

# A Flexible Arm Manipulator Control System Using Modified Discrete Sliding mode Model Following Controller with Sinusoidal Command Input

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## ABSTRACT

A Modified Discrete Sliding mode Model Following Control or MDSMFC design methodology for a flexible arm manipulator is presented. The MDSMFC algorithm uses the combination of an adaptive model following control and sliding mode control to improve the dynamics response for command tracking. A procedure is proposed for choosing the control function so that it guarantee the existence of a sliding mode and the nominal system stable in the absence of system uncertainties and disturbances. The MDSMFC approach has been simulated and applied to a position control of a tip of a single flexible link with sinusoidal command input. Simulation results showed that the MDSMFC gives a significant improvement on the tracking performances and robust to plant parameter variations and disturbances.

**Keywords:** Flexible Arm Manipulator, Sliding Mode Control

## 1. INTRODUCTION

Most industrial robots are composed of multi-links. Such a robot arm is a highly nonlinear system with complicated coupled dynamics and uncertainly. The Variable Structure Control (VSC) or Sliding Mode Control (SMC) is invariant to system parameter variations and disturbances when the sliding mode occurs. The VSC approach possesses other salient advantages such as high speed of response, good transient performance and no need for precise knowledge of the controlled plant. Although the conventional VSC approaches has been applied successfully in many applications [1-2]. But it may result in a steady state error when there is load disturbance in it. In order to improve the problem, the Integral Variable Structure Model Following Control (IVSMFC) has

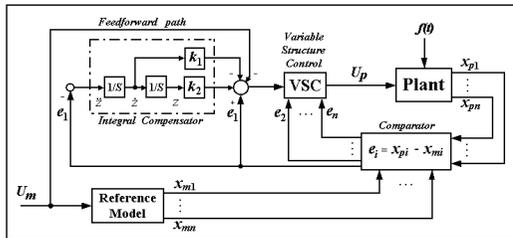
been proposed [3-5] for achieving a zero steady state error for step command input. The IVSMFC approach combines an integral controller with VSC and applied to the design of a Model Following Control (MFC). However, when command input is changing, e.g., ramp command input, the IVSMFC gives a steady state error. The Modified Integral Variable Structure Control or MIVSC approach, proposed in [6-7], uses a double integral action to solve this problem. Although, the MIVSC method can give a better tracking performance than the IVSMFC method does at steady state, its performance during transient period needs to be improved.

In this paper, a robust control scheme for a flexible arm manipulator using the Modified Adaptive Sliding mode Model Following Control or MDSMFC approach

is presented. This approach, which is the extension of DSMFC approach [8-9], incorporates a feedforward path and an adaptive model to improve the dynamics response for command tracking. The advantage of this approach is that the error trajectory in the sliding motion can be prescribed by the design. Also, it can achieve a rather accurate tracking and is fairly robust to plant parameter variations and external load disturbances. The MDSMFC method is applied to a flexible link manipulator for a position control system. As a simulation results are shown to demonstrate the potential of this control strategy, the tracking performance can be remarkably improved.

## 2. DESIGN OF MDSMFC SYSTEM

The structure of MDSMFC system is shown in Fig. 1. It combines the conventional VSC with a double-integral compensator, a feedforward path from the input command, a reference model and a comparator.



**Figure 1.** The structure of MDSMFC system.

Let the plant be described by the following equation :

$$\begin{aligned} \dot{x}_{pi} &= x_{p(i+1)} \quad ; i=1, \dots, n-1 \text{ and} \\ \dot{x}_{pn} &= -\sum_{i=1}^n a_{pi} x_{pi} + b_p U_p - f(t) \end{aligned} \quad (1)$$

where  $a_{pi}$  and  $b_p$  are the flexible arm manipulator parameters;  $f(t)$  are disturbances and  $U_p$  is the control input of the plant.

The reference model is represented by

$$\begin{aligned} \dot{x}_{mi} &= x_{m(i+1)} \quad ; i=1, \dots, n-1 \text{ and} \\ \dot{x}_{mn} &= -\sum_{i=1}^n a_{mi} x_{mi} + b_m U_m \end{aligned}$$

where  $U_m$  is the input command of the system. (2)

Defining  $e_i = x_{pi} - x_{mi} \quad ; (i=1, \dots, n)$  and subtracting (2) from (1), the error differential equation is

$$\begin{aligned} \dot{e}_i &= e_{i+1} \quad ; i=1, \dots, n-1 \text{ and} \\ \dot{e}_n &= -\sum_{i=1}^n a_{pi} e_i - \sum_{i=1}^n (a_{mi} - a_{pi}) x_{mi} + b_m U_m - b_p U_p - f(t). \end{aligned} \quad (3)$$

Using the SMFC approach [10], to the error dynamics in order to synthesise the control signal,  $U_p$  and assuming the asymptotic divergence of the error to zero, the MDSMFC system in Fig. 1 can be described as

$$\begin{aligned} \ddot{z}_i &= -e_i, \quad \dot{e}_i = e_{i+1} \quad ; i=1, \dots, n-1 \text{ and} \\ \dot{e}_n &= -\sum_{i=1}^n a_{pi} e_i - \sum_{i=1}^n (a_{mi} - a_{pi}) x_{mi} + b_m U_m - b_p U_p - f(t) \end{aligned}$$

where  $U_p$  is the control function. (4)

Consider the discretisation of the system given in (4). If the derivative is approximated by the forward difference as

$$\dot{e}_i(t) = \frac{e_i(t+T) - e_i(t)}{T}$$

where  $T$  is the sampling interval, then the discretised version of the system (4) can be represented as :

$$\begin{aligned} \dot{z}(k+1) &= \dot{z}(k) - T e_i(k) \text{ and} \\ e_i(k+1) &= e_i(k) + T e_{i+1}(k) \quad ; i=1, \dots, n-1 \\ \dot{e}_n(k+1) &= e_n(k) - T \sum_{i=1}^n a_{pi} e_i - T \sum_{i=1}^n (a_{mi} - a_{pi}) x_{mi}(k) + T b_m U_m(k) - T b_p U_p(k) - T f(k) \end{aligned} \quad (5)$$

The switching function,  $\sigma$  is given by

$$\sigma(k) = c_1[e_1(k) - K_1\dot{z}(k) - K_2z(k) - r(k)] + \sum_{i=2}^n c_i e_i(k) \quad (6)$$

In the discrete variable structure control system, the control input is computed at discrete instants and applied to the system during the sampling interval so that an ideal sliding motion cannot be obtained. The conditions ensuring the existence and reachability of a non-ideal sliding motion are :

$$\sigma(k)\Delta\sigma(k+1) < 0 \text{ and } |\Delta\sigma(k+1)| < \frac{\xi}{2} \quad (7)$$

where  $\Delta\sigma(k+1) = \sigma(k+1) - \sigma(k)$ ;  $\sigma(k)$  and  $\xi$  is a small positive constant. The control function can be chosen to guarantee that the inequalities (7) are satisfied, so a sliding mode motion control within the range of  $\xi$  will appear or  $\sigma(k) < \xi$ . If the solution of the ideal sliding motion control. Which assumes infinite sampling rate, is asymptotically stable. It will be closed to the solution of the sliding mode control within the range of  $\xi$  in infinite time interval starting at the time when the sliding mode begins.

Design of such a system involves (1) the choice of the control function  $U_p(k)$  to guarantee the existence of a sliding mode control, (2) the determination of the switching function  $\sigma(k)$  and the integral control gain  $K_I$  such that the system has the desired properties and (3) the elimination of chattering phenomenon of the control input by using the smoothing function.

### Choice of control function

Since the system is controllable. The control signal can be determined as follows. From (5) and (6), we have

$$\begin{aligned} \Delta\sigma(k+1) = & -Tc_1(K_1\ddot{z}(k) + K_2\dot{z}(k)) + T\sum_{i=2}^n c_{i-1}e_i \\ & - \sum_{i=1}^n a_{pi}e_i(k) + \sum_{i=1}^n (a_{mi} - a_{pi})x_{mi}(k) \\ & - Tb_m U_m(k) + Tb_p U_p(k) - Tf(k) \end{aligned} \quad (8)$$

Let  $a_{pi} = a_{pi}^0 + \Delta a_{pi}$  ;  $i=1, \dots, n$  and  $b_p = b_p^0 + \Delta b_p$  ;  $b_p^0 > 0$ ,  $\Delta b_p > -b_p^0$

where  $a_{pi}^0$  and  $b_p^0$  are nominal values;  $\Delta a_{pi}$  and  $\Delta b_p$  are the associated variations.

Let the control function  $U_p(k)$  be decomposed into

$$U_p(k) = U_{eq}(k) + U_s(k) \quad (9)$$

where the so called equivalent control  $U_{eq}(k)$  is defined as the solution of (9) under the condition where there is no disturbances and no parameter variations, that is

$$\Delta\sigma(k+1) = 0, f(k) = 0, a_{pi} = a_{pi}^0, b_p = b_p^0 \text{ and } U_p(k) = U_{eq}(k).$$

This condition results in

$$\begin{aligned} U_{eq}(k) = & \left\{ -c_1(K_1\ddot{z}(k) + K_2\dot{z}(k)) - \sum_{i=2}^{n-1} c_{i-1}e_i(k) + \sum_{i=1}^{n-1} a_{pi}^0 e_i(k) \right. \\ & \left. - \sum_{i=1}^n (a_{mi} - a_{pi})x_{mi}(k) + b_m U_m(k) \right\} / b_p^0 \end{aligned} \quad (10)$$

In the sliding motion,  $\sigma(k) = 0$ , one can obtain

$$e_n(k) = \left[ -c_1[e_1(k) - K_1\dot{z}(k) - K_2z(k) - r(k)] - \sum_{i=2}^n c_i e_i(k) \right] \quad (11)$$

Substitution of (11) into (10) yields

$$U_{eq}(k) = \left\{ -c_1(K_1\ddot{z}(k) + K_2\dot{z}(k)) - T\sum_{i=2}^{n-1} c_{i-1}e_i(k) + T\sum_{i=1}^{n-1} a_{pn}^0 e_i(k) \right. \\ \left. - T\sum_{i=1}^n (a_{mi} - a_{pi})x_{mi}(k) + b_m U_m(k) \right. \\ \left. + (c_{i-1} - a_{pn}^0)[c_1(e_1(k) - K_1\dot{z}(k) + K_2z(k) - U_m(k)) \right. \\ \left. + \sum_{i=2}^{n-1} c_i e_i(k)] \right\} / b_p^0 \quad (12)$$

The function  $U_s(k)$ , is employed to eliminate the influence due to  $\Delta a_{pi}$ ,  $\Delta b_p$  and  $f(k)$  so as to guarantee the existence of a sliding mode control. This function is constructed as

$$U_s(k) = \varphi_1(e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k)) \\ + T\sum_{i=2}^n \varphi_i e_i(k) + \varphi_{n+1} \quad (13)$$

where :

$$\varphi_1 = \begin{cases} \alpha_1 & \text{if } [e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k)]\sigma(k) > 0 \\ \beta_1 & \text{if } [e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k)]\sigma(k) < 0 \end{cases} \\ \varphi_i = \begin{cases} \alpha_i & \text{if } e_i\sigma(k) > 0 \\ \beta_i & \text{if } e_i\sigma(k) < 0 \end{cases} ; i = 2, \dots, n \text{ and} \\ \varphi_{n+1} = \begin{cases} \alpha_{n+1} & \text{if } \sigma(k) > 0 \\ \beta_{n+1} & \text{if } \sigma(k) < 0 \end{cases}$$

Substitute (7) and (9) into (6), to obtain

$$\Delta\sigma(k+1)\sigma(k) = \\ T \{ [-\Delta a_{p1} + a_{pn}^0 \Delta b_p / b_p^0 + c_1(c_{n-1} - a_{pn}^0)(1 + \Delta b_p / b_p^0) + b_p \varphi_1] \\ (e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k))\sigma(k) \\ + \sum_{i=2}^{n-1} \{ [-\Delta a_{pi} + a_{pn}^0 \Delta b_p / b_p^0 - c_{i-1} \Delta b_p / b_p^0 + c_i(c_{n-1} - a_{pn}^0)(1 + \Delta b_p / b_p^0) + b_p \varphi_i] e_i(k)\sigma(k) \} \\ + [-\Delta a_{pn} + (c_{n-1} - a_{pn}^0) + b_p \varphi_n] e_n \sigma(k) + [N(k) + b_p \varphi_{n+1}] \sigma(k) \} \quad (14)$$

where

$$N = -(K_1\dot{z}(k) + K_2z(k))(\Delta a_{p1} - a_{pn}^0 \Delta b_p / b_p^0) + \Delta b_p / b_p^0 [c_1(K_1\dot{z}(k) + K_2z(k))] \\ + [-\sum_{i=1}^n (a_{mi} - a_{pi})x_{mi}(k) + b_m U_m(k)] \Delta b_p / b_p^0 - f(k).$$

In order for (7) to be satisfied, the following conditions must be met,

$$\varphi_i = \begin{cases} \alpha_i & \langle \varphi L_i = \text{Inf}[\Delta a_{pi} - a_{pn}^0 \Delta b_p / b_p^0 + c_{i-1} \Delta b_p / b_p^0 \\ - c_i(c_{n-1} - a_{pn}^0)(1 + \Delta b_p / b_p^0)] / b_p \\ \beta_i & \rangle \varphi U_i = \text{Sup}[\Delta a_{pi} - a_{pn}^0 \Delta b_p / b_p^0 + c_{i-1} \Delta b_p / b_p^0 \\ - c_i(c_{n-1} - a_{pn}^0)(1 + \Delta b_p / b_p^0)] / b_p \end{cases}$$

where  $i=1, \dots, n-1$ ,  $c_0 = 0$  (15a)

$$\varphi_n = \begin{cases} \alpha_n & \langle \varphi L_i = \text{Inf}[\Delta a_{pn} + a_{pn}^0 - c_{n-1}] / b_p \text{ and} \\ \beta_n & \rangle \varphi U_i = \text{Sup}[\Delta a_{pn} + a_{pn}^0 - c_{n-1}] / b_p \end{cases}$$

$$\varphi_{n+1} = \begin{cases} \alpha_{n+1} & \langle \varphi L_{(n+1)} = \text{Inf}[-N(k)] / b_p \\ \beta_{n+1} & \rangle \varphi U_{(n+1)} = \text{Sup}[-N(k)] / b_p \end{cases} \quad (15b)$$

For satisfying (7), if the sampling interval  $T$  is enough small, one can be obtain :

$$L_1 \langle \varphi_1 \langle M_1, L_i \langle \varphi_i \langle M_i ; i = 2, \dots, n-1 \text{ and} \\ L_n \langle \varphi_n \langle M_n, L_{n+1} \langle \varphi_{n+1} \langle M_{n+1} \quad (16)$$

From (15) and (16), if the  $T$  is enough small, one can obtain the bound of  $\alpha_i$  and  $\beta_i$  as :

$$L_i < \alpha_i < \varphi L_i \quad \varphi U_i < \beta_i < M_i ; i = 1, \dots, n+1. \quad (17)$$

If  $\varphi_i$ ,  $i=1, \dots, n+1$ , are chosen as  $\varphi_i < \alpha_i < -\beta_i$

finally, the control can be represented as

$$U_p = \left\{ -c_1(K_1\dot{z}(k) + K_2z(k)) - \sum_{i=2}^{n-1} c_{i-1}e_i(k) + \sum_{i=1}^{n-1} a_{pi}^0 e_i(k) \right. \\ \left. - \sum_{i=1}^n (a_{mi} - a_{pi})x_{mi}(k) + b_m U_m(k) + (c_{n-1} - a_{pn}^0) \right. \\ \left. [c_1(e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k)) + \sum_{i=2}^{n-1} c_i e_i(k)] \right\} / b_p^0 \\ + (\varphi_1 |e_1(k) - K_1\dot{z}(k) - K_2z(k) - U_m(k)| + \sum_{i=2}^n \varphi_i |e_i(k)| \\ + \varphi_{n+1}) \text{sign}(\sigma(k)). \quad (18)$$

From (17), the upper and low bounds of the  $\varphi_i$ , can be obtain

$$\hat{L}_i < \hat{\varphi}_i < \hat{M}_i, i=1, \dots, n+1 \text{ where}$$

$$\hat{M}_i = -\max(|\phi L_i|, |\phi U_i|) \text{ and } \hat{L}_i = -\max(|L_i|, |M_i|) \quad (19)$$

### Determination of switching plane and integral control gain

In the above subsection it has been proved that if the solution of the ideal sliding motion is asymptotically stable, it will close to the solution of the non-ideal sliding within the range of  $\zeta$ . Thus one can choose the switching plane and integral control gain of the basis of the ideal sliding motion. While in the ideal sliding motion, the system can be described by (4) can be reduced to :

$$\begin{aligned} \dot{z}(k+1) &= \dot{z}(k) - T e_i(k), \\ e_i(k+1) &= e_i(k) + T e_{i+1}(k) ; i=1, \dots, n-2 \end{aligned} \quad (20a)$$

$$\dot{e}_n(k+1) = e_{n-1}(k) - T [C_1 K_1 \dot{z}(k) - C_2 K_2 z(k)] - \sum_{i=1}^n a_{ni} e_i(k) \quad (20b)$$

The characteristic equation when the system is on the sliding surface can be shown as

$$H(s) = \frac{E_i(z)}{U_m(z)} = \frac{\left(\frac{z-1}{T}\right)^2 c_1}{\left(\frac{z-1}{T}\right)^n + c_{n-1} \left(\frac{z-1}{T}\right)^{n-1} + \dots + c_1 K_1 \left(\frac{z-1}{T}\right) + c_1 K_2} \quad (21)$$

The characteristic equation of the system (21) is

$$\left(\frac{z-1}{T}\right)^n + c_{n-1} \left(\frac{z-1}{T}\right)^{n-1} + \dots + c_1 K_1 \left(\frac{z-1}{T}\right) + c_1 K_2 = 0 \quad (22)$$

Since this characteristic equation is independent of the plant parameter, the MDSMFC approach is robust to plant parameter variations. Further, one can choose the coefficients of the switching

function and the integral control gain by the pole assignment technique such that this sliding motion has desirable properties.

Let  $z-1/T = \eta$ . Then (22) can be rewritten as

$$\eta^n + C_{n-1} \eta^{n-1} + \dots + C_1 K_1 \eta + C_2 K_2 = 0 \quad (23)$$

Using the final value theorem, it can be shown from (21), that the steady-state tracking error due to a ramp command input is zero. The transient response of the system can be determined by suitably selecting the poles of the transfer function (21).

$$\text{Let } \eta^n + \alpha_1 \eta^{n-1} + \dots + \alpha_{n-1} \eta + \alpha_n = 0 \quad (24)$$

be the desired characteristic equation (closed-loop poles), the coefficient  $C_1, C_2$  and  $K_1, K_2$  can be obtained by

$$\begin{aligned} C_{n-1} &= \alpha_1, C_1 = \alpha_{n-2}, \\ K_1 &= \alpha_{n-1}/C_1 \text{ and } K_2 = \alpha_n/C_1. \end{aligned}$$

### Chattering Considerations

Normally, the sign function sign ( $\sigma$ ) given by (18), will give rise to chattering in the control signal. In order to reduce the chattering, the sign function can be replaced by the continuous function given by

$$M_\delta(\sigma) = \frac{\sigma(k)}{|\sigma(k)| + \delta_0 + \delta_1 |\ddot{z}(k)|} \text{ where}$$

$\delta = \delta_0 + \delta_1 |\ddot{z}(k)|$  ;  $\delta_0$  and  $\delta_1$  are positive constants.

$$(25)$$

### 3. FLEXIBLE LINK MANIPULATOR

A single flexible link manipulator is used in this paper to illustrate the feasibility of the control algorithms. Figure 2 shows the schematic diagram of the single flexible link manipulator. The tip position,  $y(x,t)$ , is the sum of a rigid body deflection and an



$$\begin{aligned}
 U_p(k) = & \{c_1(K_1\ddot{z}(k) + K_2\dot{z}(k)) + a_{p1}^0 e_1(k) + a_{p2}^0 e_2(k) - [(a_{m1} - a_{p1}^0)x_{m1}(k) \\
 & + (a_{m2} - a_{p2}^0)x_{m2}(k) + (a_{m3} - a_{p3}^0)x_{m3}(k) + b_m U_m]\} \\
 & + (c_2 - a_2^0)[c_1(e_1(k) - K_1\dot{z}(k) - K_2z(k) - r(k)) + c_2 e_2(k)]/b^0 \\
 & + (\Psi_1|e_1(k) - K_1\dot{z}(k) - K_2z(k) - r(k)| + \Psi_2|e_2(k)| \\
 & + \Psi_3|e_3(k)| + \Psi_4|M_\delta(\sigma)
 \end{aligned}
 \tag{31}$$

The switching function,  $\sigma(k)$  from (6), is given by

$$\sigma(k) = c_1(e_1(k) - K_1\dot{z}(k) - K_2z(k) - r(k)) + c_2 e_2(k) + e_3(k)
 \tag{32}$$

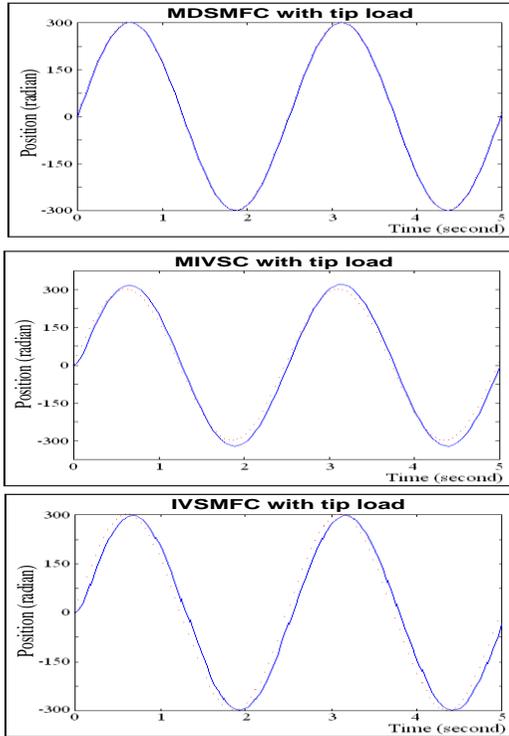
Since the mechanical dynamic system is controllable, a transformation matrix exists to achieve canonical dynamic equations expressed as (1). According to equations (8)~(19), the coefficients of the sliding surface and the integral gain can be determined by solving the following equations (21)~(24), respectively.

**Table 1.** Physical Parameters of Single Link Flexible Manipulator.

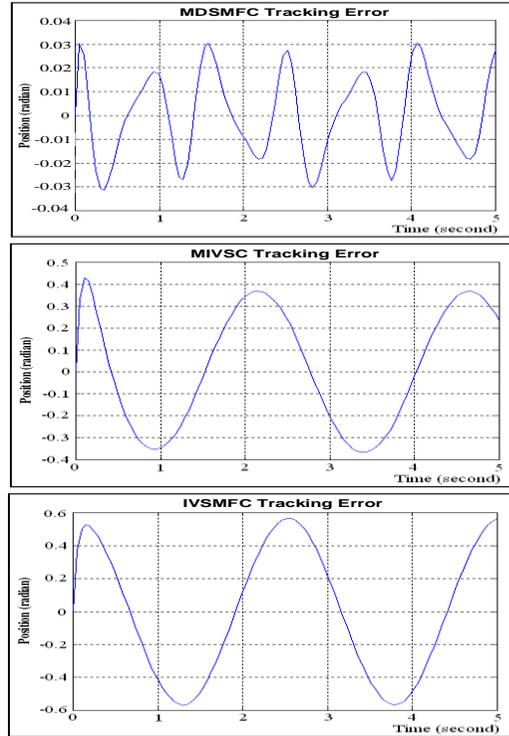
Symbol	Physical Parameter	Dimension
$I$	Cross-sectional area	$8.31934 \times 10^{-11} \text{ m}^4$
$I_b$	Moment of Inertia of the beam	$7.7724 \times 10^{-2} \text{ Kg-m}^2$
$I_h$	Hub inertia	$5.176 \times 10^{-3} \text{ Kg-m}^2$
$E$	Modulus of elasticity	$6.9 \times 10^{10} \text{ N/m}^2$
$\rho$	Linear Density	$0.233172 \text{ Kg/m}$
$H$	Height	50.8 mm
$B$	Width	6.8 mm
$L$	Length	2.0 m

**Table 2.** Parameters of MDSMFC Controller.

Parameter	Dimension
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	$-17.495 + 56.672i, -17.495 - 56.672i, -18.946, -4.867$
$C_1, C_2, K_1, K_2$	426.54, 9.98, 6.32, 19.76
$\varphi_1, \varphi_2, \varphi_3, \varphi_4$	-0.07, -0.00007, -0.0007, -0.0007
$a_{m1}, a_{m2}, a_{m3}, b_m$	5,000, 420, 25, 15,000
$a_{p2}^0, a_{p3}^0, b_p^0$	19,764, 6,626, 1,446,914
$\delta_0, \delta_1$	1, 11



**Figure 3.** Comparison of sinusoidal position tracking.



**Figure 4.** Comparison of position tracking errors.

#### 4. RESULTS AND DISCUSSION

In order to evaluate the tracking performance of the MDSMFC approach for both steady and transient periods, a sinusoidal command is first introduced for certain period of time before it is changed abruptly to a constant value. The simulation was done using the software package MATLAB. In addition the results are compared with those obtained from MIVSC and IVSMFC approaches under the same testing conditions. Here the robustness property was tested by introducing an increase of 75% in parameters and 125% in tip load, respectively. The tip position response obtained from simulation with these parameter variations is shown in Figure 3 and Figure 4, respectively, the corresponding tracking error of the tip position. It is clear from the figures that the MDSMFC can follow the command input extremely well during steady state as well

as transient periods. That is, it converges very fast to zero but the other give rise to steady state errors. Although MIVSC seems to track well during the steady state of the sinusoidal command input, it gives a noticeable overshoot on tracking error during the input change immediately. Among them, IVSMFC performs poorly, it gives a substantially sustained tracking error.

#### 5. CONCLUSIONS

Systematical design procedure for a MDSMFC approach is presented. It has been developed a procedure for determining the control function and switching plane by using model following control. Also, by using a continuous function, the chattering can be effectively suppressed. The application of MDSMFC to the positioning problem of a flexible link manipulator system has illustrated that the MDSMFC

approach can improve the tracking performance by 68% and 76% when compared to the MIVSC and IVSMFC approaches, respectively. Simulation results showed that the proposed approach can achieve accurate position tracking in face of wide plant parameter variations and external load disturbance. Furthermore, The MDSMFC approach is robust and more applicable in the object of the control of the flexible link. An interesting open problem to be studied in the future will be extending the development of this paper to the multi-input multi-output (MIMO) discrete-time control system.

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