Research on AC Power Conditioning Control Technology for Ultraprecision Machining of Steel Materials

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Abstract. This paper presents a nonlinear control technology controlled AC power conditioning with application to ultraprecision machining of steel materials. The presented technology associates the advantages of finite-time tracking control (FTTC) and cuckoo search algorithm (CSA). The FTTC allows insensitivity to system uncertainties as well as system states finite-time convergence. It is a remarkable fact that the chatter will occur in face of highly dynamic loads. The chatter causes high output-voltage distortion in AC power conditioning, and the ultraprecision machining of steel materials may be instability and unreliability. The CSA is thus used to attenuate the chatter so that the AC power conditioning can provide robust performance for ultraprecision machining of steel materials. Because the proposed control technology is easier to implement than prior technologies and achieves high tracking precision and low calculational-complexity algorithm, experiments display low total harmonic distortion and fast transience in the output voltage, and this paper will be helpful to researchers of related ultraprecision machining of steel materials.

1. Introduction
An AC power conditioning has been used as a key element for ultraprecision machining of steel materials, like rolling, forging, and drawing [1]. The high performance AC power conditioning should contain 1) the output voltage waveform with low harmonic distortion for linear or nonlinear cyclic loads. 2) the fast transient response when the abrupt load changes occurs. 3) the steady-state error should be restricted as small as possible. To gain requisitions, proportional-integral-derivative controllers perform well in the presence of constant load circumstances; however, the good performance cannot be satisfied when the plant is subject to fluctuating load disturbances [2], [3]. Nonlinear control strategies are frequently adopted, such as direct repetitive control [4], optimal state feedback [5], and adaptive hysteresis control [6]. But, they have complex algorithms, and implemented difficulty. Variable structure control (VSC) is a robust method for controlling nonlinear system where occurs system uncertainties [7], [8]; a number of VSC developed for AC power conditioning have been done, but linear sliding functions are employed, and infinite-time tracking problem exists [9], [10]. To enhance the convergence speed, the FTTC with nonlinear sliding function is used to make tracking error converge to zero in finite time [11], [12]. However, once a highly dynamic load occurs, the chatter appears in AC power conditioning output with high harmonic distortion, thus deteriorating the stability and reliability of ultraprecision machining of steel materials. The cuckoo search algorithm (CSA) is a swarm intelligence method which inspired by the unique breeding behavior of cuckoos, and has been presented for solving global optimization. Several works have improved the chatter by the use of the optimal approaches [13]; however, these have complex calculation and slow convergence rate. Therefore, the CSA is used to attenuate the chatter while the
FTTC provides system states finite-time convergence. By the combination of FTTC and CSA, the tracking error between desired and actual output will be minimized [14], [15], and the AC power conditioning of ultraprecision machining of steel materials yields low total harmonic distortion, fast dynamic response, chatter attenuation, and steady-state errors reduction. Experiments are given to verify the applicability and efficacy of using the proposed technology.

2. Presented Control Technology for Ultraprecision Machining of Steel Materials

Figure 1 shows the system block diagram of AC power conditioning in ultraprecision machining of steel materials. Let \( v_o \) be the output voltage, \( v_r \) be the desired AC waveform, \( v_e = v_o - v_r \) be the voltage error, and the load is represented by \( R \). Assume that the switching frequency is high enough, the AC power conditioning can be regarded as a constant gain, \( K_{PWM} \). Define \( e_1 = v_e \) and \( \dot{\varepsilon} = e_2 \), the tracking error can be expressed as the following matrix

\[
\begin{bmatrix}
\varepsilon \\
\dot{\varepsilon}
\end{bmatrix} = \begin{bmatrix}
e_2 \\
-a_1 e_1 - a_2 e_2 + b v - N
\end{bmatrix}
\]

where \( a_1 = 1/LC \), \( a_2 = 1/RC \), \( b \) stands for \( K_{PWM}/LC \), and \( N = v_r/LC + \varepsilon/RC + \varepsilon \) symbols system uncertainty.

Figure 1. AC power conditioning in ultraprecision machining of steel materials.

A finite-time tracking control with nonlinear sliding function is defined as

\[
s = e_1 + (1/p) \cdot e_2^{p/q}
\]

where \( p > q \), \( p \) and \( q \) are positive odd numbers \( (1 < p/q < 2) \), and a sliding-mode reaching item \( \varepsilon = -ks - \varepsilon \text{sign}(s) \) is used. Therefore, the control law \( v \) can be written as

\[
v = \frac{1}{k} \left[ a_1 e_1 + a_2 e_2 - \left( \frac{p}{q} \right) e_2^{2-p/q} - b e_2^{2-p/q} - \frac{k}{4} s + \left( L_g + \varepsilon \right) \varepsilon \text{sign}(s) \right], \quad k > 0, \quad \varepsilon > 0
\]

where \( u_{eq} \) indicates the equivalent control which determines the system dynamics, and \( u_{fl} \) signifies the sliding control which prevents the system uncertainties. Thus, the system will be driven to \( s = 0 \) and converged in finite time; however, if a highly dynamic load is applied, the chatter still occurs, and the system (1) cannot obtain precise tracking performance. To attenuate the chatter, the control gains in (3) can be optimally tuned by the use of the CSA, and the concept of CSA is briefly described as follows:
(i) Each cuckoo lays an egg at one time, and gets rid of its egg in a randomly select nest.
(ii) The best nests have high-quality eggs that keep to the next generation.
(iii) Let the number of accessible host nests be fixed, and we suppose that a host bird recognizes the cuckoo egg with the probability of \( p_a \in [0, 1] \) so that the host bird can either discard them or abandon to create a new nest in a new location.

Once a new solution \( x_i(t+1) \) is produced for a cuckoo \( i \), a Levy flight can be constructed as
\[
x_i(t+1) = x_i(t) + \gamma \oplus \text{Levy}(\lambda)
\]
where \( \gamma \) is the step size, and the product \( \oplus \) represents entry wise multiplications. Also, there is a random walk with random step size in the Levy flight that follows a Levy’s distribution below.
\[
\text{Levy} \sim u = t^{-\lambda}, \quad 1 < \lambda \leq 3
\]

3. Experiments
The proposed system parameters are listed as follows: \( V_{dc}=200 \) V; \( v_o=110 \) Vrms, \( f=60 \) Hz; \( L=0.1 \) mH; \( C=3 \) \( \mu \)F; Switching Frequency \( f_s=15 \) kHz; \( R_{\text{rated}} =12 \) ohm. To test the transient behavior for ultraprecision machining of steel materials, Fig. 2 and Fig. 3 show the output voltage and the load current obtained using the proposed control technology and the classic VSC under step change in load (from no load to full load) at a 90 degree firing angle, respectively. A detailed examination of the waveforms shows that Fig. 2 has tiny voltage sag and fast retrieval of the steady-state response. But, the classic variable structure controlled system, shown in Fig. 3 yields unsatisfactory transient response and delayed recovery time. Fig. 4 and 5 depict the tracking errors in the proposed control technology and classic VSC, respectively. It is worth noting that the tracking error of the proposed controlled system not only shows system states finite-time convergence but also approximately exists vibration-free than that of the classic variable structure controlled system. Therefore, it is well confirmed that the proposed control technology always produces higher tracking exactness, lower harmonic distortion, and faster convergence speed, as comparing the classic VSC.

![Figure 2. Proposed control technology under step change in load (100V/div; 20A/div; 5ms/div).](image1)

![Figure 3. Classic VSC under step change in load (100V/div; 20A/div; 5ms/div).](image2)
Proposed control technology

![Proposed control technology](image)

**Figure 4.** Tracking errors in the proposed control technology.

Classic VSC

![Classic VSC](image)

**Figure 5.** Tracking errors in the classic VSC.

4. Conclusions
This paper has proposed FTTC with CSA for designing AC power conditioning to improve ultraprecision machining of steel materials. This proposed control technology not only has the robustness of classic VSC but also provides finite time convergence of the system state, and attenuates the chatter. According to theory and experimental results, the validity of the proposed control technology is successfully demonstrated and thus more appropriate for use in ultraprecision machining of steel materials. Further, in future research, the proposed control technology can be used to more complex three phase AC power conditioning for machining applications.

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6. References
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