NCTF-EMRAN Control Method for a Two-Mass Rotary Positioning Systems

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Abstract: In this study, a nominal characteristic trajectory following (NCTF) controller with extended minimal resource allocation network (EMRAN) compensator is introduced for two-mass rotary point-to-point (PTP) positioning systems. Generally, the NCTF controller consists of a nominal characteristic trajectory (NCT) and a compensator. The objective of the compensator is to make the object motion follow the NCT and end at its origin. The NCTF controller is designed based on a simple open-loop experiment of the object. The parameters and an exact model of the plant are not necessary for controller design. This paper presents a new method to improve the conventional NCTF controller in order to increase the positioning performance and robustness of the system by using EMRAN as a compensator. The NCTF-EMRAN controller is evaluated and discussed based on results of simulation. The effect of the design parameters on the robustness of the NCTF-EMRAN controller to inertia variations is evaluated and compared with conventional NCTF controller. It is shown that NCTF-EMRAN controller has a better positioning performance and much more robust than existed NCTF controller.

Keywords: NCTF; EMRAN, two-mass rotary system; notch filter; simulation.

1. INTRODUCTION

Electric driving systems with elastic coupling are widely used in positioning system fields such as advanced manufacturing systems, robot systems, machine tools, and long shaft driving systems. The dynamic performances of speed and position controlled multi-mass driving system can deteriorate especially due to the elastic coupling, non-linear friction and backlash. In two-mass system applications, like the rolling mill drive, the mechanical part of the drive has a very low natural resonant frequency because of the large roll inertia and the long shaft including the gear box and the spindle. Due to this, the finite but small elasticity of the shaft gets magnified and has a vibrational effect on the load position which may reduce positioning accuracy [1].

This is the reason why researcher looks for new solutions for their position control. Basically, point-to-point (PTP) positioning systems are required to have fast response speed and high accuracy. In order to satisfy the design requirements, a good controller is required. Many types of controllers have been proposed and evaluated for positioning systems. The use of proportional-integral-derivative (PID) controllers are the most popular controller used in industrial control systems including motion control systems due to their simplicity and also satisfactory performances [2]. However, it is difficult to achieve a fast response with no or small overshoot simultaneously.

An improved of nominal characteristic trajectory following (NCTF) controller as practical controller for two-mass rotary PTP positioning systems had been proposed [3]. The existed NCTF controller consists of two elements namely a nominal characteristic trajectory (NCT) and a PI with notch filter as a compensator. It had been reported that the existed NCTF controller had a good positioning performance and robustness to parameters variations compared with conventional PID controller [3].

In this paper, the NCTF with extended minimal resource allocation algorithm (EMRAN) as a compensator is introduced for two-mass rotary PTP positioning systems. On the side, EMRAN is a powerful variation of the standard minimal resource allocation network (MRAN) is applied to train the neural network in this research that well suited for real-time implementation of nonlinear systems [4]. In this paper, the proposed NCTF-EMRAN controller is expected to control the position at desired target and reduces the vibration due to mechanical resonance of the system [5]. The positioning performances of the NCTF-EMRAN controller is evaluated and compared with the existed NCTF controller for two-mass rotary PTP positioning systems.

The paper is organized as follows: Section 2 describes the mathematical model of the systems. NCTF concept, determination of the NCT and controller design is explained in Section 3. Next, the effectiveness of the NCTF-EMRAN controller for two-mass rotary PTP positioning systems is examined through simulations is described in Section 4. Then, conclusions are given in the last section.

2. SYSTEM MODEL

The schematic diagram of the two-mass rotary system is illustrated in Fig. 1. Two masses, having the moments of inertia \(J_m\) and \(J_r\), are coupled by low stiffness shaft which has the torsion stiffness \(K_s\) and a damping.
The electrical part of the DC motor is derived by using Kirchoff voltage law (KCL):

\[ V_m(t) - E_{emf}(t) = L_m \frac{di_m(t)}{dt} + R_m i_m(t), \]

where \( V_m(t) \) is input voltage, \( E_{emf}(t) \) is electromagnetic field, \( L_m \) is motor inductance, \( R_m \) is motor resistance and \( i_m(t) \) is current. SI units are applicable for all notations.

Next, modeling on the mechanical parts of the system can be accurately modeled without considering the major nonlinear effects by the speed dependent friction, dead time and time delay, a linear model for two-mass mechanical system can be obtain using the conventional torque balance rule [6]:

\[ J_m \frac{d\theta_m(t)}{dt} = T_m(t) - B_m \dot{\theta}_m(t) - K_c \theta_m(t) + K_t \theta(t), \]

where \( J_m \) is motor inertia, \( B_m \) is motor viscous damping and \( K_c \) is shaft constant. The torque of the load is expressed as follows:

\[ J_l \frac{d\theta_l(t)}{dt} = T_l(t) - B_l \dot{\theta}_l(t) - K_c \theta_l(t) + K_t \dot{\theta}_m(t), \]

where \( J_l \) is inertia of the load, \( B_l \) is load viscous damping and \( T_l(t) \) is load torque.

The detailed model of the two-mass rotary positioning systems is used only for making simulation is shown in Fig. 2. The parameter of the object used only for making simulation is shown in Table 1.

### Table 1. Nominal object parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor inertia, ( J_m )</td>
<td>17.16e-6</td>
<td>Kg( \cdot )m(^2)</td>
</tr>
<tr>
<td>Inertia load, ( J_l )</td>
<td>24.17e-6</td>
<td>Kg( \cdot )m(^2)</td>
</tr>
<tr>
<td>Stiffness, ( K_c )</td>
<td>0.039</td>
<td>Nm/rad</td>
</tr>
<tr>
<td>Motor resistance, ( R )</td>
<td>5.5</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Motor inductance, ( L )</td>
<td>0.85e-3</td>
<td>H</td>
</tr>
<tr>
<td>Torque constant of the motor, ( K_t )</td>
<td>0.041</td>
<td>Nm/A</td>
</tr>
<tr>
<td>Motor voltage constant, ( K_v )</td>
<td>0.041</td>
<td>V/s/rad</td>
</tr>
<tr>
<td>Frictional torque, ( T_f )</td>
<td>0.0027</td>
<td>Nm</td>
</tr>
<tr>
<td>Motor viscous friction, ( B_m )</td>
<td>8.35e-6</td>
<td>Nms/rad</td>
</tr>
<tr>
<td>Load viscous friction, ( B_l )</td>
<td>8.35e-6</td>
<td>Nms/rad</td>
</tr>
</tbody>
</table>

### 3. NCTF-EMRAN CONTROLLER

#### 3.1 NCTF control concept

The structure of the NCTF control system is shown in Fig. 3. The NCTF controller consists of a NCT and a compensator. The NCTF controller works under the following two assumptions [7]:

a) A DC or an AC servo motor is used as an actuator of the object.
b) PTP positioning systems are discussed, so \( \theta_1 \) is constant and \( \theta_1' = 0 \)

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. 3, 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. 4 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.

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Fig. 1 Schematic diagram of two-mass rotary positioning systems

Fig. 2 Exact model of the two-mass rotary positioning systems

Fig. 3 NCTF Controller for two-mass rotary positioning systems
3.2 NCT determination

The NCTF controller is designed based on a simple open-loop experiment of the object as follows [8]:

1) Open-loop-drive the object with a stepwise input and the load displacement and load velocity responses of the object are measured. Fig. 5 shows the stepwise input, load velocity and load displacement responses of the object. In this case, the object vibrates due to its mechanical resonance. In order to eliminate the influence of the vibration on the NCT, the object response must be averaged.

In Fig. 6, moving average filter is used to get the averaged response because of its simplicity [9]. 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. 6) is used. Variable $h$ in Fig. 6 is the maximum velocity, which depends on the input step height. From the curve in area $A$ and $h$ in Fig. 6, the NCT in Fig. 7 is determined.

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.

3.3 Compensator design

The following EMRAN and notch filter compensator is proposed for two-mass systems as it shown in Fig. 8.

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 easy.

3.4 Extended minimum resource allocating network (EMRAN) algorithm

EMRAN is a fast on-line training algorithm for train the radial basis function neural network (RBFNN). It was firstly proposed by Yan et.al. [11]. During the training process, the number of neurons at RBFNN will be added or pruned until desired result is achieved. Since the only “winner” neurons will be updated, it attempts to reduce the computational load which leads to reduce computation time and memory. Therefore it is so powerful to perform on-line training as it used in this work.
RBFNN model with single input and single output is adopted as in Fig. 9 below. N-th hidden nodes are used to mapping the input (u_p) to the output control law (u_o). The hidden layer consists of N neurons (φ_j - φ_N) connected to the output by N weight vectors (a_j).

The output of RBFN network is:

\[ u_o = f(u_p) = b + \sum_{j=1}^{N} \alpha_j \phi_j(u_p) \]  

(4)

where b is bias and \( \phi_j \) is Gaussian function of j-th hidden neuron which is defined as:

\[ \phi_j(u_p) = \exp\left(-\frac{\|u_p - \mu_j\|^2}{\sigma_j^2}\right), \]  

(5)

where \( \mu_j \) is the center for the j-th hidden neuron and \( \sigma_j \) is the width of Gaussian function. \( \| \cdot \| \) denotes the Euclidean norm.

In EMRAN algorithm, the RBFNN begins with 1 hidden neuron, that is j = 1. As each input-output training data (u_p,i, u_o,i) (i is time index) is received, the network is built up based on certain growth criteria as follows:

\[ \| \theta_e - \theta_i \| > E_i, \]  

(6)

\[ e_{max} = \frac{1}{M-1} \sum_{j=2}^{M} \frac{e_j^2}{\epsilon_j^2} > E_2, \]  

(7)

\[ \| a_{pj} - \mu_i \| > E_3, \]  

(8)

where \( \mu_j \) is the center of the hidden neuron. \( \theta_e \) and \( \theta_i \) are desired load position and actual load position output in each time index respectively. \( E_i, E_2 \) and \( E_3 \) are error threshold to be selected appropriately by the designer. Eq. (6) decides if the existing nodes are insufficient to obtain a network output that meets the error specification, \( E_i \). Eq. (7) checks whether the network met the required mean squared error specification for the past M outputs of the network. Eq. (8) ensures that the new node to be added is sufficiently far from all the existing nodes. Only when all these criteria are met, a new hidden node is added.

During training phases, an adaptive rule is employed on-line to adjust the the RBFN network parameters, \( \omega \), to minimize the error of desired position with actual position \( (\theta_e - \theta_i) \). As for EMRAN algorithm, not all hidden neurons are updated but special hidden neurons which are referred to the “winner neurons” only. The network parameters, \( \omega^* = R[\mu^*, \sigma^*, b, \alpha^*] \), are updated using Extended Kalman Filter (EKF) as follows,

\[ \omega^*_i = \omega^*_{i-1} + K^*_i(\theta_e - \theta_i), \]  

(9)

In this equation, \( K^*_i \) is the Kalman gain matrix which is defined as:

\[ K^*_i = P^*_i B^*_i \left( R_i + B^*_i P^*_{i-1} B^*_i \right)^{-1} \]  

(10)

The RBFN network parameters, \( \omega^* \), are trained on-line based on the real plant. To train the RBFN network, square type signal with various input are applied. Once the training phase is done, the final weight is used in RBFN network to generate feedback control law, \( u_o \).

### 4. CONVENTIONAL NCTF CONTROLLER

The following PI and notch filter compensator is used for two-mass rotary systems [3]:

\[ G_c(s) = \frac{(K_c + s) K_c}{s \left( s + 2 \omega_o s + \omega_o^2 \right) + \left( s + 2 \omega_o s + \omega_o^2 \right)}, \]  

(11)

The PI compensator is adopted for its simplicity to forces the object motion to reach the NCT as fast as possible and control the object motion to follow the NCT and end at the origin. Notch filter is added to improve the gain margin of an actuator and cancels the effect of the two resonant modes which cause the vibration of the system [12].

### 5. SIMULATION RESULTS

The significance of this research lies in the fact that a simple and easy controller can be designed for high precision positioning system which is very practical. By introduced the NCTF-EMRAN controller, it will be more reliable and practical for realizing high precision positioning systems for two-mass positioning systems compared with conventional NCTF in term of controller performances.

Table 2 shows the parameters of the compensator of the conventional NCTF controller and NCTF-EMRAN controller.

<table>
<thead>
<tr>
<th>Controller</th>
<th>( K_c )</th>
<th>( K_i )</th>
<th>( \omega_e )</th>
<th>( \omega_f )</th>
<th>( \omega_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMRAN-NCTF</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>NCTF</td>
<td>4.79e-1</td>
<td>2.65e-1</td>
<td>0.7</td>
<td>40</td>
<td>0.9</td>
</tr>
</tbody>
</table>
In order to evaluate the robustness of the improved NCTF control system, the simulations were conducted in two conditions: with normal load and with increasing the load inertia as shown in Table 3. All process within 5 second simulation time.

<table>
<thead>
<tr>
<th>Object</th>
<th>Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load</td>
<td>( J_l = 14.17 \times 10^{-6} \text{kgm}^2 )</td>
</tr>
<tr>
<td>Increased inertia load</td>
<td>( 2 \times J_l )</td>
</tr>
<tr>
<td></td>
<td>( 5 \times J_l )</td>
</tr>
</tbody>
</table>

### 5.1 Controller performances

Fig. 10 shows step responses to 30 deg step input when the NCTF-EMRAN controller and conventional NCTF controller is used to control a normal object. The positioning performance is evaluated based on percentage of overshoot, settling time and positioning accuracy. Fig. 11 shows step responses to 90 deg step input to control the normal object for both controllers. Fig. 12 shows step responses to 90 deg step input to control the object with the variation load increased for NCTF-EMRAN controller. The positioning performances based on simulations for normal and increased object inertia are presented in Table 4.

In nominal object, the NCTF-EMRAN controller gives the smallest percentage of overshoot which is almost no overshoot and has the fastest settling time compared with conventional NCTF controller. In case for steady state error, the NCTF-EMRAN controller gives a better positioning accuracy than conventional NCTF controller.

With increased object inertia, NCTF-EMRAN controller still gives the fastest settling time and smaller overshoot than conventional NCTF controller. Again, NCTF-EMRAN controller has no steady state error compared to conventional NCTF controller. So, NCTF-EMRAN controller is much more robust to inertia variation compared with existed NCTF controller.
6. SUMMARY

This paper introduced a nominal characteristic trajectory following (NCTF) controller with extended minimal resource allocation network (EMRAN) compensator for two-mass rotary point-to-point (PTP) positioning systems. The effectiveness of the NCTF-EMRAN controller is examined by simulation and it showed that the NCTF-EMRAN controller has a better positioning performance than the existed NCTF controller. The simulation results also proved that proposed controller is much more robust than the conventional NCTF controller due to load variations for two-mass rotary PTP positioning systems. The comparison performance for two-mass systems based on experimental is left for further work.

REFERENCES


