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NCTF Control Method of Two Mass System for PTP Positioning

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Abstract- **In this study, a nominal characteristic trajectory following (NCTF) controller for point-to-point (PTP) positioning system is introduced for two mass systems and its performance is evaluated. The NCTF controller consists of a nominal characteristic trajectory (NCT) and a compensator. The objective of the NCTF controller is to make the object motion follow the NCT and end at its origin. Therefore, the NCT is used as an intended object motion and the compensator is used to make the motion of the controlled object follow the NCT. The NCTF controller is designed based on a simple open-loop experiment of the object and no information except the NCT is necessary for controller design. The effectiveness of the NCTF controller is evaluated and discussed through simulations. The effect of the design parameters on the robustness of the NCTF controller to inertia and friction variations is evaluated. The effect on the positioning performance and robustness are compared with conventional PID controller.**

I. INTRODUCTION

Positioning systems play an important role in industrial engineering applications such as advanced manufacturing systems, semiconductor manufacturing system and robot systems. A nominal characteristic trajectory following (NCTF) controller as practical controller for point-to-point positioning systems had been proposed. The NCTF controller consists of two elements namely a nominal characteristic trajectory (NCT) and a compensator. It had been reported that the NCTF had a good positioning performance and robustness to parameters variations [3].

However, the NCTF controller is designed based on assumption that the positioning system is a one-mass system. The positioning system can only be assumed as one-mass positioning system in the case a rigid coupling (a coupling with high stiffness) is used and there are no flexible elements. On the other hand, the systems should be modeled as multi-mass system when flexible couplings (couplings with low stiffness) or other flexible elements are used to connect the actuator to other elements. In multi-mass systems, low stiffness elements such as couplings cause mechanical resonance, which may reduce positioning accuracy. Therefore, the NCTF controller can not be used directly in the case there is a flexible connection between elements of the positioning systems. Improvements in the design of NCT and compensator are required to make the NCTF controller is suitable for multi-mass positioning system.

II. NCTF CONTROL CONCEPT

The structure of the NCTF control system is shown in Fig.1. The NCTF controller consists of a NCT and a compensator. The NCTF controller works under the following two assumptions: a) A DC or an AC servo motor is used as an actuator of the object. b) PTP positioning systems are discussed, so θr is constant and θr' =0. Here, the objective of the NCTF controller is to make the object motion follow the NCT and end at the origin of the phase plane (*e, e'*). Signal *u*p shown in Fig.1 represents the difference between the actual error rate *e'* and that of the NCT. The value of u_p is zero if the object motion perfectly follows the NCT. The compensator is used to control the object so that the value of u_p, which is used as an input to the compensator, is zero.

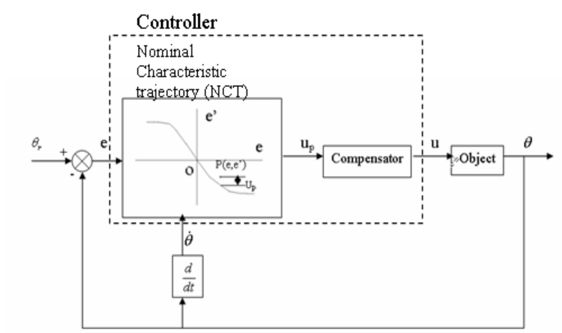


Fig 1: Structure of NCTF control system for PTP positioning.

Fig.2 shows an example of object motion controlled by the NCTF controller. The object motion comprises two phases: one is the reaching phase and the other, the following phase. In the reaching phase, the compensator forces the object motion to reach the NCT as fast as possible. In the following phase, the compensator controls the object motion to follow the NCT and end at the origin. The object motion stops at the origin, which represents the end of the positioning motion. Thus, the NCT governs the positioning response performance.

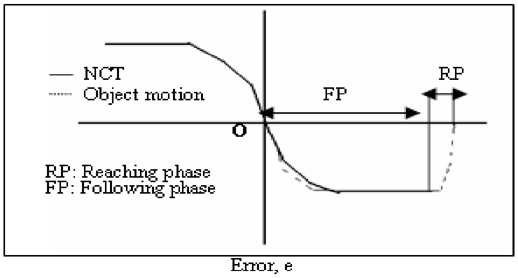


Fig 2: NCT and object motion.

The NCTF controller is designed based on a simple open-loop experiment of the object as follows [4]:

1) Open-loop-drive the object with a stepwise input and measure the displacement and velocity responses of the object.
2) Construct the NCT by using the object responses. Since the NCT is constructed based on the actual responses of the object, the NCT includes effects of nonlinear characteristics such as friction and saturation.
3) Design the compensator by using the NCT information. The NCT includes information of the actual object parameters. Therefore, the compensator can be designed by using only the NCT information.

Due to the fact that the NCT and the compensator are constructed from a simple open-loop experiment of the object, the exact model including the friction characteristic and the conscious identification task of the object parameters are not required to design the NCTF controller. The controller adjustment is easy and the aims of its control parameters are simple and clear.

III. Controller Design

A. NCT Constructions

In order to construct the NCT, a simple open-loop experiment has to be conducted. In the experiment, an actuator of the object is driven with a stepwise input and, displacement and velocity responses of the object are measured. Fig.3 shows the stepwise input and, the velocity and displacement responses of the object. In this case, the object vibrates due to its mechanical resonance [5]. In order to eliminate the influence of the vibration on the NCT, the object response must be averaged. The exact model of the object used only for making simulation is shown in Table I.

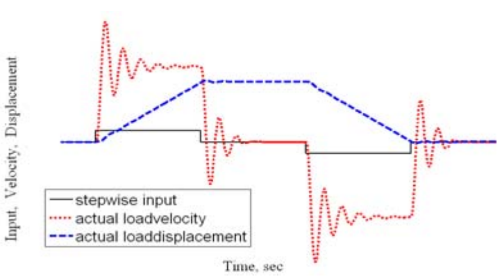


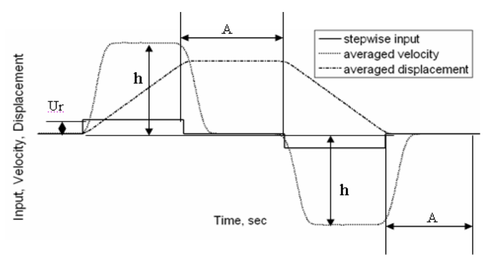
Fig 3: Input and actual object response

TABLE I
Nominal Object Parameters

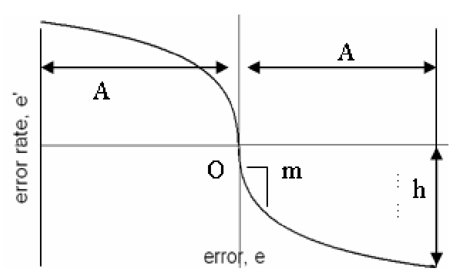
Parameter	Value	Unit
Motor inertia, J_m	11.17e-6	Kgm^2
Inertia load, J_l	11.5e-6	Kgm^2
Stiffness, K_c	0.6	Nm/rad
Motor resistance, R	5.5	
Motor inductance, L	0.85e-3	H
Torque constant of the motor, K_t	0.041	Nm/A
Motor voltage constant, K_b	0.041	Vs/rad
Frictional torque, T_f	0.0027	Nm
Motor viscous friction, B_m	8.35e-6	Nms/rad
Load viscous friction, B_l	8.35e-6	Nms/rad

In Fig.4, moving average filter is used to get the averaged response because of its simplicity [6]. The moving average filter operates by averaging a number of points from the object response to produces each point in the averaged response. The averaged velocity and displacement responses are used to determine the NCT. Since the main problem of the PTP motion control is to stop an object at a certain position, a deceleration process (curve in area *A* of Fig. 4) is used. Variable *h* in Fig.4 is the maximum velocity, which depends on the input step height. From the curve in area *A* and *h* in Fig.4 (a), the NCT in Fig.4 (b) is determined.

There are two important parameters in the NCT as shown in Figure. 4(b): the maximum error rate indicated by *h*, and the inclination of the NCT near the origin indicated by *m*. As discussed in the following section, these parameters are related to the dynamic parameters of the object. Therefore, the parameters are used to design the compensator.



a) Stepwise input and response



b) Nominal characteristic trajectory

Fig 4: Construction of the NCT

An exact modeling including friction and conscious identification processes are not required in the NCTF controller design. The compensator is derived from the parameter m and h of the NCT. Since the DC motor is used as the actuator, the simplified object can be presented as a following fourth order system: The NCT is determined based on the averaged object response which is does not include the vibration.

$$G_o(s) = \frac{\Theta(s)}{U(s)} = K\frac{\alpha_2}{s(s+\alpha_2)}\frac{\omega_f^2}{s^2+2\zeta_f\omega_f s+\omega_f^2} \qquad (1)$$

Where $\Theta(s)$ represents the displacement of the object, U(s), the input to the actuator and K, ζ_f, α_2 and w_f are simplified object parameters. The NCT is determined based on the averaged object response which is does not include the vibration. So, it can be assumed that the averaged object response is a response of the averaged object model as follows:

$$\frac{\Theta_{av}(s)}{U(s)} = \frac{K\alpha_2}{s(s+\alpha_2)} \qquad (2)$$

Where $\Theta_{av}(s)$ is the averaged load displacement, U(s), input to the actuator and K and α_2 are simplified object parameters.

B. Compensator Design

The following PI compensator is proposed for two mass systems:

$$G_c(s) = \frac{(K_p s + K_i)(s^2 + 2\zeta_f\omega_f s + \omega_f^2)}{s} \qquad (3)$$

The compensator is used so that the poles of simplified object model which cause the vibration was canceled. The compensator parameters K_i and K_p are designed by using w_n and ζ as the design parameters as follows:

$$K_p = \frac{2\zeta\omega_n}{\alpha_2 K\omega_f^2} = \frac{2\zeta\omega_n u_r}{mh\omega_f^2} \qquad (4)$$
$$K_i = \frac{\omega_n^2}{\alpha_2 K\omega_f^2} = \frac{\omega_n^2 u_r}{mh\omega_f^2}$$

A higher w_n and a larger ζ are preferable in the compensator design. However they are constrained by the slew rate of the power amplifier and sampling time of the systems. The compensator and the simplified object model of the NCTF control system is constructed as shown in Fig 5.

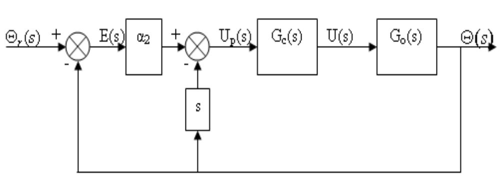


Fig 5: Simplified NCTF control system

IV. SIMULATION RESULTS

The detailed model of the object used only for making simulations is shown in Fig.6. In the detailed model of the object, friction and saturation are taken into consideration [1]. The significance of this research lies in the fact that the simple and ease control design for high precision positioning system is required in practical application. By improving the NCTF controller, it will be more reliable and practical for realizing high precision positioning systems not only for one-mass but also for two-mass positioning systems.

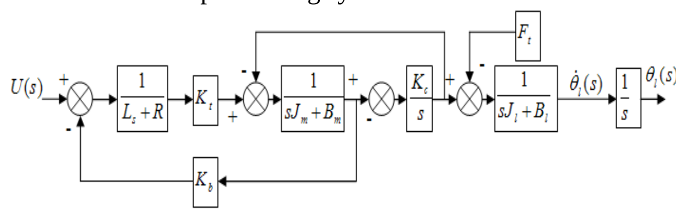


Fig 6: Dynamic model of the object

According to Fig.4, the inclination, *m* and maximum error rate, *h* of the NCT are 108.24 and 157.8 respectively. When designing the PI compensator, design parameters for ζ and ω_n are chosen as 36 and 59.25 in order to evaluate the performance of NCTF controller, it is compared with PID controller with tuned using Ziegler-Nichols rule [8]. Table II shows the PID and PI compensator controller parameters.

TABLE II
CONTROLLER PARAMETERS

Controller	Kp	Ki	Kd
NCTF	2.585e-3	21.271e-4	-
Conventional PID	0.7764	55.06	0.00274

A. Positioning Performances

The positioning performance is evaluated based on percentage overshoot, settling time, and steady state error by using simulation on rotary two mass positioning system. Fig.7 (a) shows comparison simulated step response due to 10 degree and 45 degree. Whereas Fig.7 (b) presents comparison simulated control signal to the plant.

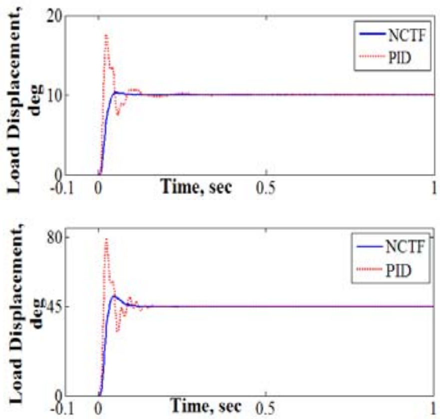


Fig 7(a): Comparison due to step response, Normal object

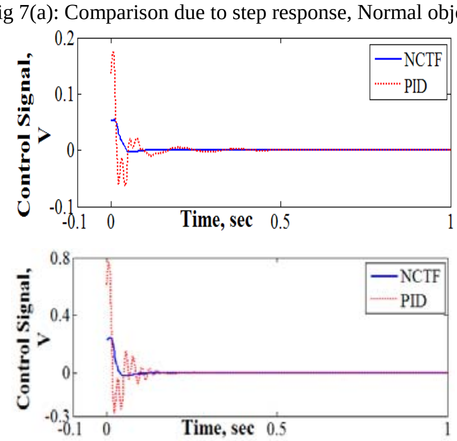


Fig 7(b): Comparison of the control signal, Normal object

Fig.7 shows that the NCTF control system have a very better positioning performance of the responses due to the percentage overshoot, settling time and steady state error with the various step input compared to conventional PID control system. Their positioning performances are shown in Table III.

TABLE III
POSITIONING PERFORMANCE COMPARISON, NORMAL OBJECT

Controller	Overshoot (%)	Settling time (sec)	Steady state error (deg)
NCTF (10deg)	2.7	0.0449	0.01
PID (10 deg)	75.9	0.1931	0.01
NCTF (45deg)	11.5	0.08841	0.01
PID (45 deg)	76.7	0.1308	0.02

Next, Fig.8 (a) shows comparison simulated step responses due to a 10 deg and 45 deg step input when the controllers are implemented on increased inertia object load ($2xJ_l$). Whereas, Fig.8 (b) shows comparison simulated when the controllers are implemented on increased inertia object load ($5xJ_l$). Their positioning performances are also shown in Table IV. Fig.8 (c) presents comparison simulated control signal to the plant.

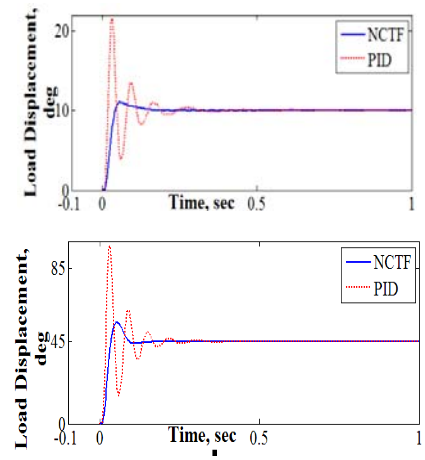


Fig 8(a): Comparison due to step response, Increase inertia object ($2xJ_l$)

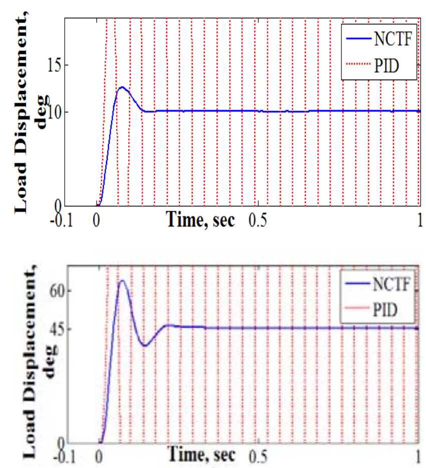


Fig 8(b): Comparison due to step response, Increase inertia object ($5xJ_l$)

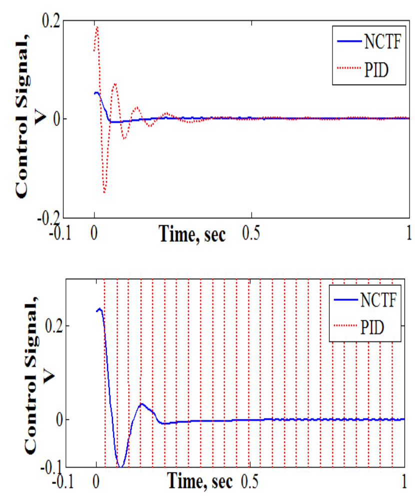


Fig 8(c): Comparison of the control signal, Increase inertia object

TABLE IV
POSITIONING PERFORMANCE COMPARISON, INCREASE INERTIA OBJECT

Controller		Overshoot (%)	Settling time (sec)	Steady state error (deg)
2 x J_l	NCTF (10deg)	10.4	0.1367	0.02
	PID (10 deg)	115.6	0.298	0.03
	NCTF (45deg)	24	0.09047	0.02
	PID (45 deg)	116.9	0.2296	0.03
5 x J_l	NCTF (10deg)	25.5	0.1393	0.02
	PID (10 deg)		unstable	
	NCTF (45deg)	42.6	0.2034	0.02
	PID (45 deg)		unstable	

Furthermore, Fig.9 (a) shows comparison simulated step responses due to a 10 deg and 45 deg step input when the controllers are implemented on increasing friction object (2xft). Whereas, Fig.9 (b) shows comparison simulated when the controllers are implemented on increased inertia object load (5xft). Their positioning performances are also shown in Table V.

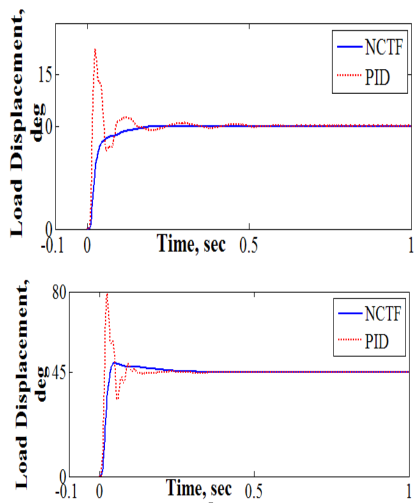


Fig 9(a): Comparison due to step response, Increase friction object (2xft)

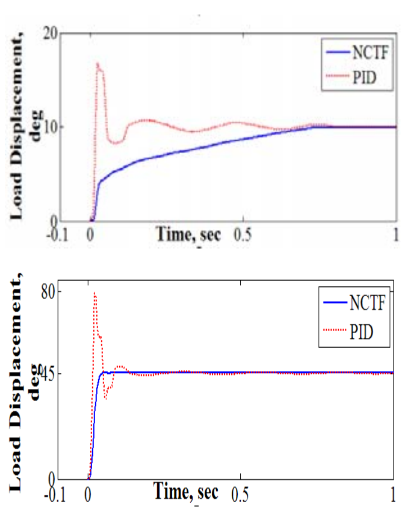


Fig 9(b): Comparison due to step response, Increase friction object (5xft)

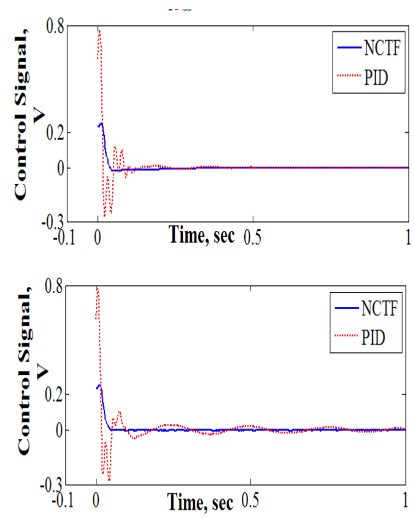


Fig 9(c): Comparison of the control signal, Increase friction object

TABLE V
POSITIONING PERFORMANCE COMPARISON, INCREASE FRICTION OBJECT

Controller		Overshoot (%)	Settling time (sec)	Steady state error (deg)
2 x ft	NCTF (10deg)	0	0.1711	0.034
	PID (10 deg)	74.9	0.3897	0.021
	NCTF (45deg)	8.6	0.2167	0.04
	PID (45 deg)	78.6	0.1165	0.01
5 x ft	NCTF (10deg)	0	0.7097	0.01
	PID (10 deg)	67.2	0.6584	0.048
	NCTF (45deg)	0.51	0.0404	0.19
	PID (45 deg)	75.9	0.1307	0.3

V. SUMMARY

The NCTF controller as a new practical control for positioning systems has been introduced and discussed. The NCTF controller consists of the NCT and the PI compensator. The NCT is constructed using the object response data in a simple open-loop experiment and the compensator parameters are designed based on the NCT. The effectiveness of the NCTF controller is examined by simulation and it showed that the NCTF controller is much more effective and robustness then the conventional PID controller for positioning systems. The comparison between the simulated and experimental for two mass systems is left for further work.

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