

Contouring control of ball screw mechanism using a practical control method

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Abstract. This paper presents an improved practical controller for enhancing the contouring motion of a ball screw mechanism. Practically, a high motion control performance and ease of controller design are desired. A continuous motion nominal characteristic trajectory following (CM NCTF) control has been considered to fulfill the desired performance. The NCTF controller comprises of a nominal characteristic trajectory (NCT) and a PI compensator where the controller parameters are easily determined and it is free from exact modeling. In the present paper, the CM NCTF controller has been proposed in order to enhance the continuous motion performance such as tracking and contouring accuracies of the system. In order to justify the advantages, the CM NCTF controller was examined in tracking motion performances using an AC driven X-Y ball screw mechanism. The bandwidth of the CM NCTF controller is larger compared to the PID controller, therefore, it proved that the CM NCTF controller has fast response as compared with the PID controller. The experimental results proved that the CM NCTF controller achieves better contouring motion performances than the PID controller by showing a two times smaller motion error.

1. Introduction

AC servo mechanisms are commonly used in industrial application due to its advantages in greater efficiency, fewer stability problems, less maintenance and smoother operation as compared to the DC servo mechanism. But, the AC servo mechanism is tougher to be controlled in positioning applications and it frequently suffers due to its inherently nonlinear characteristics.

Recently, several researchers had studied the effectiveness of conventional PID control versus advance PID control system in ball screw mechanism. The advance PID control system used such as nonlinear PID control, P/PI control, nonlinear PID control cascade with feedforward [1, 2], and fuzzy PID control [3]. These researchers prove that, the advance PID control has better positioning performance as compared to the conventional PID control when the control system is applied to a nonlinear mechanism. In terms of contouring control, [4] had proposed a PID controller with friction feedforward for the ball screw system, but the results do not able to provide a sufficient friction compensation in the system. A position domain PID controller had been introduced by [5] to a 2-DOF Cartesian robot, where the results demonstrated that the proposed control is stable and can obtain very good contour tracking performances. However, the design procedures required an inverse kinematics analysis with mathematical derivations.



Advanced controllers have been suggested to achieve better positioning performance in ball screw mechanism. In [6], a disturbance observer with variable structure controller has overcome the problems due to friction and disturbances. A back-stepping sliding mode controller was proposed by [6,7] to improve the performance of the system used. Besides that, a Reinforcement Learning methods by learning the feedback controller of a ball screw feed drive is used in [8] can be an alternative to typical feedback control approaches such as PID controllers. Although these advanced controllers are able to show good performance in the robustness of precision positioning, but it involves with model parameter determination and the performance of these controllers is based on how accurate the known model and known parameters are used in their design procedures, which affect the design processes in terms of time consuming and more work is acquired to identify the accurate parameters, which create hurdles to their practical use.

A control method using NCTF control was first proposed by [9] as a practical controller for point-to-point positioning system and was examined with a rotary mechanism. After that, the continuous motion nominal characteristic trajectory following (CM NCTF) controller has been proposed by [10] as a high performance and simple control structure to a DC ball screw mechanism in 2009. The best part of this controller is it has a simple control structure as compared with the other advanced controllers. Besides that, the design procedure of a NCTF controller is much simpler and easy to understand. It does not require an exact model or parameter identification of the plant which sometimes troublesome the researchers. It applied a general pulse input to drive the mechanism and stop smoothly in open-loop response.

In year 2010, the CM NCTF controller was validated with a non-contact mechanism [11]. It proved that the procedure of the NCTF controller is independent of the friction characteristic. The effectiveness of the CM NCTF controller was evaluated by [12] using the 1-DOF rotary system, which is driven using DC servo motor in 2013. The third generation, Acceleration Reference-Continuous Motion NCTF (AR-CM NCTF) controller was proposed in year 2010 [13].

The main goal of this paper is to examine and clarify the usefulness of the CM NCTF control to a ball screw mechanism that driven using AC servo motor. AC servo motor produces higher acceleration as compared to DC motor. A suitable input signal is used in this paper which is able to produce sufficient rapid and smooth response during deceleration motion in open-loop experiment. The open-loop responses are then used to construct the nominal characteristic trajectory (NCT). This procedure is simple yet important because it has significant influences to the reference following characteristic of the control system. The detail procedures in designing the CM NCTF controller and PID controller can be referred to [14]. Experiments in tracking motion in difference axis will be conducted in order to validate the effectiveness of the CM NCTF control system in comparison to the PID controller.

The rest of this paper is written as follows: Section 2 describes the experimental setup of the ball screw mechanism that used in this research. In section 3, the control structure of the CM NCTF controller and PID controller control system with their design procedure are discussed. The performance of both controller are validated and discussed in section 4. Lastly, the remark conclusion and future studies are made.

2. Experimental setup

The contouring control performance in this research is examined using a ball screw mechanism shown in Figure 1. The mechanism is driven by an AC servo motor (model: MSMD022P1U) through ball

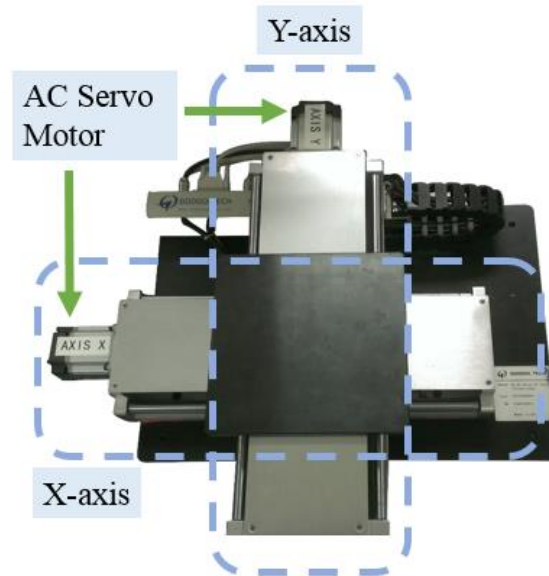


Figure 1. X-Y ball screw mechanism.

screws with a 5 mm pitch and the lead of the ball screw is 1.25 mm/rev. Each motor is controlled independently by the same servo driver. The ball screw movement is measured by an incremental encoder with a resolution of 0.5 m/pulse. The maximum travel of the table is 175 mm in X and Y directions. The velocity in this research is obtained using a backward differential algorithm from the measured displacement. Basically, the material for both mechanism (X-axis and Y-axis) are similar except for their weight. As X-axis is mounted at the bottom of Y-axis, therefore, the weight for X-axis is heavier (total mass ± 16.71 kg) compared to Y-axis is only about 3.11 kg since it only sustain the mass of the moving table.

3. Controller Design

A controller with a similar control structure is chosen to compare with the CM NCTF controller in tracking to see their contouring motion performance. The design procedure of the Continuous Motion Nominal Characteristic Trajectory Following (CM NCTF) controller and the PID controller will be explained in this section.

3.1. Continuous Motion Nominal Characteristic Trajectory Following (CM NCTF) Control Design

The CM NCTF controller is a NCTF based controller where it has a simple structure and easy to design. The NCTF controller is adjusted to improve the contouring motion performance. The CM NCTF controller comprises of a nominal characteristic trajectory (NCT) element and a Proportional and Integrator (PI) compensator as illustrates in Figure 2. The NCT plays an important role as a virtual error rate for the object to follow and it is expressed on the phase plane. The NCT is designed using the object responses in open loop experiment and the inclination of the NCT near origin is denoted as β . Instead, the PI compensator controls the velocity of the ball screw mechanism and make it follows the NCT and end at origin. When the object stops at the origin, it means the end of the positioning motion.

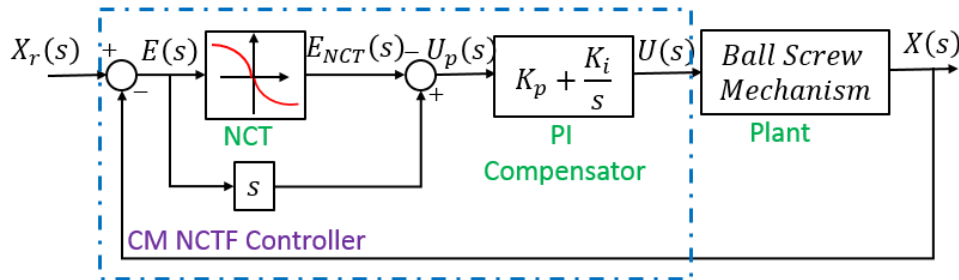


Figure 2. Control Structure of Continuous Motion NCTF (CM NCTF) controller.

The design procedure of the CM NCTF controller is consisted of three simple steps:

- I. **Open-loop response**, where the ball screw mechanism is driven in open loop and the displacement and velocity responses are measured.
- II. **Construction of NCT**, where the NCT is constructed on the phase plane using the displacement and velocity of the mechanism during deceleration motion.
- III. **Design of PI compensator**, where it is designed based on the open-loop responses and NCT information.

The constructed NCT with inclination near origin, β equals to 87 s^{-1} is used in this research. The values of K_p and K_i of the PI compensator are 0.08 Vs/mm and 1.34 V/mm respectively. The details design procedures for the CM NCTF controller and PID controller are discussed in [14].

3.2. PID Control Design

PID controller is chosen to be compared with the CM NCTF controller because it has a similar control structure with the CM NCTF controller. Furthermore, the design procedure of the PID controller and the CM NCTF controller are simple and easy. Figure 3 shows the control structure of the PID controller used in this research. The step to design a PID controller is simple where the values of K_p , K_i and K_d are chosen using trial error method. Next, all the compensator gains are fine-tuned until the transient response of the PID controller similar with the CM NCTF controller. The final values of K_p , K_i and K_d are 3.00 V/mm , $0.80/\text{mms}$, and 0.03 Vs/mm respectively.

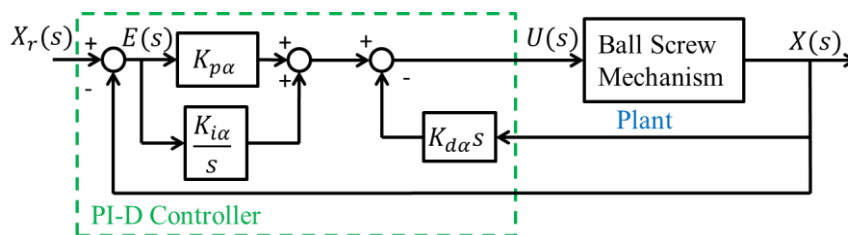


Figure 3. Control structure of PID controller.

4. Performance Evaluation

In this section, the contouring performance for both controllers are experimentally examined and the effectiveness of the CM NCTF controller is evaluated in comparison with PID controller. The performance of both controller is evaluated based on the continuous motion for X-axis and Y-axis. For circular motions, sinusoidal reference inputs are applied to the ball screw mechanism. Figure 4 shows the continuous motion performances of the PID controller at frequency of 0.1 Hz and the reference radius is 10 mm, while the performance of the CM NCTF controller is shown in Figure 5. The experiments conducted in such a way that the Y-axis is mounted on top of X-axis. Then, a cosine wave reference is used for X-axis and a sine wave for Y-axis mechanism, thus the resulting contour is a circle. The CM NCTF controller generates a much smaller tracking errors than the PID controller. The reference used in the experiments is a circle with 10 mm radius and the frequency is 0.1 Hz. The radial error is reduced by more than ten times with the CM NCTF controller, and it guarantees the proposed controller is suitable for continuous motion.

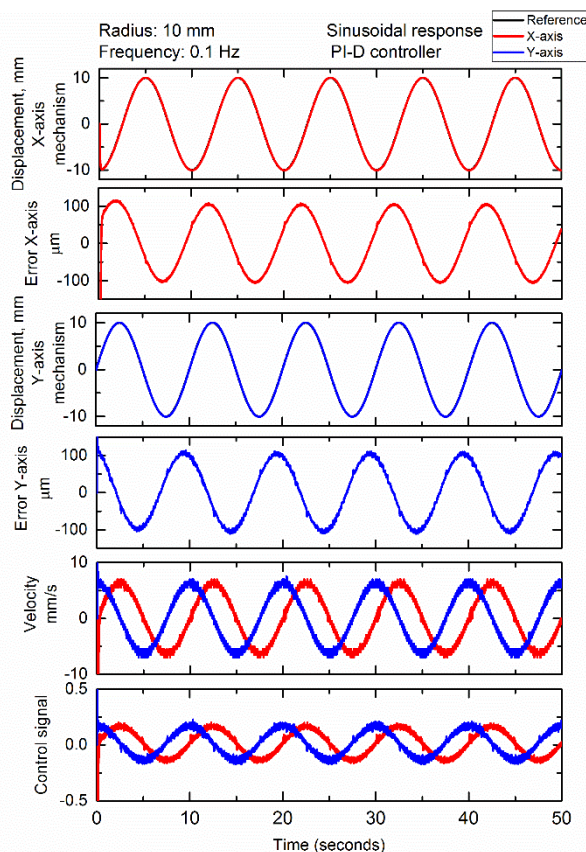


Figure 4. Continuous motion performances with the PID controller at frequency 0.1 Hz.

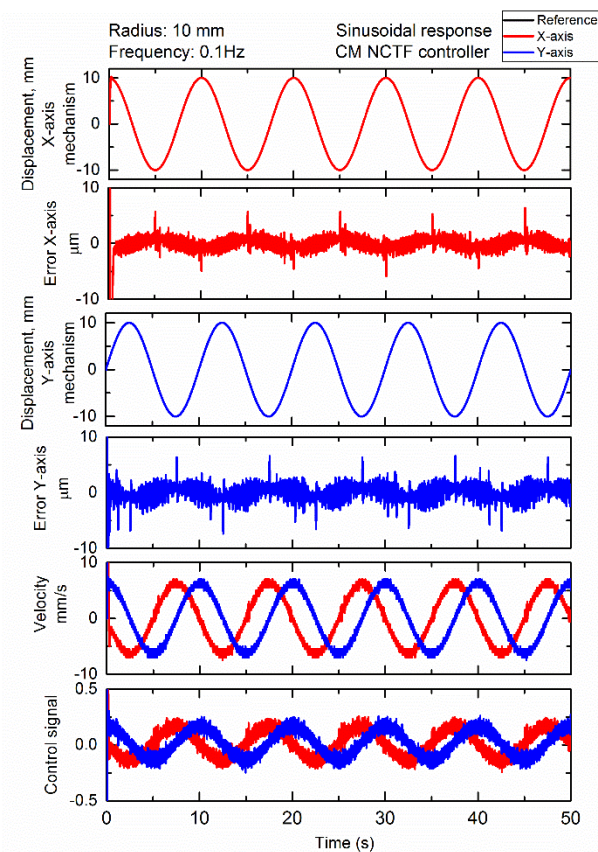


Figure 5. Continuous motion performances with the CM NCTF controller at frequency of 0.1 Hz.

4.1. Contouring control performances

Figure 6 shows the circular motion of both CM NCTF controller and PID controller at frequency of 0.1 Hz with radius 10 mm and 1 mm. At lower frequency, both controller managed to perform with less error compared to higher frequency, however, PID still outperforms by more than twice those obtained using the CM NCTF controller. The circular motion at 5 Hz with 0.1 mm and 1 mm are shown in Figure 7 and 8 respectively. The outer and inner radial errors are summarized in Table 1. Based from Table 1,

it can be clearly observed that the experimental results proved that the CM NCTF controller achieves better contouring motion performances than the PID controller by showing at least two times smaller motion error.

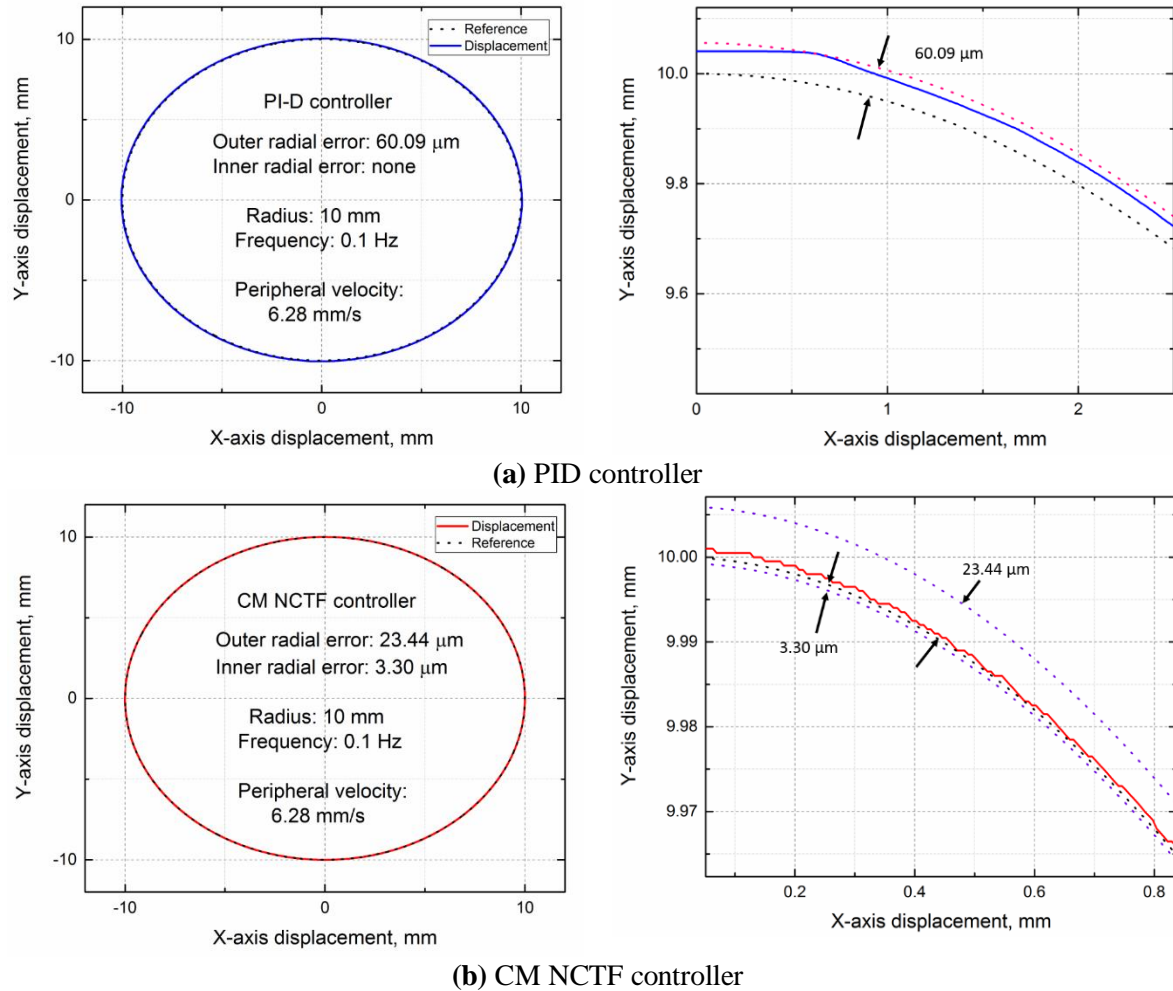


Figure 6. Circular motion with reference input of 10 mm and frequency 0.1 Hz.

Table 1. Contour control performances of the CM NCTF and PID controllers.

Frequency (Hz)	Amplitude (mm)	Radial error (μm)					
		PID controller			CM NCTF controller		
		Outer	Inner	Total	Outer	Inner	Total
0.1	10.0	60.09	none	60.09	23.44	3.30	26.74
	0.1	13.54	17.51	31.05	11.80	none	11.80
5.0	1.0	none	175.55	175.55	37.00	25.05	62.05

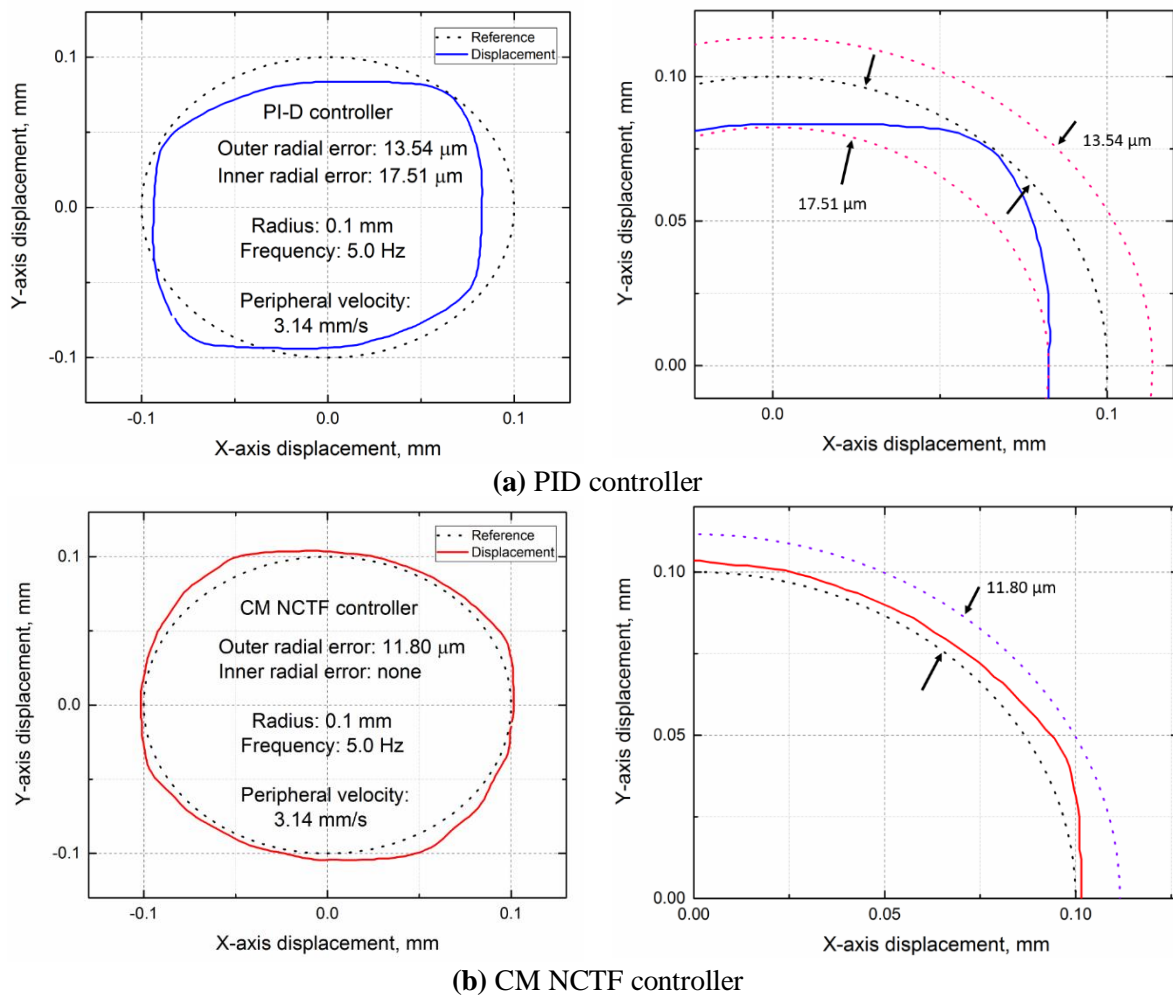


Figure 7. Circular motion with reference input of 0.1 mm and frequency 5.0 Hz.

5. Conclusion

In this paper, the CM NCTF controller was suggested as a high-performance with a practical design method controller. The designed controller was then realized to a ball screw mechanism to evaluate its performances. The CM NCTF has almost similar control structure with PID controller and their design procedure are simple and easy. The experimental results proved that the CM NCTF controller achieves better contouring motion performances than the PID controller by showing a two times smaller motion error.

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