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# POINT TO POINT POSITIONING CONTROL OF ROTARY SYSTEM WITH NCTF CONTROLLER AND PID CONTROLLER

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## ABSTRACT

A practical control scheme is proposed for a one mass rotary system. It was written to demonstrate the controller performance towards positioning and tracking control. For this system, the Nominal Characteristic Trajectory Following (NCTF) controller is proposed and improved. The objective of NCTF controller is to make the object motion to follow the NCT and ends at it origin. Generally, the NCTF controller consists of a Nominal Characteristic Trajectory (NCT) obtained from open loop response and Proportional Integral (PI) compensator. The CM-NCTF controller is proposed for evaluating the motion performance and compare with the conventional NCTF controller and PID controller. For positioning control, both NCTF controllers demonstrate almost identical positioning performance. However, for tracking control, CM-NCTF controller demonstrates better tracking performance than the conventional NCTF controller with the smallest motion error presented. Besides, the robustness of the CM-NCTF controller to the variation load is also examined.

**Keywords:** one mass rotary system, NCTF controller, PID Controller positioning, tracking.

## INTRODUCTION

Positioning system development has raised the attention of researchers and industry developers, especially for those who seek for automation development such as robotic field, machine tools, precision control and manufacturing system. They normally demand to have a precise and high speed positioning performance in order to maintain their product quality and quantity. So, to produce a promising positioning system, there are few things can be done such as 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 will be proposed 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 influences of disturbance or uncertainties. The saturation that produced by a system actuator may cause the slow system performance and affecting the system stability, while too much friction may cause too large steady state error and limit output cycles near the reference input. Hence, the designed controller must be able to consider all mentioned issues to possess a promising control performance.

For that reason, many controllers have been proposed in order to improve positioning performance and robustness such as disturbance observer(Yoon, Jung and Sul, 2010), sliding mode control(Liu, Wu and Zhang, 2011)and time optimal control(Shieh and Lu, 2010)has been proposed for the positioning and tracking control performance. The controllers mentioned above may have good response but it require complexes design procedure.

For some reason, engineers prefer to use classic controller than an advanced controller in industry application. Classic controller basically has a simple control structure and easy to understand. However, for some reason, the controller is not robust enough especially for a system which has high nonlinearities problem. The classical controller will reach its limitation when systems require high robustness characteristic and high positioning performance.

As an example, for high positioning performance, a robust digital controller has been designed which consist four elements(Liu, Wu and Zhang, 2011). There is friction compensator, disturbance observer, feedback controller and also feed forward controller. The controller performance was compared with another digital tracking controller that is ZPETC-PD Controller and ZPETC-PD controller with friction compensation. The ZPETC-PD controller with friction compensation has yield small error compared to the other controllers. Even though it is able to compensate the disturbance and uncertainties, but it has a complexes design procedure, and the system parameter variation must be known to design it. The controller demonstrated a good response because it was designed together with friction compensation. The implementation of disturbance observer also popular among researchers because it can reduce the effect of disturbance to the system. As an example, a disturbance observer(Chen, 2006; Jia, 2009) approach has been studied well through many researches and case studies.

Despite the entire controllers that have been suggested before by other researchers, most of them require exact and accurate model parameters which sometimes troublesome the researcher in the controller design procedures. Hence, the Nominal Characteristic Trajectory Following (NCTF) controller is proposed for this research as a practical method. The study on NCTF Controller was done towards various type of system. In(Sato, Shimokohbe and Wahyudi, 2003), NCTF controller was first time proposed for a rotary system. Then, the performance of NCTF controller has been proposed and examined using ball screw mechanism for

point-to-point (PTP) and tracking control(Maeda and Sato, 2008; Sato and Maeda, 2009). The NCTF controller also has been proposed to 1-DOF air slide mechanism for non-contact mechanism and it proves that the NCTF control design procedures is independent of friction characteristic(Chong and Sato, 2010, 2012). For this paper, the conventional NCTF controller is proposed for positioning and tracking control performance experimentally. Besides, the CM-NCTF controller has been proposed to improve tracking performance of the conventional one.

Basically, conventional NCTF controller is the first generation of NCTF controller. The controller has been improved to Continuous Motion NCTF (CM-NCTF) controller to improve system accuracy in tracking motion and has a rapid positioning response. Referring to(Rozilawati binti Mohd Nor; Chong Shin Horng, 2013; Mohd Nor and Chong, 2014; Mohd Nor, Rozali and Horng, 2018), the CM-NCTF controller demonstrates almost identical positioning performance as compared to the conventional one. A part from that, there is other experiment done to evaluate the performance of the NCTF controller too with various type of system recently such as in (My, Akmeliawati and Wijaya, 2018; Herianto, Riyadi and Mastrisiswadi, 2020). Hence, this paper will demonstrate both NCTF controllers performance and comparing to the PID controller for positioning and tracking performance. Then the experiment also been done to evaluate the controller robustness and tracking motions.
The rest of this paper is written as follows: Section 2 shows the controller concepts and design procedures. Section 3 focuses on experimental setup and section 4, shows the result and discussion of positioning and tracking control performance. The last part of the paper will conclude the whole presented studies in this paper.

## CONTROLLER CONCEPT AND DESIGN PROCEDURE

### A. NCTF Controller structure

The NCTF Controller was proposed since 2002 with its simple and practical design procedure. The controller design procedure is much simpler and easy to understand because it does not require any known model parameter. NCTF Controller consists of two important elements that are nominal characteristic trajectory (NCT) and a PI compensator. The NCT is constructed using object responses during open loop experiment and the PI compensator is designed so that it can 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 the NCT has been designed, the PI element is designed based on the stability of the system. Figure-1 and Figure-2 shows the physical structure for both conventional NCTF and CM-NCTF controller. Figure-3 shows the constructed NCT the control law for conventional NCTF controller is shown in Eq. (1):

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

Where

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

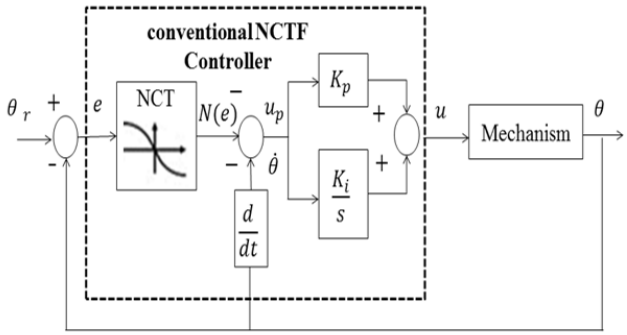


**Figure-1.** Conventional NCTF controller structure.

Basically, both NCTF controllers have almost identical control laws in PTP. However, CM-NCTF controller is improved to rapid up the object motion and reduce tracking motion errors.

The control laws for CM-NCTF controller are shown in Eq. (2):

$$U(s) = (K_p + \frac{K_i}{s})U_p(s) \tag{2}$$

Where

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

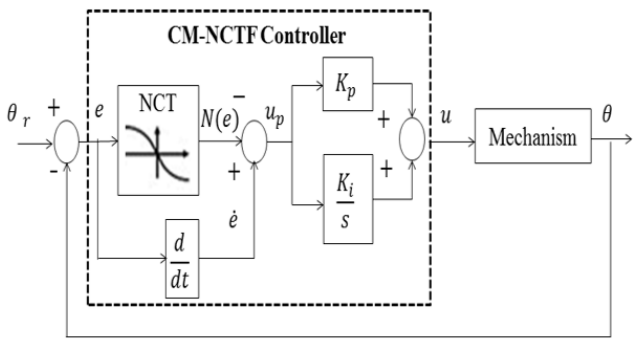


**Figure-2.** CM-NCTF controller structure.

### B. Design Procedure

From the physical structure of conventional NCTF and CM-NCTF controllers, both controllers have almost similar design. The design procedures for NCTF controller are as below:

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**a) System open loop response:** The system is driven by stepwise open loop input and its displacement and velocity response are measured. The input amplitude is designed to not exceed the rated input of the system to avoid the system from damaged. The selected input must obtain fast and smooth response. The specification of selected input is 10V in amplitude, and sampling time 0.002 second. Figure-3 shows the open loop response result. The result obtained will be used to construct NCT for NCTF controller. The information that can be gathered from open loop result are time for the object to accelerate ($\boldsymbol{t_1}$), time for the system to decelerate ($\boldsymbol{t_2}$), input voltage ($\boldsymbol{u_r}$), and maximum velocity ($\boldsymbol{h}$). This information is needed to construct the NCT.

**b) NCT construction:** The displacement and velocity results obtained from open loop experiment is used to construct the NCT. It is constructed by using only deceleration phase of displacement and velocity. Figure-4 shows the constructed-NCT. The inclination near origin of NCT is $\boldsymbol{m = 439s^{-1}}$.

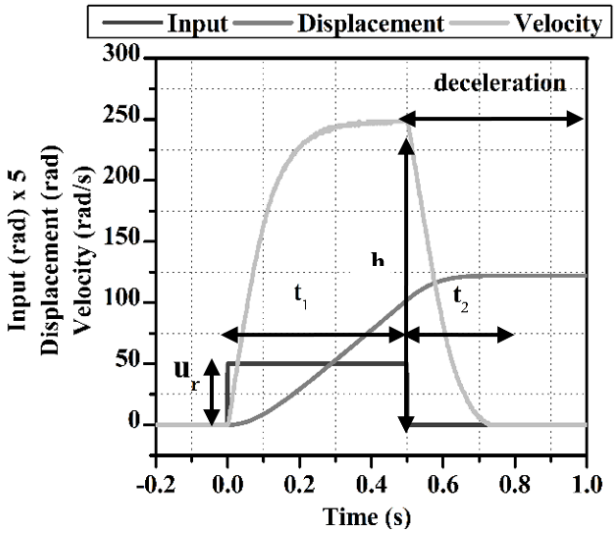


**Figure-3.** Open loop result.

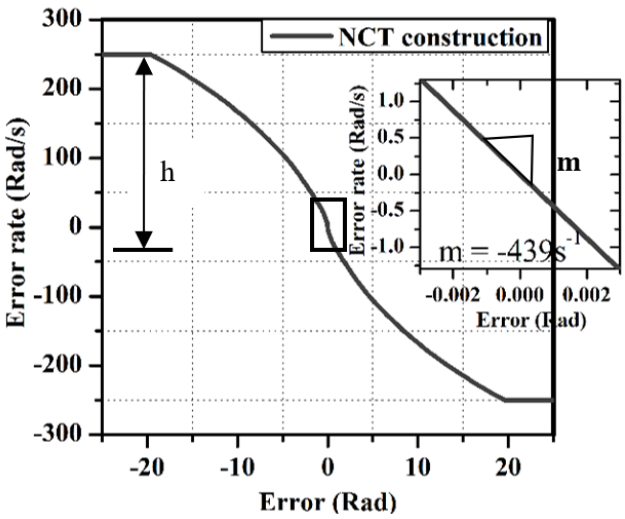


**Figure-4.** Constructed-NCT.

The Beta($\beta$) value is represented by inclination near origin of NCT which follows Eq. 3. From the equation, by letting the input into actuator equal to zero, and considering $e = \theta_r - \theta$ the value of $m$ is obtained. From the figure above, the inclination near the origin is:

$$\frac{d\dot{e}}{de} = m$$
$$\beta = -m \qquad (3)$$
$$\beta = 439s^{-1}$$

**c) PI Compensator designs:** The proportional gain is increased to get the sufficient ultimate proportional gain $(u_p)$. The sufficient $(u_p)$. is obtained when sustain periodic output yield during steady state condition. PI compensator plays an important role for NCTF controller to make sure object motion to follow NCT.

Since NCTF controller does not require the exact parameter. Hence the parameter value of the compensator is derived from $h$ and $\beta$ parameter obtain from the constructed-NCT. The object is assumed to followed 2nd order system by neglected the nonlinear characteristic as shown in Eq. 2.

$$\frac{\theta(s)}{U(s)} = K\frac{\beta}{s(s+\beta)}$$

Where, represents output displacement, $U(s)$represents control signal and $K, \beta$ is simplified object parameter. Since the object is driven by DC servo motor, hence the simplified model is reasonable. The information of simplified object parameter is obtained from system open loop response. The information of $\beta$ is as stated in Eq. 3. While the information of maximum velocity in open loop result is related to steady state velocity due to input of the actuator $u_r$ as stated below.

$$Ku_r = -h$$

$$K = \frac{-h}{u_r}$$

For a closed loop system transfer function,

$$\frac{\theta(s)}{\theta_r(s)} = \frac{\beta}{(s+\beta)}(G(s))$$

Where:

$$G(s) = \frac{K_pK\beta s + K_iK\beta}{s^2 + K_pK\beta sK_iK\beta}$$

By comparing with the 2nd order characteristic transfer function, the value of $K_p$ and $K_i$ is obtain as below:

$$K_p = \frac{2\zeta\omega_n u_r}{mh} \qquad K_i = \frac{{\omega_n}^2 u_r}{mh}$$

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To obtain $K_p$ and $K_i$ parameter, the choice of suitable $\zeta$ and$\omega_n$ is important to obtain a good positioning and tracking performance. The $\zeta$and$\omega_n$is obtained from practical stability result. Different value of $\zeta$ and$\omega_n$ may result in different performance. Figure-5 shows the practical stability graph result obtained from experiment. To get the suitable $K_p$ and $K_i$ values, the selection of $\zeta$ and$\omega_n$ must not exceed the boundary. The region inside the boundary is stable region for the system.

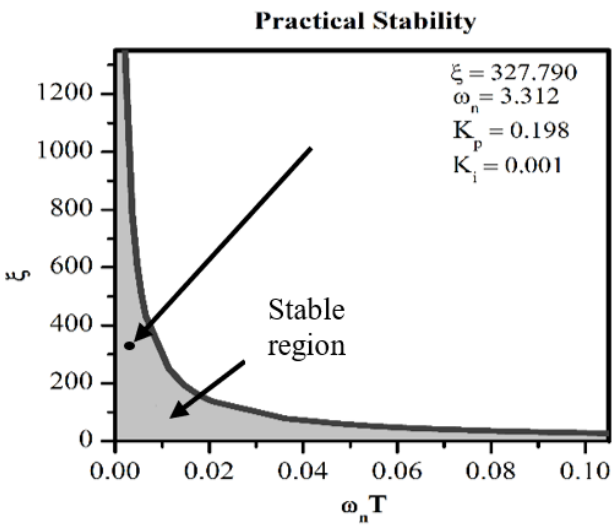


**Figure-5.** Practical stability graph.

For this system, the suitable value for $\zeta$ and$\omega_n$ is 327.790 and 3.312 respectively. By substituting into equation for $K_p$ and $K_i$, the value obtain is as below:

$K_p = 0.198$
$K_p = 0.001$

## EXPERIMENTAL SETUP

The one mass rotary system was used as the test bed to examine the effectiveness of the NCTF controller for positioning control. Figure-6 shows physical structure of a one mass rotary system.

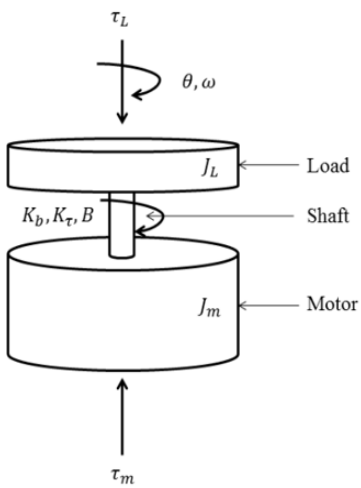


**Figure-6.** One mass rotary system.

The system is driven by DC servo motor and an incremental rotary encoder with 500 counts per resolutions. The rated voltage for the DC servo motor is $\pm 10V$ and for experiment, the sampling time used is 0.002s.

## PERFORMANCE EVALUATION

This paper proposed on two types of NCTF controller to evaluate both positioning and tracking performance for a one mass rotary system. The performance of both NCTF controllers then was compared to PID controller. PID controller is designed to have same damping frequency as NCTF controller to make sure the result obtained is comparable

### A. Positioning Control Performances

The experiment was done using three different positions which are 0.5 radian, 1 radian, 1.5 radian and 2 radians. Table-1 shows the controller parameter used for positioning control of a one mass rotary system. Figures-7, 8, 9 and 10 shows the positioning control experiment result.

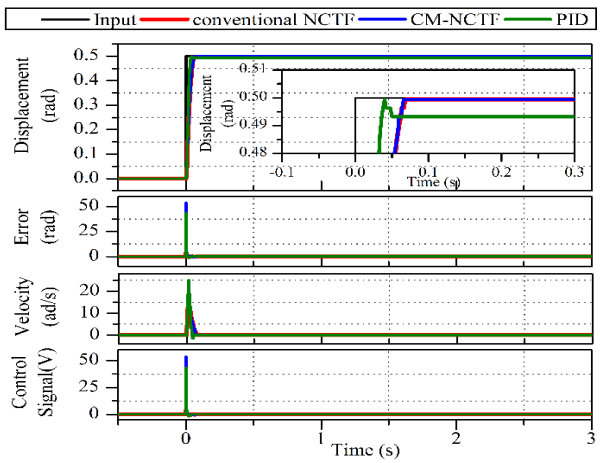


**Figure-7.** Experiment of positioning control using 0.5 radian input.

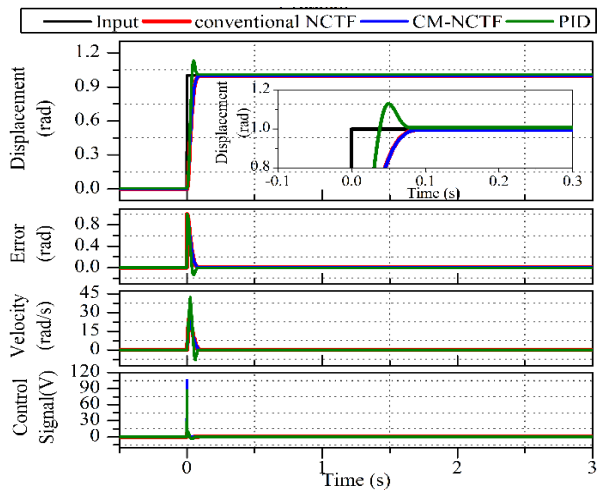


**Figure-8.** Experiment of positioning control using 1 radian input.

**Table-1.** Controller parameters.

| Controller | β $s^{-1}$ | $K_p$ | $K_i$ | $K_d$ |
|---|---|---|---|---|
| C-NCTF | 439 | 0.198 | 0.001 | 0 |
| CM-NCTF | | 0.198 | 0.001 | 0 |
| PID | - | 12 | 0.5 | 0.15 |

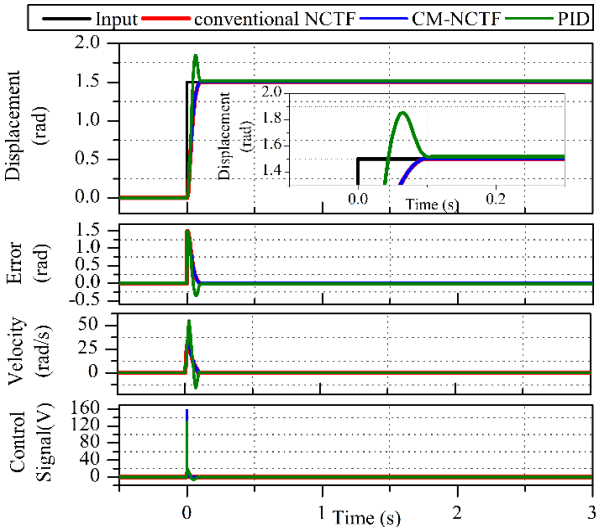


**Figure-9.** Experiment of positioning control using 1.5 radian input.

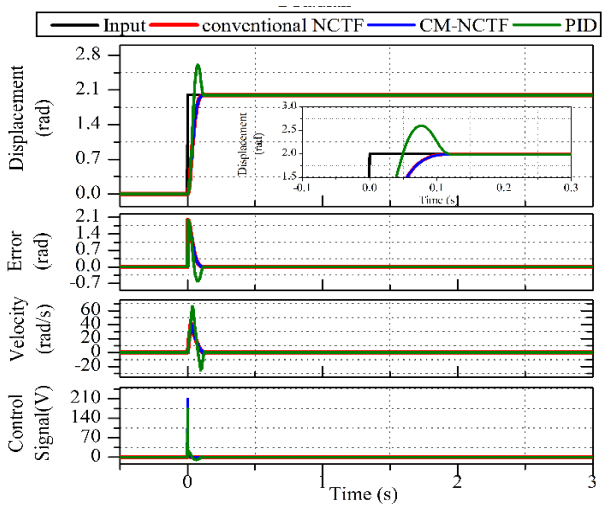


**Figure-10.** Experiment of positioning control using 2 radian input.

The PID controller produces large overshoot especially when the desired position is increased. Both NCTF controllers also produce less error than PID controller with different input. When 0.5 radian input use, PID controller produce 18% larger error than conventional NCTF controller and 30% larger error than CM-NCTF controller. The result is as shown in Table -1.

**Table-2.** Conventional NCTF controller positioning parameter evaluation.

| 10 x N | Controller | Input (Radian) | Rise Time(s) | Settling Time(s) ($\times 10^{-2}$) | Overshoot (%) ($\times 10^{-2}$) | Error(Radian) ($\times 10^{-3}$) |
|---|---|---|---|---|---|---|
| Mean | Conventional NCTF | 0.5 | 4.03 | 1.06 | 6.00 | 3.30 |
| | | 1.0 | 4.45 | 1.07 | 0.00 | 4.10 |
| | | 1.5 | 4.34 | 1.09 | 6.00 | 1.70 |
| | CM-NCTF | 0.5 | 3.86 | 1.06 | 0.00 | 3.00 |
| | | 1.0 | 4.26 | 1.07 | 0.00 | 3.70 |
| | | 1.5 | 5.32 | 1.08 | 6.00 | 1.60 |
| | PID | 0.5 | 2.06 | 1.03 | 69.00 | 3.90 |
| | | 1.0 | 2.41 | 1.07 | 1390.00 | 5.20 |
| | | 1.5 | 2.66 | 1.09 | 2177.00 | 9.90 |
| 10 x N | Controller | Input (Radian) | Rise Time(s) ($\times 10^{-2}$) | Settling Time(s) ($\times 10^{-2}$) | Overshoot (%) | Error (Radian) ($\times 10^{-3}$) |
| Standard Deviation | Conventional NCTF | 0.5 | 0.04 | 0.16 | 0.19 | 2.20 |
| | | 1.0 | 0.04 | 0.05 | 0.00 | 2.00 |
| | | 1.5 | 0.02 | 0.04 | 0.10 | 0.10 |
| | CM-NCTF | 0.5 | 0.04 | 0.03 | 0.00 | 1.90 |
| | | 1.0 | 0.03 | 0.05 | 0.00 | 1.10 |
| | | 1.5 | 0.02 | 0.04 | 0.10 | 0.10 |
| | PID | 0.5 | 0.05 | 0.11 | 0.65 | 2.20 |
| | | 1.0 | 0.11 | 0.50 | 3.95 | 1.70 |
| | | 1.5 | 0.14 | 0.14 | 2.89 | 2.10 |

*N=Reapeatability

When 1.5 radian reference input use, the PID controller produce 482% larger error than conventional NCTF and 518% larger error than CM-NCTF. For error result, as the reference input increase, the error produce also increases especially for the PID controller. Other than comparing the error, the overshoot, the rise time and settling time also produce an obvious different between controllers.

**B. Tracking Control Performances**

For tracking control, to evaluate the controllers performance two different amplitudes and three different frequencies for sine wave input is used. Figures 11 and 12 show tracking control performance for frequency 0.3 Hz and amplitude 0.5 and 2 radian. Figures 13 and 14 show the tracking control results for frequency 0.7 Hz and amplitude 0.5 and 2 radian.

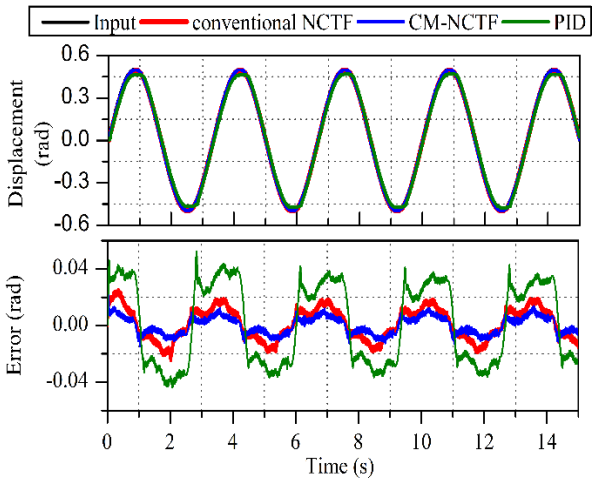


**Figure-11.** Experiment of tracking control for 0.3 Hz and 0.5 radian amplitude.

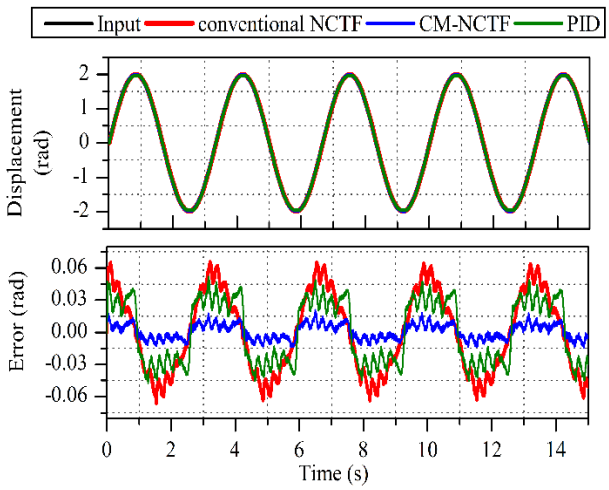


**Figure-12.** Experiment of tracking control for 0.3 Hz and 2 radian amplitude.

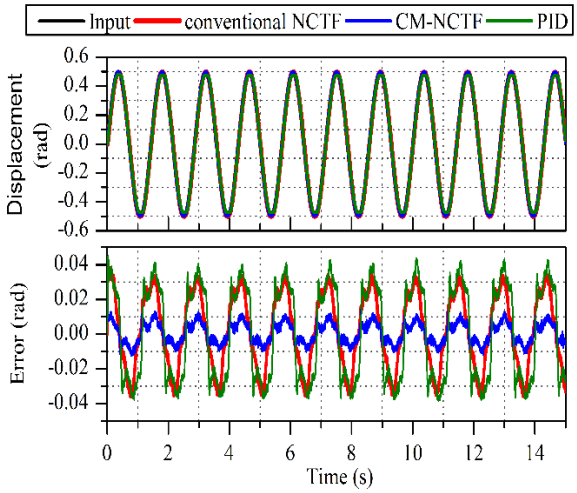


**Figure-13.** Experiment of tracking control for 0.7 Hz and 0.5 radian amplitude.

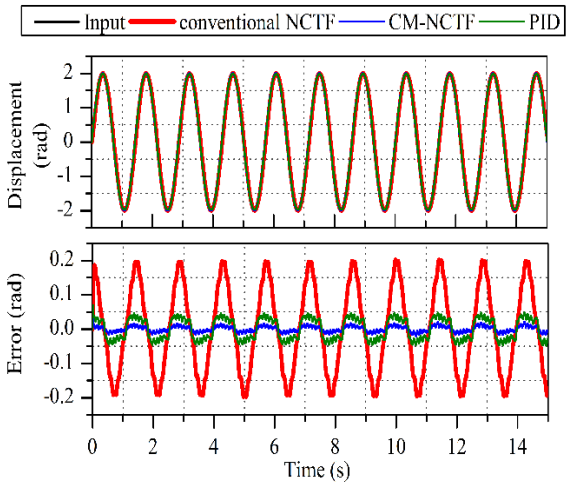


**Figure-14.** Experiment of tracking control for 0.7 Hz and 2 radian amplitude.

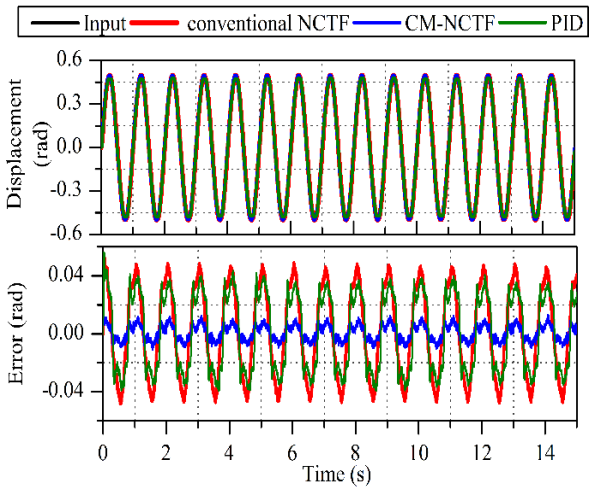


**Figure-15.** Experiment of tracking control for 1 Hz and 0.5 radian amplitude.

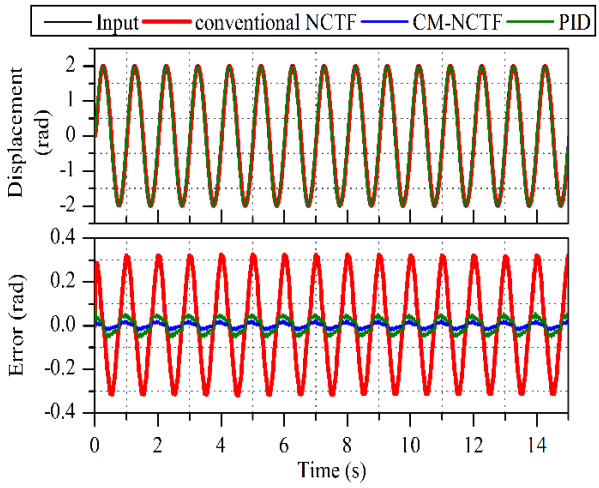


**Figure-16.** Experiment of tracking control for 1 Hz and 2 radian amplitude.

Figures 15 and 16 show the tracking control results for frequency 1 Hz and amplitude 0.5 and 2 radian. From tracking result, it shows that at lower frequency and lower amplitude, less error produce for CM-NCTF controllers. At lower amplitude and frequency, Conventional NCTF controllers perform slightly better tracking than PID controller. However, at large amplitude and frequency, PID controller tracking better than Conventional NCTF controller.

**Table-3.** Tracking control Parameter Evaluation.

| Parameter | Controller | | | | | |
|---|---|---|---|---|---|---|
| | Conventional NCTF | | | | | |
| Frequency (Hz) | 0.3 | | 0.7 | | 1 | |
| Amplitude (Rad) | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 |
| Error (Rad) | 0.050 | 0.132 | 0.074 | 0.399 | 0.102 | 0.644 |
| | CM-NCTF | | | | | |
| Frequency (Hz) | 0.3 | | 0.7 | | 1 | |
| Amplitude (Rad) | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 |
| Error (Rad) | 0.039 | 0.044 | 0.032 | 0.077 | 0.033 | 0.100 |
| | PID | | | | | |
| Frequency (Hz) | 0.3 | | 0.7 | | 1 | |
| Amplitude (Rad) | 0.5 | 2 | 0.5 | 2 | 0.5 | 2 |
| Error (Rad) | 0.097 | 0.099 | 0.084 | 0.117 | 0.096 | 0.146 |

At smaller input and lower frequency, the Conventional NCTF controller produces 28% larger error than CM-NCTF while PID controller produces 149% larger error. It shows that, at this condition, apart from CM-NCTF controller, Conventional NCTF controller performs better than PID controller. While CM-NCTF demonstrated smoother tracking performance compared to other controllers. It can be proved from the Table-3.

From Table-3, it shows the tracking error result for all controllers. From tracking result graph, it clearly shows that CM-NCTF controller perform smoother performance and produce lesser error. However, at large input and higher frequency, Conventional NCTF controller produced 544% larger error than CM-NCTF controller compared to the PID controller with 49% larger error. In this condition, PID controller demonstrates better tracking performance, and it is because classical controller usually performs better when large position applied. However, from all observation, CM-NCTF controller gives the best tracking performance and robust to parameter variation.

## ROBUSTNESS EVALUATION

Other than analyzing controller performance towards positioning and tracking control, experiment also done to analysed controller robustness towards mass changing. There are three different mass and different dimension used which are 75 gram, 120 gram and 208 gram. Figures-17, 18 and 19 show the positioning performance of all controllers towards 1 radian desired position.

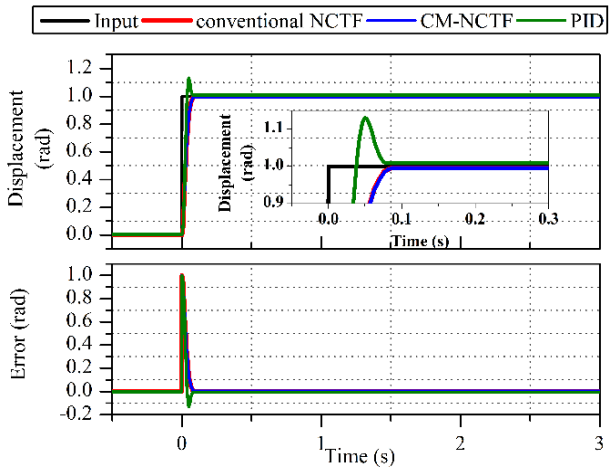


**Figure-17.** Original mass (75 gram).

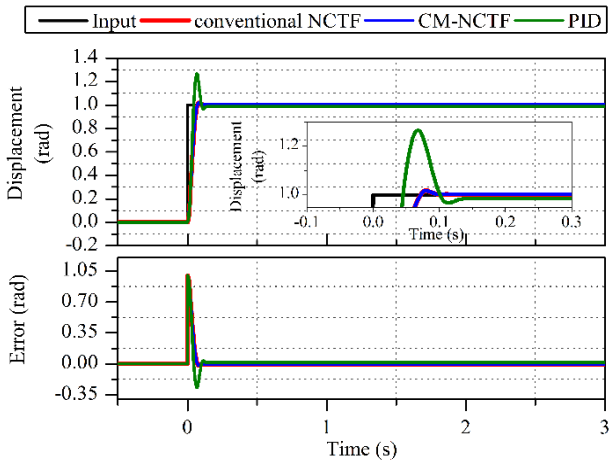


**Figure-18.** 2nd mass (120 gram).

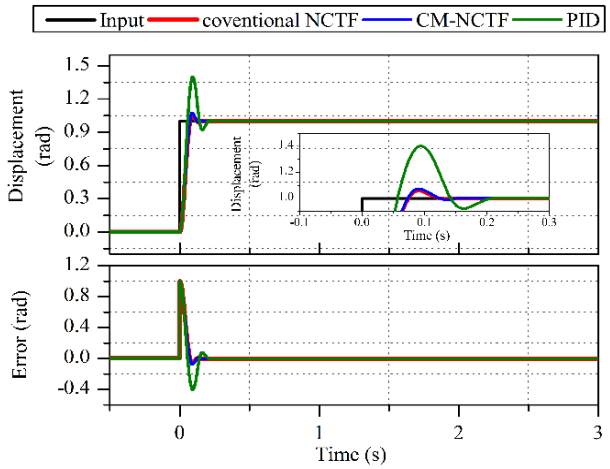


**Figure-19.** 3rd mass (208 gram).

When mass is changing, both NCTF controller still demonstrate better positioning response compared to PID controller. PID controller produces large overshoot when mass is changing, while for NCTF controller, only slightly overshoot produces.

## CONCLUSIONS

For the conclusion, for positioning and tracking control experiment, CM-NCTF controller demonstrates better response of all. Even though Conventional NCTF controller demonstrate almost identical positioning performance, but it has a bad tracking result when larger input and higher frequency applied. For PID controller, it produces bad positioning and tracking performance.

It yields large overshoot during positioning performance large error during tracking performance. When different mass applied to the mechanism, CM-NCTF also produce the smoother response of all and it prove that CM-NCTF controller is robust to parameter variation either frequency, position or mass changing.

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