Supervisory Genetic Algorithm Control for Linear Ultrasonic Motor Drive

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Abstract

This study presents a supervisory genetic algorithm (SGA) control system for a linear ultrasonic motor (LUSM) driven by a two-inductance two-capacitance (LLCC) resonant driving circuit. First, the motor configuration and driving circuit of an LUSM are introduced, and its hypothetical dynamic model is described briefly. Since the dynamic characteristics and motor parameters of the LUSM are highly nonlinear and time varying, an SGA control system is therefore investigated to achieve high-precision position control. The proposed SGA control system is composed of two parts. One is a genetic algorithm (GA) control and the other is a supervisory control. The effectiveness of the proposed control system is verified with hardware experiments under the occurrence of uncertainties.

1. Introduction

Linear ultrasonic motor (LUSM) is a new type of motor, which is driven by the ultrasonic vibration force of piezoelectric ceramic elements and the mechanical friction effect [1]–[3]. It has useful merit that cannot be found in electromagnetic-type motor [1]–[6]. However, this motor has highly nonlinear dynamic characteristics that vary with motor drive operating conditions. So far, the result of investigations into the design of drive and control systems for LUSMs are still poor except for the recurrent-fuzzy-neural-network (RFNN) position control for a LC-resonant LUSM drive proposed by Lin et al. [6]. However, the voltage gain of the LC-resonant inverter varies significantly so that the output voltage is different under the same driving conditions. Furthermore, the stability of the RFNN control system cannot be guaranteed.

On the driving aspect, an LLCC resonant driving circuit is implemented in this study to build a high-frequency voltage-source inverter for an LUSM since the fourth-order LLCC-type resonant technique combines the merits of both the third-order LCC-type and LLC-type inverters [7]. However, there is no discussion concerned with the design of feedback control system to deal with the positioning problem under the possible occurrence of uncertainties. The aim of this study is to design an LLC resonant inverter so that the output voltage will not be influenced by the variation of quality factor. On the control aspect, genetic algorithm (GA) is a more recent technique to search optimum solutions [8]–[13]. Over the last few years, GA has been applied in optimizing the design of fuzzy logic controller (FLC), neuro-fuzzy logic controller (NFLC), proportional-integral-derivative (PID) or adaptive sliding-mode controller. In the previous works, the conventional GA is only instated as minor compensators to adapt some specific parameters such that the whole control framework is still complex.

Because the dynamic characteristics and motor parameters of an LUSM are highly nonlinear and time varying, it is difficult to design a suitable control scheme for the LUSM. Hence, a supervisory genetic algorithm (SGA) control system is proposed in this study to afford an optimum control effort under the possible occurrence of uncertainties. Experimental results, in which the SGA control system is implemented in a PC-based computer control system and the LUSM is driven by a high-frequency voltage source inverter using LLC resonant technique, are provided to validate the effectiveness of the proposed methodologies.

2. Characteristics of LUSM

2.1. Driving circuit

The proposed driving circuit, which is composed of a push-pull DC/DC converter with pulse-width-modulation (PWM) duty control and an LLC resonant inverter, is depicted in Fig. 1. When the switching frequency is operated at the geometric frequency, the amplitude of the voltage gain is equal to one and is not affected by the variation of the quality factor, i.e. the amplitude of the output voltage, \( V_o \), is equal to \((4V_x)/\pi \) [7]. Moreover, the voltage gain of the push-pull DC-DC converter can be represented as \( V_o/V_x = (2N_xD_x)/N_1 \), in which \( D_x \) is the duty ratio of the switches \((S_1, S_2)\), and \( N_x \), \( N_1 \), and \( N_2 \) denote the turns ratio of the transformer. Thus, the whole voltage gain of the proposed driving circuit can be obtained as \( V_o/V_x = (8D_xN_x)/(\pi N_1) \). However, the duty ratio...
where $|·|$ represents the absolute value and $\rho$ is a given positive constant.

3. Supervisory genetic algorithm control

Consider the actual LUSM drive represented by (4), the control problem is to find a suitable control law so that the position of the moving table of the LUSM can track desired specific commands. Define a tracking error, $e(t) = d_s(t) - d(t)$, in which $d_s(t)$ represents a reference trajectory specified by a reference model. The control law for a SGA control system is assumed to take the following form:

$$U = U_{\text{GA}} + U_s$$  \hspace{1cm} (7)

where $U_{\text{GA}}$ is a GA control that is the major component, and $U_s$ is a supervisory control. The overall scheme of the SGA control system is depicted in Fig. 3 and the detailed descriptions of each control part are exhibited in the following subsections.

3.1. GA control design

The proposed GA control, utilized to generate the optimum control effort ($U_{\text{GA}}$), is formed by a survival -of-the-fittest strategy and error back-propagation genetic operators to construct a search mechanism with surprising power and speed. The tracking error is used to decide whether mutation would be undergone or not. The difference between two adjoining generations is utilized to decide the stepsize of crossover and mutation, while its surprising power and speed. The tracking error is used to decide whether mutation would be undergone or not.

The basic construction of the proposed GA in this study is described as follows.

1) Solution Representation: To reduce the computing time, the real number representation is used to represent the candidate solutions in this study.

2) Size of Population: The size of the population, $N$, is chosen according to the specific control performance and the limitation of control efforts.

3) Initial Chromosomes: Before proceeding GA operation, $N$ sets of initial chromosomes should be randomly generated from the domain of solution.

4) Performance Index Function: It is used to...
discriminate the usefulness of each chromosome. The defined matching error function is chosen as the performance index function in this study.

\[ e_{\text{err}} = e(t)^2 / 2 \]  

(8)

5) Evolution Operation: After the evolution operation, the chromosomes with lower matching error will be bequeathed as new candidate solutions and new sequence will be generated.

6) Error-based Genetic Operation: Crossover and mutation are performed to mimic the process of heredity of genes to create new offspring at each generation. The detailed operations are summarized as follows.

**Crossover:** The direction-based crossover operator is adopted in this study. The principle is that the more the tracking error is the more the crossover must be undergone. The offspring generated from two parents \( U_{\text{GAf}} \) and \( U_{\text{GAF}} \) can be represented as

\[ U_{\text{SGA}} = U_{\text{GAf}} - \alpha_1 \left( U_{\text{GAF}} - U_{\text{GAf}} \right) \]  

(9)

where \( U_{\text{SGA}} \) is the generated offspring; \( U_{\text{GAF}} \) is one parent of previous generation that has the smallest minimum matching error; \( U_{\text{GAf}} \) is another parent that has the matching error slightly larger than \( U_{\text{GAF}} \); the value of \( \alpha_1 \) is a variant step size which is quantified from the tracking error and expressed as

\[ \alpha_1 = \begin{cases} 
1 & \text{if } e(t) \leq -a_1 \\
-e(t)/a_1 & \text{if } -a_1 < e(t) \leq a_1 \\
-1 & \text{if } e(t) > a_1 
\end{cases} \]  

(10)

in which \( a_1 \) is a positive constant. An executing upper level, named as the crossover rate (denoted by \( p_c \)), must be predetermined.

**Mutation:** The error-based mutation operator is adopted. The offspring generated from the best parent \( U_{\text{GAF}} \) can be represented as

\[ U_{\text{GAf}} = U_{\text{GAF}} + \alpha_2 \cdot r \]  

(11)

where \( r \) is a non-negative real number and the value of \( \alpha_2 \) is quantified as

\[ \alpha_2 = \begin{cases} 
-1 & \text{if } e(t) \leq -a_2 \\
e(t)/a_2 & \text{if } -a_2 < e(t) \leq a_2 \\
1 & \text{if } e(t) > a_2 
\end{cases} \]  

(12)

in which \( a_2 \) is a positive constant. To prevent reducing the learning ability from history of the research, another executing upper level, named as the mutation rate (denoted by \( p_m \)), must be predetermined.

3.2. Supervisory control design

To further ensure the stability of the GA control system, a supervisory controller derived from the Lyapunov stability theorem is utilized to prevent the condition of divergence of states and to pull the states back to the predetermined bound region. If the lumped uncertainty of the uncertain LUSM drive system is well known, a perfect control law can be defined as follows:

\[ U^* = \bar{B}_p \left[ -\bar{A}_p d(t) + \bar{d}_p(t) - \bar{C}_p - L + KE \right] \]  

(13)

where \( K = [k_x \ k_z] \) and \( E = [e \ \dot{e}]^T \). From (4), (7), and (13), an error equation can be obtained as

\[ \dot{E} = \Lambda E + G_v (U^* - U_{GAf} - U_{GAF}) \]  

(14)

where \( G_v = [0 \ \bar{b}_z]^T \) and \( \Lambda = \begin{bmatrix} 0 & 1 \\ -k_1 & -k_2 \end{bmatrix} \) is a stable matrix. Define a Lyapunov function as

\[ V_s = E^T \mathbf{P} E / 2 \]  

(15)

where \( \mathbf{P} \) is a symmetric positive definite matrix which satisfies the following Lyapunov equation:

\[ \mathbf{A}^T \mathbf{P} + \mathbf{PA} = -\mathbf{Q} \]  

(16)

and \( \mathbf{Q} > 0 \) is selected by the designer. To satisfy \( \dot{V}_s \leq 0 \), the supervisory control \( U_s \) is designed as follows:

\[ U_s = I \text{sgn}(E^T \mathbf{P} G_v) \left( |U_{GAf}| + |\bar{d}_p| + |\bar{A}_p d| + |\bar{C}_p| + |\mathbf{P}E| \right) \]  

(17)

Using the designed supervisory control \( U_s \) as shown in (17), the inequality \( \dot{V}_s < 0 \) can be obtained for nonzero value of the tracking error vector \( E \) when \( V_s > \mathbf{P} \). As a result, the stability of the SGA control system can be guaranteed.

4. Experimental results

The block diagram of the computer control system for the LUSM drive is depicted in Fig. 4. The position of the moving table is fed back using a linear scale. Digital filters and the frequency multiplied by 4 circuits are built into the encoder interface circuits to increase the precision of position feedback, and the resulting resolution is 0.1 \( \mu \text{m} \). The control interval of the position control system is set at 2ms. The amplitude of the DC-link voltage is controlled by the push-pull DC/DC converter according to the output of the proposed SGA control system. \( A, A' \) or \( B, B' \) to move the table in the desired direction.

The experimental results of the SGA control system due to the mixed reference trajectory at the nominal and parameter variation conditions are exhibited in Fig. 5 for comparison. The position responses are depicted in Fig. 5(a) and (d); the associated control efforts are depicted in Fig. 5(b) and (e), and the tracking errors are depicted in Fig. 5(c) and (f). From the experimental results, favorable tracking responses can be obtained without chattering control effort. Moreover, robust control
characteristics under the occurrence of parameter variations and different reference trajectories are obvious. The mean square error (MSE) and maximum error ($e_{\text{max}}$) of the SGA control system for the mixed reference trajectory at the nominal and parameter variation conditions are summarized in Table I.

![Figure 5. Experimental results of SGA control system due to mixed reference trajectory.](image)

**Table I.** Experimental data of MSE and $e_{\text{max}}$

<table>
<thead>
<tr>
<th>Measure System</th>
<th>Nominal condition</th>
<th>Parameter variation condition</th>
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<tbody>
<tr>
<td>SGA control</td>
<td>MSE 0.4133, $e_{\text{max}} 0.0664$</td>
<td>MSE 0.4072, $e_{\text{max}} 0.0783$</td>
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5. Conclusions

The main contributions of this study are summarized as follows. 1) Successful implementation of a driving circuit based on the concept of LLCC resonant technique to overcome the problem of voltage gain of the LC resonant inverter varying significantly with the variation of the quality factor in [6]. 2) Successful utilization of the survival-of-the-fittest strategy and error back-propagation genetic operation to design a major GA control with self-organizing property. 3) Successful derivation of a hypothetical dynamic model of an LUSM drive to guarantee the stability of SGA control system at the aid of a supervisory control. 4) Successful application of the proposed LLCC resonant driving circuit and SGA control methodology to control an LUSM for periodic motion with different regimes.

6. Acknowledgment

The authors would like to acknowledge the financial support of the National Science Council of Taiwan, R.O.C. through grant number NSC 92-2213-E-155-063.

7. References