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Robustness Evaluation for Point-to-Point Positioning Control of A One Mass Rotary System

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Abstract: In this paper, the Continuous Motion (CM) NCTF controller is proposed for a point-to-point (PTP) positioning system of a one mass rotary system. For this system, the CM-NCTF controller is designed based on the conventional structure of NCTF controller and improved. The CM-NCTF controller consists of Nominal Characteristic Trajectory (NCT) and Proportional Integral (PI) compensator. It is designed without knowing exact system modeling and parameter evaluation. The NCT is constructed from open loop responses while the PI compensator is designed based on the constructed-NCT itself. The effectiveness of the CM NCTF controller is evaluated and compared with the PID controller for positioning and tracking motion performances experimentally. The robustness of the CM NCTF controller is validated by varying the mass load. Overall, the CM-NCTF controller demonstrates promising positioning and tracking performances, and low sensitivity towards the change of mass load in comparison with the PID controller.

Keywords: CM NCTF; PID; Positioning control; Tracking control; Sensitivity

1. INTRODUCTION

Point-to-point (PTP) positioning system plays an important role in industrial application such as semiconductor industries, manufacturing system, precision control and robotics. An advance machine and equipment are needed to ensure the production could possess a better product quality and quantity. For some reason, the effectiveness of the equipment may not yield a good performance because of a non-linear characteristic of positioning system. The examples of non-linear characteristics are friction, saturation and also parameter uncertainties. This behavior may affect the system performance by limited the system cycles, cause large steady state error and make the system unstable.

In order to perform the promising positioning system, many engineers or researchers have tried to improve the machine mechanism, use an advanced sensor or design a controller. All three features are important because each of them has significant influence towards the system. For some reason, the use of an advanced sensor or improve the machine mechanism may not suitable because it requires high cost and maintenances. As an alternative solution, a controller is necessary needed to demonstrate high accuracy, fast response, high speed and robust to uncertainties, parameter variations and disturbance.

Positioning system performance usually affected by nonlinear characteristics such as actuator saturation, friction and also the influences of disturbance or uncertainties. The saturation that produced by an actuator may cause the slow system performance and affect the system stability, while too much friction may cause too large steady state error and limit output cycles near the reference input. Hence, the proposed controller must be able to consider all the above-mentioned issues in the design criteria to possess a promising control performance.

Up to date, many controllers have been proposed in order to improve positioning and continuous motion performances of a system, such as disturbance observer [1], sliding mode control [2] and time optimal control [3]. The above-mentioned controllers may demonstrate sufficient responses, however, it requires complexes design procedure. Besides, the advanced controllers require exact and accurate model parameters in the design procedure that sometimes time consuming to the researcher or engineer.

As a result, the Nominal Characteristic Trajectory Following (NCTF) controller is proposed for this research as a practical control method. Until now, the study on NCTF Controller has been done towards various types of system. In [4], the NCTF controller was first time proposed for a rotary system. Then, the NCTF controller has been proposed and examined using a ball screw mechanism for point-to-point and tracking controls [5]. In [6], the NCTF controller has been proposed to 1-DOF air slide non-contact mechanism and it was proved that the NCTF control design procedures is independent of friction characteristic. In this paper, the Continuous Motion NCTF (CM NCTF) controller is proposed for the positioning and tracking control of a rotary system.

The CM NCTF controller is an improved NCTF control system for tracking and contouring motions. The CM NCTF control performance is applied to a one mass rotary system, and its motion control performance is evaluated from the experimental tracking and positioning control results.

2. CONTROLLER DESIGN

2.1 Continuous Motion (CM) NCTF control system

The CM NCTF controller is comprised of Nominal

Characteristic Trajectory (NCT) and PI compensator. The design procedure of the CM NCTF controller remains similar as the conventional NCTF control system. The NCT is constructed by using the object responses during open loop experiment and the PI compensator is designed so that it is able to control the object motion to follow NCT and finishing at the origin.

The NCT is constructed on phase plane using velocity and displacement of the system motion during deceleration in open loop. After NCT has been constructed, the PI compensator is designed based on the stability of the system. Fig. 1 shows the CM NCTF controller structure and Eq. 1 shows the control laws of the CM NCTF controller.

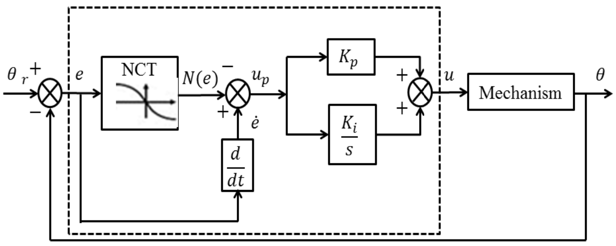

Fig. 1 Structure of the Continuous Motion (CM) NCTF control system

The control laws for CM NCTF controller are shown in Eq.(1):

$$U(s) = (K_p + \frac{K_i}{s})U_p(s) \qquad (1)$$

where,

$$U_p(s) = \dot{E}(s)_{virtual} - \dot{E}(s)_{actual}$$

$$E(s) = \theta_r(s) - \theta(s)$$

$$N(e) = \dot{E}(s)_{virtual} = \beta \times E(s)$$

$$\dot{E}(s)_{virtual} = \frac{d(\theta(s))}{dt}$$

From the Eq. (1), the $U_p(s)$ is obtained by comparing the virtual error rate and actual error rate. The value of $U_p(s)$ is equal to zero when the object motion is completely following the NCT that has been constructed.

2.2 Design procedure

They are a few steps to design the CM NCTF controller. The design procedures of the CM NCTF controller are as below:

a) System open loop response: The system is driven by a stepwise open-loop input and its displacement and velocity responses are measured. The input amplitude must not exceed the rated input of the system to avoid the mechanism from damaged. The amplitude of the input signal is 10V and duty cycle (t_1) is 0.5sec. Fig. 3 shows the open loop response result. The obtained open-loop results will be used to construct NCT.

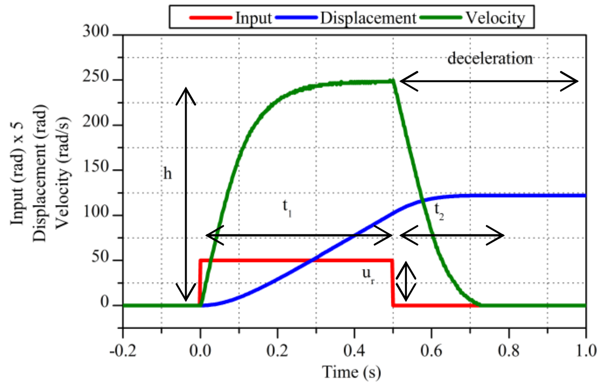

Fig. 2 Open-loop system result.

b) Construct NCT: The displacement and velocity result obtained from open loop experiment is used to construct the NCT. It is constructed by using only deceleration phase of displacement and velocity. Fig. 3 shows the constructed-NCT with inclination near origin of NCT, β is 439 s^{-1}.

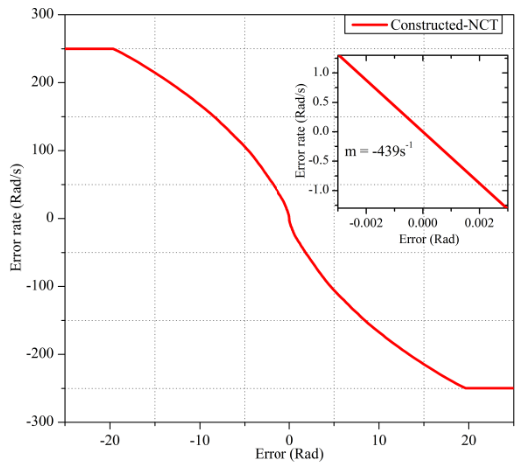

Fig. 3 Constructed NCT

c) PI Compensator designs: The mechanism is driven with the NCTF controller using only the proportional element. The proportional gain is increased to get the sufficient ultimate proportional gain (K_u). The sufficient (K_u) is obtained when sustain periodic output yield during steady state condition. The PI compensator plays an important role to make sure object motion to reach and follow NCT precisely.

On the phase plane, the object motion can be divided into reaching phase and following phase. During reaching phase, the PI compensator controls the object motion to reach the NCT as fast as possible. When the object motion has successfully reach NCT, the PI compensator needs to control the object motion to follow the NCT and ends at its origin which known as the following phase.

Hence to design the PI compensator, the selection of the PI gains must be under the stable region of practical stability limit. The PI gain is selected from the practical stability limit (see Fig. 4) to ensure the system has a promising performance. From the stability limit, the value of PI compensator gains are:

$$K_p = 0.198$$
$$K_i = 0.001$$

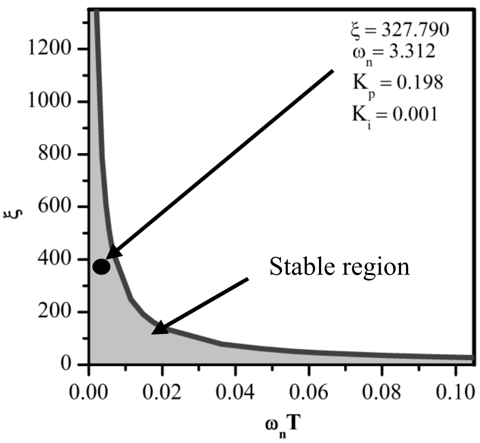

Fig. 4 System stability

3. EXPERIMENTAL RESULT

3.1 Experimental setup

The one mass rotary mechanism is driven by a dc servo motor as shown in Fig. 5. The feedback position is determined by an incremental rotary encoder with resolution 500 counts per revolution. The rated voltage of the dc servo motor is ±10V and the sampling time is 2ms. This system is suitable to use as a test bed to implicate the real machine used in industry for positioning performance.

Two types of motion control performances that is, tracking and positioning performance are experimentally examined. The effectiveness of the CM NCTF controller is evaluated in comparison with a PID controller.

3.2 Positioning control

To evaluate the point-to-point (PTP) performance of the system, the positioning control experiment has been done. The experiment was done using four different amplitudes: 0.5-rad, 1-rad, 1.5-rad and 2-rad. Table 1 shows the controller parameter used for positioning control of a one mass rotary system. Figs. 6~9 show the positioning control experimental result.

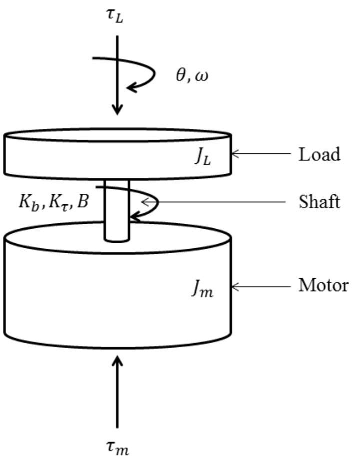

Fig. 5 One mass rotary system structure

Table 1 Controller parameters

Controller	β s^{-1}	K_p	K_i	K_d
CM NCTF	439	1.98×10^{-1}	1×10^{-3}	0
PID	-	12	5×10^{-1}	1.5×10^{-1}

For the positioning control experiment, it is clearly showed that the CM NCTF controller produces better positioning response as compared to the PID controller. The PID controller has a faster rise time than the CM NCTF controller but it produces poor result in term of From the experiment result, the CM NCTF controller produces less 30% error than the PID controller for 0.5-rad input. Similar positioning results are obtained for the rest of input amplitudes. Overall, the experimental results indicate that the PID controller demonstrates larger positioning error than the CM NCTF controller.

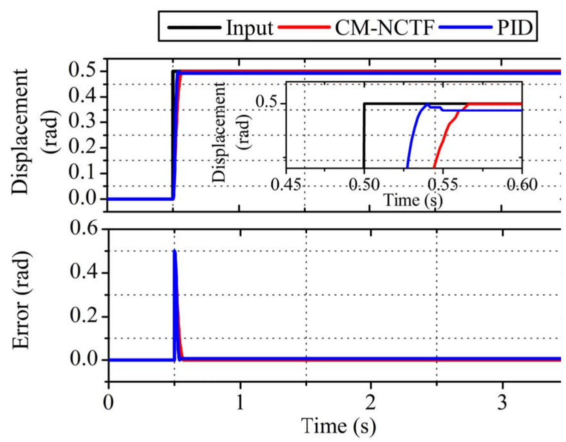

Fig. 6 Experimental response for amplitude 0.5-rad

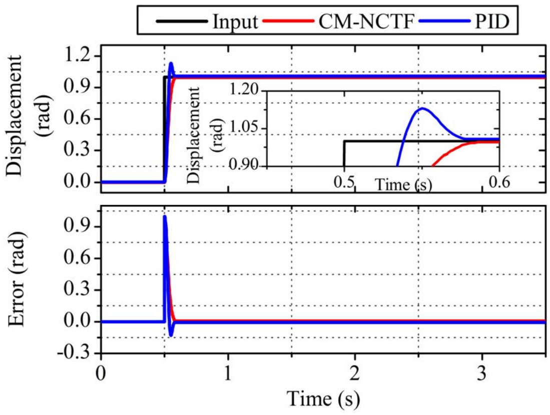

Fig. 7 Experimental response for amplitude 1-rad.

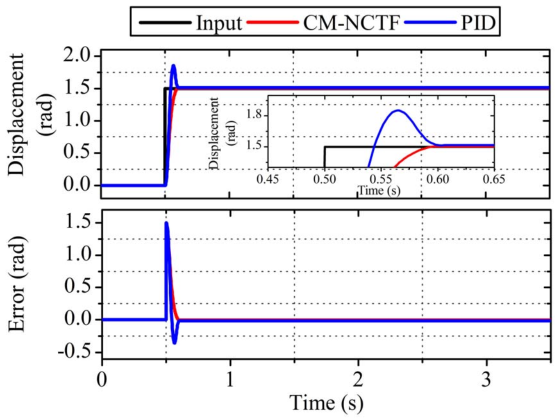

Fig. 8 Experimental response for amplitude 1.5-rad.

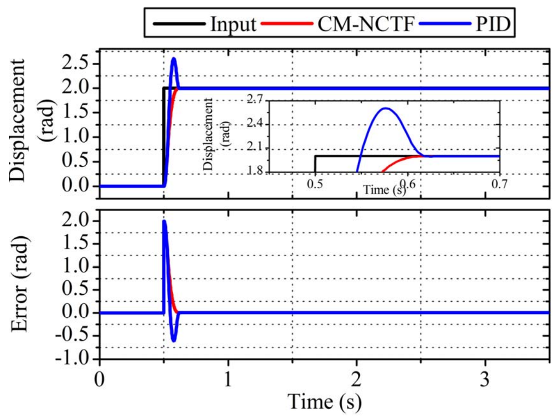

Fig. 9 Experimental response for amplitude 2- rad.

3.3 Tracking control

For tracking control, to evaluate the controller's performance two different amplitudes and two different frequencies for sine wave input is used. Fig. 10 and 11 show tracking control performance for frequency 0.3 Hz and amplitude 0.5 and 1.5 radian. Fig. 12 and 13 show the tracking control results for frequency 0.7 Hz and amplitude 0.5 and 1.5 radian.

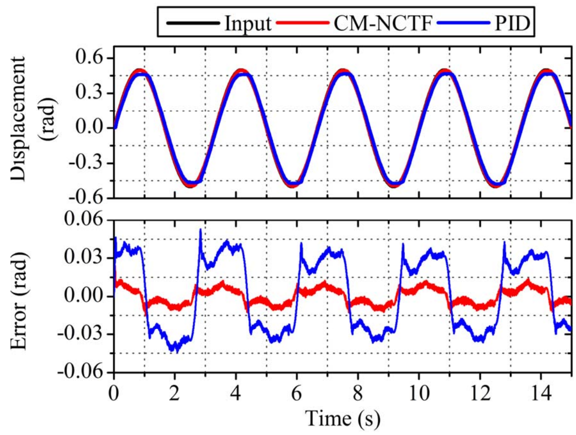

Fig. 10 Experiment tracking result using 0.3 Hz frequency and 0.5 radian amplitude

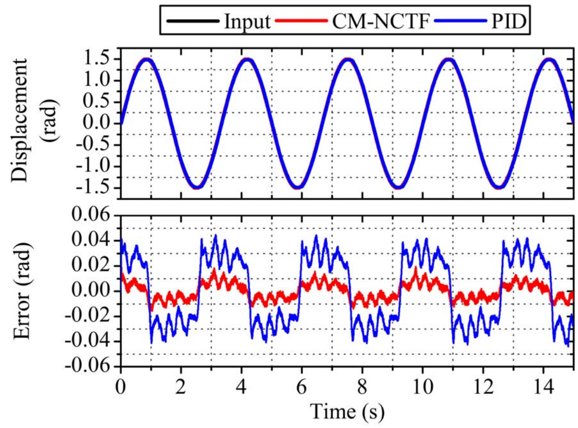

Fig. 11 Experiment tracking result using 0.3 Hz frequency and 1.5 radian amplitude

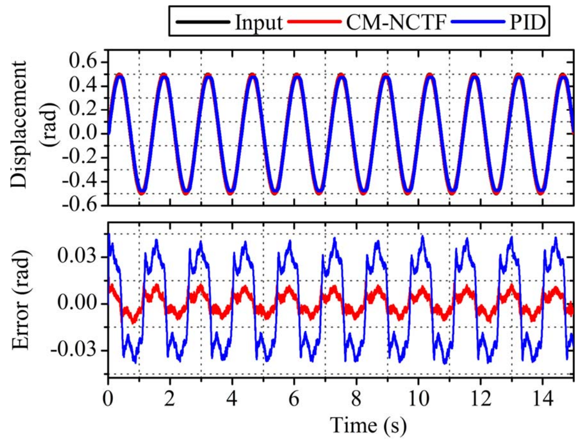

Fig. 12 Experiment tracking result using 0.7 Hz frequency and 0.5 radian amplitude

From the results, the CM NCTF controller demonstrates better tracking performance by showing less tracking error as compared to the PID controller. Table 2 shows the tracking performance results for amplitude input at 0.3 and 0.7-Hz.

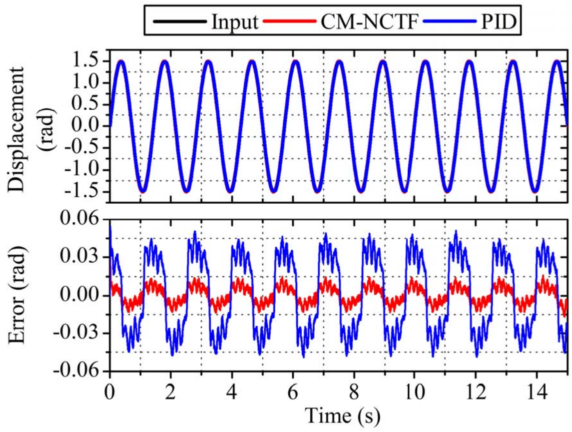

Fig. 13 Experiment tracking result using 0.7 Hz frequency and 1.5 radian amplitude

Table 2 Tracking control performances

Parameter	Controller			
	CM-NCTF			
Frequency (Hz)	0.3		0.7	
Amplitude (Rad)	0.5	1.5	0.5	1.5
Error (Rad)	0.04	0.04	0.03	0.08
	PID			
Frequency (Hz)	0.3		0.7	
Amplitude (Rad)	0.5	1.5	0.5	1.5
Error (Rad)	0.10	0.10	0.08	0.12

At smaller input and lower frequency, the PID controller produces 149% larger error than CM-NCTF controller. Besides, for large input and higher frequency, CM-NCTF controller also produce less error compare to the PID controller as much as 49%. It is clearly shown that, the CM-NCTF controller gives the best tracking performance and robust to parameter variation than the PID controller.

4. ROBUSTNESS

To evaluate the controller robustness, the disturbance rejection of CM-NCTF and PID controller is addressed. Fig. 14 and 15 show the block diagram for both NCTF controller and PID controller.

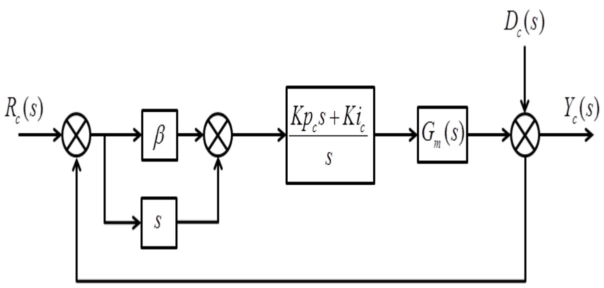

Fig. 14 CM-NCTF controller block diagram

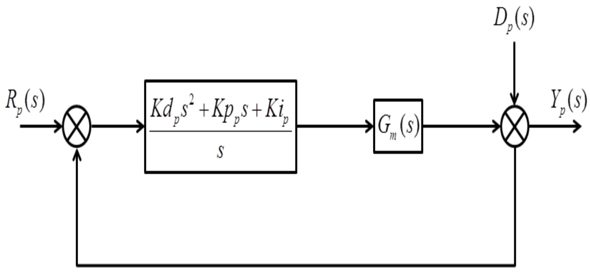

Fig. 15 PID controller block diagram

From the block diagram, the $G_m(s)$ represent by the system transfer function of the DC servo motor. From the diagram, the disturbance rejection characteristics are expressed as following sensitivity function. In order to get a better disturbance rejection performance, the sensitivity function of the closed loop must be low [8] . Eq. 2 shows the sensitivity function of CM-NCTF controller while Eq.3 shows the sensitivity function of PID controller.

$$S_{CM} = \frac{JLs^4 + (JR + bL)s^3 + (bR + K^2)s^2}{\begin{array}{c} JLs^4 + (JR + bL)s^3 + (bR + K^2 + KKp_{CM})s^2 \\ +(\beta KKp_{CM} + KKi_{CM})s + \beta KKi_{CM} \end{array}} \quad (2)$$

$$S_{PID} = \frac{JLs^4 + (JR + bL)s^3 + (bR + K^2)s^2}{\begin{array}{c} JLs^3 + (JR + bL + KKd_{PID})s^2 + \\ (bR + K^2 + KKp_{PID})s + KKi_{PID} \end{array}} \quad (3)$$

Hence, the sensitivity of both controllers is shown in Eg.4 below.

$$\frac{S_{CM}}{S_{PID}} = \frac{Kp_{PID} + Ki_{PID}}{(\beta Kp_{CM} + Ki_{CM})s + Kp_{CM} + \beta Ki_{CM}} \quad (4)$$

From Eq. 9, the sensitivity function of the CM-NCTF controller is able to produces less magnitude than the PID controller. SO, it can be conclude that CM-NCTF controller provides higher disturbance rejection characteristic than the PID controller.

5. CONCLUSION

For the conclusion, for positioning and tracking control experiment, CM-NCTF controller demonstrates better response of all. For PID controller, it produces bad positioning and tracking performance. It yields large overshoot during positioning performance large error during tracking performance. As for the disturbance rejection characteristic, it is clearly shows that CM-NCTF controller possesses low sensitivity result. This indicate that the CM-NCTF controller have higher disturbance rejection characteristic compared to PID controller.

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