Sliding Mode and PI Controllers for Uncertain Flexible Joint Manipulator

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Abstract: This paper is dealing with the problem of tracking control for uncertain flexible joint manipulator robots driven by brushless direct current motor (BDCM). Flexibility of joint in the manipulator constitutes one of the most important sources of uncertainties. In order to achieve high performance, all parts of the manipulator including actuator have been modeled. To cancel the tracking error, a hysteresis current controller and speed controllers have been developed. To evaluate the effectiveness of speed controllers, a comparative study between proportional integral (PI) and sliding mode controllers has been performed. Finally, simulation results carried out in the Matlab simulink environment demonstrate the high precision of sliding mode controller compared with PI controller in the presence of uncertainties of joint flexibility.

Keywords: Flexible joint manipulator, uncertainties, proportional integral (PI) controller, sliding mode, brushless direct current motor.

1 Introduction

Manipulator robots play a crucial part in the domain of flexible automation. Most of the papers dealing with manipulator robots use a mechanical structure with a rigid joint whereas a few of the papers are concerned with flexible joint manipulator. The latter offers several advantages with respect to their rigid counterpart, such as lower cost, smaller actuators, light weight, larger work volume, better transportability and maneuverability, higher operational speed and power efficiency^[1,2]. Moreover, joint flexibility represents one of the major significant cause of uncertainties^[3]. Many researchers have proposed many types of controllers for flexible joint manipulators such as the adaptive controller^[4], the nonlinear controller^[5], the robust controller^[6], the type-2 fuzzy controller^[7] and the neural fuzzy sliding controller^[8]. Besides, the proportional integral derivative (PID) controller has been proposed in [9, 10]. Moreover, Huang and Chen^[11] proposed an adaptive sliding controller for a single link flexible joint manipulator with mismatched uncertainties. Several studies have shown that the system performance has been degraded due to neglect of flexibility in the design of controller^[12, 13]. Thus, the problem of trajectory tracking always encounters gaps in the design of an efficient controller.

The main contribution of this paper is to design controllers for flexible joint manipulator driven by brushless direct current motor which constitutes the actuator. The latter has been neglected by the previous works. This pa-

per is structured as follows: In Section 2, we described the model of the flexible joint manipulator and the model of the brushless direct current motor (BDCM). Section 3 was reserved for the control strategy. In the first part of Section 3, we explained the hysteresis controller functioning. Whereas, the second part was reserved to the representation of speed controller strategy. Two types of controllers have been studied (a proportional integral (PI) controller and a sliding mode controller). The controller which is based on sliding mode has been developed by synthesizing the convergence condition and the control law which contains an equivalent control term and a switching term. Section 4 was dedicated to the implementation of the sliding mode and PI controllers in the Matlab simulink environment for uncertain flexible joint manipulator. Besides, analysis of simulation results will be done.

2 Problem statement

Many manipulator robots have flexible joint due to the gear elasticity, the bearing deformation and the shaft windup, etc.^[14, 15] In this study, we consider one link manipulator robot with revolute joint actuated by brushless direct current motor. The system includes two principal parts which are flexible joint manipulator and brushless direct current motor. However, to obtain good performance, the flexible joint must be taken into consideration in the modeling step^[5, 6, 16, 17].

Given the desired position and velocity trajectories defined respectively by q_{ref} and $\dot{q}_{ref}$, the objective is to propose a control law Γ which ensures that the manipulator's posi-

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tion q and velocity $\dot{q}$ follow their desired trajectories under uncertain dynamics and in the presence of disturbances. The proposed controller uses q and $\dot{q}$ as the measurable state variables of the system.

2.1 Model of flexible joint manipulator

The flexible element of joint manipulator may be represented by many rigid elements which are connected by springs as shown in Fig. 1.

Fig. 1 Manipulator with flexible joint

The mathematical model of n flexible joint manipulator can be described by^[4, 8, 18]

$$A(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + K(q - \frac{\theta}{\eta N}) = 0 \quad (1)$$

$$J\ddot{\theta} - K(q - \frac{\theta}{\eta N}) = \Gamma \quad (2)$$

where q , $\dot{q}$ and $\ddot{q}$ represent the n angular position, speed and acceleration vectors, respectively. $A(q)$ is the $n \times n$ positive definite symmetric inertia matrix, $C(q, \dot{q})\dot{q}$ represents the centrifugal and Coriolis forces matrix, $G(q)$ represents the gravity vector, J is the inertia matrix, K represents joint stiffness vector, θ is the motor angle vector and Γ is the torque vector applied to the n axes of the robot.

The model of single flexible joint manipulator can be expressed as^[11]

$$J_1\ddot{q} + m_1gl_1 \sin(q) + K(q - \frac{\theta}{\eta N}) = 0 \quad (3)$$

$$J_m\ddot{\theta} - K(q - \frac{\theta}{\eta N}) = \Gamma \quad (4)$$

where J_1 , J_m , m_1 and l_1 represent the link inertia, the motor inertia, the mass and the length of the articulation, respectively.

We consider that N is the reduction ratio, η is the efficiency of the gearbox and g is the gravity constant which is equal to $9.81 \text{ m} \cdot \text{s}^{-2}$.

2.2 Model of brushless direct current motor

The brushless direct current motor is a three phase synchronous motor. The BDCM is supplied by a three phase inverter as shown in Fig. 2.

Fig. 2 BDCM associated to an inverter

The electrical equation of brushless direct current motor for each coil is written as

$$\frac{dI}{dt} = -\frac{R}{L}I + \frac{V - E}{L}. \quad (5)$$

Then, the mechanical equation of BDCM is expressed as

$$\frac{d\Omega_m}{dt} = -\frac{f}{J_m}\Omega_m + \frac{C_{em} - C_m}{J_m} \quad (6)$$

where C_{em} and C_m are the electromagnetic and load torques of the motor, f represents the friction, J_m is the inertia of the motor, Ω_m is the velocity of the motor, E is the electromotive force (EMF), I is the current in the phases of motor, V is the tension in the phases of the motor, L is the inductance of the motor, R is the resistance of the motor, $E = K_E\Omega_m$ and $C_{em} = K_tI$, K_E and K_t are constants.

3 Control strategy

The aim is to design a controller so that the behavior of the controlled system remains close to the behavior of the desired trajectories, despite the presence of flexibility uncertainties.

The control strategy for the flexible joint manipulator driven by BDCM is given in Fig. 3.

The control diagram includes four blocks. The first includes the flexible joint manipulator. The second block concerns the speed controller. The third block represents the current controller. The fourth block contains the BDCM associated to the inverter. In the following, we will explain the hysteresis current controller and the speed controller.

3.1 Hysteresis controller

The inverter topology is given in Fig. 2. Each branch of the inverter includes two insulated-gate bipolar transistor (IGBTs) and diodes which are connected on antiparallel with them^[19]. Moreover, each sequence of the control signals of the IGBTs $S1-S6$ throughout a period is divided into active sub-sequence Seq_i^a and regenerative sub-sequence Seq_i^r which are summarized in Table 1^[19]. U_{DC} is the direct current voltage applied to the inverter, e_a , e_b and e_c are the trapezoidal electromotive forces in the three phases a , b and c , V_a , V_b and V_c are the voltages given from the output of the inverter to the three phases a , b and c . $S1-S6$ and $D1-D6$ represent the control signals of the IGBTs and diodes switches as shown in Fig. 2. In the case of a supply by trapezoidal EMF, the current amplitude of

Fig. 3 Block diagram of flexible joint manipulator driving by BDCM control

BDCM is I with a rectangular shape and width phase equal to $\frac{2\pi}{3}$.

Table 1 Characterization of operating sequences of the BDCM (Seq_i^a and Seq_i^r indicate the active subsequence and the regenerative one of sequence i , with $1 \leq i \leq 6$)

Sub-sequence	Conducting switch(es)	Phase voltages		
		V_a	V_b	V_c
Seq ₁ ^a	S3 and S5	e_a	$-\frac{U_{DC}}{2}$	$\frac{U_{DC}}{2}$
Seq ₁ ^r	D2 and D6	e_a	$\frac{U_{DC}}{2}$	$-\frac{U_{DC}}{2}$
Seq ₂ ^a	S1 and S5	$\frac{U_{DC}}{2}$	$-\frac{U_{DC}}{2}$	e_c
Seq ₂ ^r	D2 and D4	$-\frac{U_{DC}}{2}$	$\frac{U_{DC}}{2}$	e_c
Seq ₃ ^a	S1 and S6	$\frac{U_{DC}}{2}$	e_b	$-\frac{U_{DC}}{2}$
Seq ₃ ^r	D3 and D4	$-\frac{U_{DC}}{2}$	e_b	$\frac{U_{DC}}{2}$
Seq ₄ ^a	S2 and S6	e_a	$\frac{U_{DC}}{2}$	$-\frac{U_{DC}}{2}$
Seq ₄ ^r	D3 and D5	e_a	$-\frac{U_{DC}}{2}$	$\frac{U_{DC}}{2}$
Seq ₅ ^a	S2 and S4	$-\frac{U_{DC}}{2}$	$\frac{U_{DC}}{2}$	e_c
Seq ₅ ^r	D1 and D5	$\frac{U_{DC}}{2}$	$-\frac{U_{DC}}{2}$	e_c
Seq ₆ ^a	S3 and S4	$-\frac{U_{DC}}{2}$	e_b	$\frac{U_{DC}}{2}$
Seq ₆ ^r	D1 and D6	$\frac{U_{DC}}{2}$	e_b	$-\frac{U_{DC}}{2}$

Considering the steady state operation, we can distinguish the active subsequences during which the motor is fed through IGBT(s) and regenerative sub-sequences where the motor is connected to the direct current bus through diode(s).

The outputs of the hysteresis controller determine the control signals for the IGBTs. Indeed, the principle of the hysteresis control is to maintain the measured current within a band of centered given width around the reference current I_{ref} .

The latter depends on the intersection of the measured actual current with upper limits (signal blocking) and lower

limits (ignition signal) of the hysteresis band.

3.2 Speed controller

In this subsection, we use two types of controllers: the proportional integral controller and sliding mode controller. The basic idea of speed controller is based on the exploitation of the errors in position and velocity.

3.2.1 PI controller

The proportional integral controller is extensively used in several industrial applications. In fact, PI controller is characterized by its simple structure.

The PI control law is given by

$$\Gamma = K_p(\Omega_{ref} - \Omega) + K_I \int (\Omega_{ref} - \Omega) dt \quad (7)$$

where $\Omega_{ref} = \dot{q}_{ref}$ indicates the reference of joint speed, $\Omega = \dot{q}$ indicates the measured joint speed, K_p and K_I are the proportional gain and the integral gain, respectively.

The choice of the PI controller parameters is done so that the error between the desired value and the measured value tends towards zero^[20]. However, it is necessary to determine the global transfer function of the system which includes the inverter, the BDCM and the flexible joint manipulator. On the basis of (3) and (4), we approximate our system around an operating point and we suppose that $q \rightarrow 0$. However, $\sin(q)$ can be approximated to q .

So, the Laplace equations are obtained from (3) and (4) around the operating point as

$$Q(p) = \frac{K}{\eta N(J_1 p^2 + m_1 g l_1 + K)} \theta(p) \quad (8)$$

$$Q(p) = H_1(p) \theta(p) \quad (9)$$

$$\theta(p) = \frac{K}{J_m p^2 + \frac{K}{\eta N}} Q(p) + \frac{K_t}{J_m p^2 + \frac{K}{\eta N}} I(p) \quad (10)$$

$$\theta(p) = H_2(p) Q(p) + H_3(p) I(p). \quad (11)$$

On the basis of (9) and (11), the transfer function is described by

$$\frac{Q(p)}{I(p)} = \frac{H_1(p) H_3(p)}{1 - H_1(p) H_2(p)}. \quad (12)$$

Then,

$$\frac{Q(p)}{I(p)} = \frac{K_t K}{(\eta N J_m p^2 + K)(J_1 p^2 + m_1 g l_1 + K) - K^2}. \quad (13)$$

On the basis of the numerical values of the system parameters, the transfer function (13) can be reduced to the third order. The controller parameters have been chosen to compensate the most dominant pole. We have chosen that $K_p = 153$ and $K_I = 0.04$.

3.2.2 Sliding mode controller

The sliding mode control approach has been extensively studied over many decades^[21]. It is known as one of the efficient tools to design robust controllers for nonlinear dynamic plant operating under uncertainty conditions. The sliding mode control uses a switching control action to force state trajectory toward a particular hyper surface in the state space. Once the states variables reach the sliding surface, the system is called to be in sliding mode. The major advantages of sliding mode control are the low sensitivity to plant parameters variation and disturbances^[22–26].

The switching function $S(x, t)$ is also named as the sliding function, and the hypersurface $S(x, t) = 0$ is named as the sliding surface.

Next, we analyze the stability of the system. We consider that the system is described by

$$\dot{x}(t) = f(x, t) + g(x, t)u(t) \quad (14)$$

where $x(t)$ is the state variable vector, $f(x)$ and $g(x)$ are two continuous bounded nonlinear functions and u is the control vector. The sliding surface can be defined by^[27]

$$S = Gx \quad (15)$$

where G is a row vector which describes the dynamics of the sliding surface. It can be chosen as $G = [K_1 \ 1]$. The sliding mode existence condition on hypersurface S is given by the expression $S\dot{S} < 0$.

We use the reaching law

$$\dot{S} = -\sigma S - K_s \text{sgn}(S) \quad (16)$$

where K_s and σ are positive gains.

To prove the stability of the system, we use the Lyapunov approach. The Lyapunov candidate function is chosen as

$$V = \frac{1}{2}S^2 > 0. \quad (17)$$

The sufficient condition which guarantees the stability of the system is given by

$$\dot{V} < 0 \quad (18)$$

$$\dot{V} = \dot{S}S. \quad (19)$$

Then,

$$\dot{V} = (-\sigma S - K_s \text{sgn}(S))S. \quad (20)$$

So,

$$\dot{V} = -\sigma S^2 - K_s S \text{sgn}(S) \quad (21)$$

$$\dot{V} = -\sigma S^2 - K_s |S| < 0 \quad (22)$$

which imply that the convergence condition and stability are guaranteed.

After that, we establish the control law expression. It is well known that in sliding mode theory, the control law has two terms which are the equivalent control term u_{eq} and the switching or the discontinuous term u_s . The control law is expressed as

$$u(t) = u_{eq}(t) + u_s. \quad (23)$$

The equivalent control term is computed such that it keeps the system on the sliding surface. In this stage, both the sliding surface and its derivative are equal to zero, i.e., $S(x, t) = 0$ and $\dot{S}(x, t) = 0$. However, the derivative of the sliding surface is written as

$$\dot{S}(x, t) = \frac{dS}{dt} = \frac{\partial S}{\partial x} \frac{\partial x}{\partial t} = \frac{\partial S}{\partial x} \dot{x}. \quad (24)$$

So,

$$\dot{S}(x, t) = \frac{\partial S}{\partial x} [f(x, t) + g(x, t)u_{eq}]. \quad (25)$$

We recall that in sliding mode, $\dot{S}(x) = 0$. So, we deduce that

$$u_{eq}(t) = -\left[\frac{\partial S}{\partial x} g(x, t)\right]^{-1} \left[\frac{\partial S}{\partial x} f(x, t)\right]. \quad (26)$$

Then,

$$u_{eq}(t) = \frac{J_1}{K_t} \left(-K_1 x_2 + \frac{m_1 g l_1}{J_1} \sin(x_1) + \frac{J_m}{J_1} \ddot{x}_3 \right) \Omega. \quad (27)$$

In the tracking problem, $x \rightarrow x_{\text{ref}}$, $e_1 = q_{\text{ref}} - q$ and $\dot{e}_1 = \dot{q}_{\text{ref}} - \dot{q}$. So, $\Omega = -\dot{e}_1 + \Omega_{\text{ref}}$.

Then, the expression of the equivalent control term u_{eq} becomes

$$u_{eq}(t) = \frac{J_1}{K_t} \left(-K_1 (\dot{e}_1 + \Omega_{\text{ref}}) + \frac{m_1 g l_1}{J_1} \sin(e_1 + q_{\text{ref}}) + \frac{J_m}{J_1} \ddot{\theta} \right). \quad (28)$$

Once the sliding surface is reached, u_{eq} keeps the state variable in the manifold $S(x, t) = 0$ independent of disturbance.

To reach the sliding regime, we resort to a discontinuous robust control u_s . It is determined to guarantee the variable attractiveness and satisfy the convergence condition. It ensures insensitivity to changes of the system parameters. The popular control law for u_s is given by

$$u_s = -\sigma S - K_s \text{sgn}(S). \quad (29)$$

So, the global control law is expressed as

$u =$

$$\frac{J_1}{K_t} \left(-K_1 (\dot{e}_1 + \Omega_{\text{ref}}) + \frac{m_1 g l_1}{J_1} \sin(e_1 + q_{\text{ref}}) + \frac{J_m}{J_1} \ddot{\theta} \right) - \sigma S - K_s \text{sgn}(S). \quad (30)$$

4 Simulation results and analysis

4.1 Simulation description

In order to evaluate the performance of the controllers applied to the single flexible joint manipulator driving by BDCM, PI and sliding mode controllers have been implemented in the Matlab simulink environment for system parameters given by Table 2.

The simulation stage shows the behavior of the closed loop system with variation of flexibility parameter $K \pm \Delta K$ for the two previously described controllers, where ΔK represents the uncertainty value. The evolution of uncertainties is given by Table 3.

Figs. 4–9 represent the evolution of speed, position, position error, speed error, electromagnetic torque and the load

torque, respectively.

4.2 Analysis

On the basis of Figs. 4–9, it is clear that:

1) The position errors and speed errors are more near to zero in the case of sliding mode controller than PI controller. It confirms that the sliding mode controller is better than PI controller.

2) Even in the presence of uncertain flexibility parameter, the simulation results show that the system output for sliding mode controller reaches its desired value with more precision than the PI controller where we observe the presence of the oscillations. It proves the high performance of sliding mode controller compared with PI controller in the presence of flexibility parameter disturbance.

Table 2 Parameters of system

R	L	J_m	m_1	l_1	J_1	N	η	f	K_t	K_E
0.625Ω	1.595 mH	$0.01 \text{ g}\cdot\text{m}^2$	0.8619 kg	0.3 m	$0.0065 \text{ N}\cdot\text{m}^2$	74	0.72 m	$1.162 \text{ g}\cdot\text{m}^2/\text{s}$	0.0382	0.0382 m

Table 3 Variation of flexibility parameter

Time (s)	[0 s;0.07 s]	[0.07 s;0.12 s]	[0.12 s;0.17 s]	[0.17 s;0.22 s]	[0.22 s;0.27 s]	[0.27 s;0.32 s]	[0.32 s;0.35 s]
K	K	$K + 2$	K	$K - 2$	K	$K + 2$	K

Fig. 4 Evolution of the speed with PI controller (left) and sliding mode controller (right)

Fig. 5 Evolution of the position with PI controller (left) and sliding mode controller (right)

Fig. 6 Evolution of the position error with PI controller (left) and sliding mode controller (right)

Fig. 7 Evolution of the speed error with PI controller (left) and sliding mode controller (right)

Fig. 8 Evolution of the control signal with PI controller (left) and sliding mode controller (right)

Fig. 9 Evolution of the load torque with PI controller (left) and sliding mode controller (right)

5 Conclusions

In this paper, two types of controllers have been proposed for uncertain flexible joint manipulator driving by brushless direct current motor. This latter has been modeled. Then, the control strategy has been adopted. It includes hysteresis controller for current control and PI or sliding mode controller for speed control. The parameters for both latest controllers have been computed. Also, the stability analysis and control law expression have been provided. Finally, the PI and sliding mode control strategies have been implemented in Matlab simulink environment for uncertain flexibility parameter. The simulation results have shown that the sliding mode controller leads to high performance by the reduction of oscillations observed in the case of PI controller and the minimization of the effect due to flexibility parameter disturbance.

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