} \) increases and rotor speed decreases with applied load torque at the fixed drive frequency. The speed and voltage characteristics are used to estimate rotor speed because the speed variation involved with the applied load torque is reflected by the input voltage \( V_{rms} \).

Fig. 4 shows temperature versus speed characteristics. It shows that surface temperature variation affects rotor speed. Hence, the surface temperature of the USM is used as an input of the speed estimator.

4. Speed Estimation Using NN

Fig. 5 shows a block diagram, which illustrates the speed estimation structure using a NN speed estimator with input voltage \( V_{rms} \) [V], drive frequency \( f \) [kHz] and surface temperature \( T \) [°C], as input information. As discussed in the previous section, input voltage \( V_{rms} \) represents the effect of load torque and the increase in temperature \( T \) effects as the rotor speed drops. In the proposed method, the NN is trained off-line to define the properties of the USM. The off-line training used measured speed characteristics data for each input signal. The estimated rotor speed \( \hat{\omega} \) is generated by a trained NN. Then the PI controller calculates the control input according to the speed difference calculated from \( \hat{\omega} \) and
reference rotor speed $\omega^*$. The control input of the PI controller is determined by

$$u_{pi} = k_p e + k_i \int e dt$$

(1)

$k_p (=0.5)$ and $k_i (=0.02)$ are the proportional and integral gains of the PI controller, respectively.

Fig. 6 illustrates the structure of the applied three-layer NN. To make a correct NN output, which follows the supervised signal, the energy function is defined as

$$E = \frac{1}{2} (y^* - y_k)^2$$

(2)

where $y^*$ is the supervised signal and $y_k$ is the estimated speed of the NN. Table 2 shows the parameters of the applied NN. The experimental system was structured on RTLinux (Real Time Linux), which enables real-time applications. The controller and NN based speed estimator were developed using C language.

5. Experimental Results

The NN off-line training results are shown in Fig. 7. These results show that the proposed method has good speed estimation performance over a wide range and under various drive conditions.

Figs. 8(a) and (b) show the experimental results of speed control by a PI controller using a NN speed estimator under a no load condition. The experimental results demonstrate that the proposed method achieves a good speed control performance when the surface temperature is changed under a no load condition. In the proposed method, input voltage $V_{rms}$, drive frequency $f$, and surface temperature $T$ are used as the inputs of the NN for speed estimation because the speed estimator deals with various drive conditions for applied load torque and variations in temperature. The robustness of the proposed control scheme with temperature variation and load torque is also demonstrated by experimental investigations.

6. Conclusions

In this paper, a speed sensorless control of a USM which estimates rotor speed using NN, was proposed. In the proposed method, a three-layer NN is used with off-line
Fig. 7 Results of off-line training

Fig. 8 Experimental results of speed control using NN speed estimator
training. The drive frequency, input voltage, and surface temperature of the USM are used as input information for the NN speed estimation. This speed estimation structure has robustness for drive condition changes. Also nonlinearities of speed properties are considered. The nonlinear identification ability of the NN has realized enhanced control performance which includes nonlinearities associated with load torque and surface temperatures of USMs. The validity of the proposed method has been demonstrated and confirmed by experimental results.

References


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