Electrical motor drive parameter estimation via higher order sliding mode control

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Abstract. This paper proposes a practical parameter estimation scheme for electrical motor drive under substantial model's uncertainties. Here, higher order sliding mode controller is used in the cascaded structure for velocity regulation due to its precision tracking and higher level of robustness to un-model's dynamics and disturbances. During the progress of one cycle of acceleration and deceleration, relevant parameters including moment of inertia, viscous friction coefficient and load torque are respectively calculated. Numerical simulation validates the effectiveness of the proposed approach.

1 Introduction

The controller design for an electrical motor drive consists of cascaded loop (current control loop and velocity/speed loop) to handle the electrical and mechanical parts of this system correspondingly. While in most cases, a simple P or PD type controller is utilised for the current control loop, various control scheme is employed at the velocity loop of which PI/PID is typically used [1-4]. Here, the system's mechanical parameters (i.e. Moment of Inertia, Viscous Friction Coefficient and Load Torque) directly dominate the control performance; and often, PI/PID type of controllers would not be capable to effectively handle this kind of model's uncertainties, thus the closed-loop response is not adequate [5-9].

Sliding mode control approach is superior for its strong robustness property to model's uncertainty and disturbances [10-11]. Nevertheless, traditional sliding mode control method suffers from its inherent "chattering" phenomenon which is undesired high-frequency discontinuous switching at the control signal. This makes it less favourable for motion control application since "chattering" would cause severe damages to or even destroy the mechanical components / parts of the mechanical system, i.e. gearbox, transmission system, etc.

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Higher order sliding mode control (HOSLM), on the other hand, provides a power solution for this application due to its excellent “chattering” elimination, precision tracking and robustness properties [12-16]. In this paper, HOSLM is used at the outer loop for velocity tracking. Via referenced velocity trajectory design and HOSLM control input, relevant mechanical parameters of electrical motor drive are estimated / calculated accordingly within a cycle of acceleration and deceleration.

The remainder of this paper is structured as in the following. Section 2 presents the HOSLM design scheme. The parameter calculation is formulated in Section 3, and consequently validated in Section 4. Finally, Section 5 concludes the paper.

2 Higher Order Sliding Mode Controller Design Scheme

2.1 Mechanical Model of Electrical Motors

For an electrical motor of J and B as moment of inertia and viscous friction coefficient correspondingly, its mechanical model is given by the following equation:

$$J\dot{\omega} + B\omega = u - T_L \tag{1}$$

In which, u and T_L denote the driving electrical torque and the load torque respectively; ω and $\dot{\omega}$ regard the angular velocity and its first derivative (acceleration).

In the practical situation where load and working environment changes can result in variation of J and B, that is

$$\Delta J = J - \hat{J} \tag{2}$$

$$\Delta B = B - \hat{B} \tag{3}$$

Here, $\hat{J}$ and $\hat{B}$ are the initial known values of the motion system's moment of inertia and viscous friction coefficient. As the result, Equation (1) can be re-written as

$$\hat{J}\dot{\omega} + \hat{B}\widehat{\omega} = u - T_L - \Delta J\dot{\omega} - \Delta B\omega \tag{4}$$

Let $d(t,\omega,\dot{\omega},T_L) = T_L + \Delta J\dot{\omega} + \Delta B\omega$ which reflects the system's uncertainties and disturbance, Equation (4) takes the following form:

$$\hat{J}\dot{\omega} + \hat{B}\widehat{\omega} = u - d \tag{5}$$

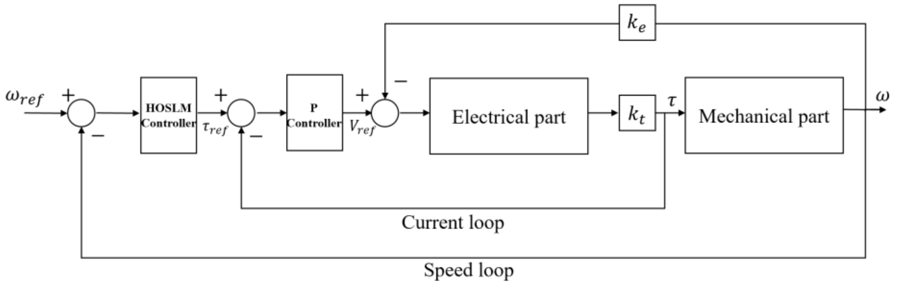

Figure 1. Schematic of cascaded HOSLM based velocity control (τ_{ref} denotes the referenced torque, V_{ref} denotes the reference Voltage, $k_t and\ k_e$ regard the back emf and torque constant respectively)

2.2 HOSLM Controller Design

Let us define the higher order sliding mode manifold s as

$$\varepsilon = \omega_{ref} - \omega \tag{6}$$

$$s = \ddot{\varepsilon} + \gamma_1 \dot{\varepsilon} + \gamma_2 \varepsilon \tag{7}$$

Where ω_{ref} denotes the referenced velocity and $\gamma_1, \gamma_2 > 0$ is the higher order sliding mode manifold characteristic parameter. Here, for simplification, a critically damped response of $\ddot{\varepsilon} + \gamma_1 \dot{\varepsilon} + \gamma_2 \varepsilon = 0$ is selected. That is $\gamma_1 = 2\sqrt{\gamma_2}$.

Theorem 1. The velocity error *e* can converge to zero asymptotically if the HOSLM manifold *s* is chosen as in Equation (7) and the control law is designed as follows:

$$\begin{gathered} u = u_{eq} + u_n \\ u_{eq} = \hat{B}\omega + \hat{J}\dot{\omega}_{ref} \\ \dot{u}_n + \gamma_1 u_n = \varphi \\ \varphi = \varphi_{eq} + \varphi_n \\ \varphi_{eq} = \hat{J}\gamma_2 \varepsilon \\ \dot{\varphi}_n = \hat{J}(k + \mu) sign(s) \\ k \geq |\dot{d}|, \mu > 0 \end{gathered}$$

Proof.

$$\begin{aligned} \dot{\varepsilon} &= \dot{\omega}_{ref} - \dot{\omega} \\ &= \dot{\omega}_{ref} + \frac{\Delta J}{\hat{J}}\dot{\omega} + \frac{\Delta B}{\hat{J}}\omega + \frac{T_L}{\hat{J}} + \frac{\hat{B}}{\hat{J}}\omega - \frac{u}{\hat{J}} \\ \dot{\varepsilon} &= \frac{\Delta J}{\hat{J}}\dot{\omega} + \frac{\Delta B}{\hat{J}}\omega + \frac{T_L}{\hat{J}} - \frac{u_n}{\hat{J}} \end{aligned}$$

Then,

$$\ddot{\varepsilon} = \frac{\Delta J}{\hat{J}}\ddot{\omega} + \frac{\Delta B}{\hat{J}}\dot{\omega} + \frac{\dot{T}_L}{\hat{J}} - \frac{\dot{u}_n}{\hat{J}}$$

Thus,

$$\begin{aligned} s &= \frac{\Delta J}{\hat{J}}\ddot{\omega} + \frac{\Delta B}{\hat{J}}\dot{\omega} + \frac{\dot{T}_L}{\hat{J}} - \frac{\dot{u}_n}{\hat{J}} + \gamma_1\left(\frac{\Delta J}{\hat{J}}\dot{\omega} + \frac{\Delta B}{\hat{J}}\omega + \frac{T_L}{\hat{J}} - \frac{u_n}{\hat{J}}\right) + \gamma_2 \varepsilon \\ &= \underbrace{\frac{\left(\Delta J\ddot{\omega} + (\Delta B + \gamma_1 \Delta J)\dot{\omega} + \dot{T}_L + \gamma_1 T_L\right)}{\hat{J}}}_{d} - \frac{(\dot{u}_n + \gamma_1 u_n)}{\hat{J}} + \gamma_2 \varepsilon \\ &= d - \frac{\varphi}{\hat{J}} + \gamma_2 \varepsilon \end{aligned}$$

As a result,

$$\dot{s} = \dot{d} - \frac{\dot{\varphi}_n}{\hat{J}}$$

Consider the following Lyapunov function candidate

$$V = 0.5 s^2$$

Differentiate *V* with respect to time, we get

$$\dot{V} = s\dot{s} = s\left(\dot{d} - \frac{\dot{\varphi}_n}{\hat{J}}\right)$$

In the other word,

$$\dot{V} = -k|s| - \mu|s| + \dot{d}s$$

Since

$$k \geq |\dot{d}|$$

The following inequality is obtained

$$\dot{V} \leq -\mu|s| \leq -\mu\sqrt{2}V^{\frac{1}{2}} = -\beta V^{\frac{1}{2}}$$

This demonstrates the the higher order sliding mode manifold $s = 0$ is reached in finite time $t_r \leq \frac{\sqrt{V(0)}}{\beta}$. Once $s = 0$ is reached, ε will exponentially converge to zero as governed by the dynamics of $\ddot{\varepsilon} + \gamma_1\dot{\varepsilon} + \gamma_2\varepsilon = 0$. This concludes the proof.

3 Velocity Profile Design and Parameter Calculation Formulation

Figure 2 describes the referenced velocity profile design for tracking. It consists of a full acceleration and deceleration cycle of phases:

- Phase 1 $[t_1 \rightarrow t_2]$: $\dot{\omega}$ *is constant*,
- Phase 2 $[t_2 \rightarrow t_3]$: $\dot{\omega} = 0$,
- Phase 3 $[t_3 \rightarrow t_4]$: $\dot{\omega} \neq 0$.

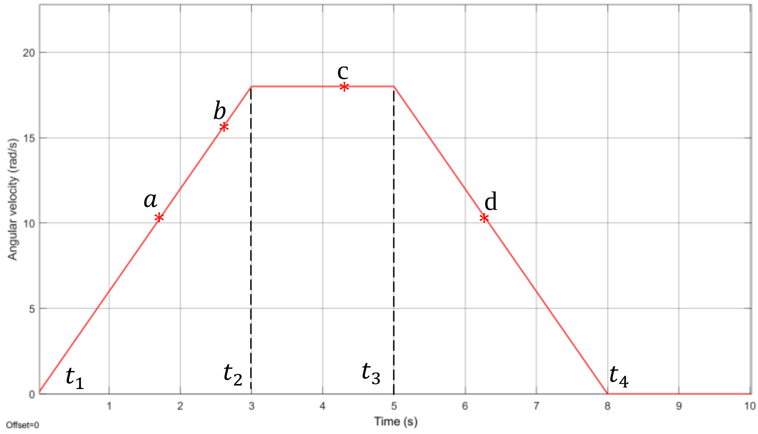

Figure 2. Referenced velocity profile

❖ **To calculate B:** In phase 1, two arbitrary point were picked (a and b) after velocity converging such as: $t_a < t_b < t_2$, the following equations can be obtained:

$$J\dot{\omega} + B\omega_a = u_a - T_L$$
$$J\dot{\omega} + B\omega_b = u_b - T_L$$

From the above equations, we derive:

$$B = \frac{u_a - u_b}{\omega_a - \omega_b}$$

❖ **To calculate T_L:** In "phase 2", after $\dot{\omega}$ reach zero, we select a point "c" such as $t_c < t_3$, and then T_L is calculated as follow:

$$T_L = u_c - B\omega_c$$

❖ **To calculate J:** In "phase 3", after B *and* T_L were determined, J can be easily calculated at any point "d" where $\dot{\omega}_d \neq 0$, by using the follow equation:

$$J = \frac{u_d - T_L - B\omega_d}{\dot{\omega}_d}$$

4 Validation Results

The physical parameters of the electrical motor are shown in Table 1.

Table 1. The physical parameters of electrical motor

	Real value	**Initial Known value**	**Unit**
$\boldsymbol{J}$	0,016	0,02	$kg.m^2$
$\boldsymbol{B}$	0,01	0,015	$N.m.rad/s$
$\boldsymbol{T_L}$	0,005	0,01	$N.m$

The initial known values in Table 1 are used to design the controller based on HOSLM with the coefficients as follows: $\gamma_1 = 20, \gamma_2 = 100, k = 300, \mu = 0{,}1$
The sliding manifold is designed as:

$$s = \ddot{\varepsilon} + 20\dot{\varepsilon} + 100\varepsilon$$

The controller is designed as:

$$u = u_{eq} + u_n$$
$$u_{eq} = 0{,}015\omega + 0{,}02\dot{\omega}_{ref}$$
$$u_n = e^{-20t}\int_0^t e^{-20t}\,\varphi dt$$
$$\varphi = 2\varepsilon + \int_0^t 6{,}002 sign(s)\, dt$$

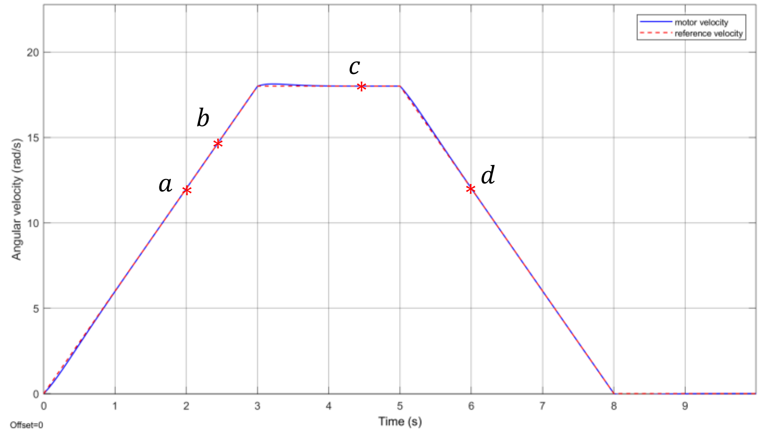

Figure 3. HOSLM controller's tracking of referenced velocity profile

In phase 1, the angular velocity converges at $t > 1s$, we choose a and b at: $t_a = 2s$ *and* $t_b = 2{,}5s$.

$$B = \frac{u_a - u_b}{\omega_a - \omega_b}$$

$$= \frac{0{,}221 - 0{,}251}{12 - 15} = 0{,}01$$

In phase 2, the angular acceleration reaches zero at $t > 4$s, we choose c at: $t_c = 4{,}5$s

$$\begin{aligned} T_L &= u_c - B\omega_c \\ &= 0{,}185 - 0{,}01.18 = 0{,}005 \end{aligned}$$

In phase 3, we choose d at: $t_d = 7s$

$$\begin{aligned} J &= \frac{u_d - T_L - B\omega_d}{\dot{\omega}_d} \\ &= \frac{-0{,}03103 - 0{,}005 - 0{,}01.5{,}998}{-6{,}001} = 0{,}016 \end{aligned}$$

5 Conclusion

A practical parameter estimation/calculation scheme of electrical motor drive using higher order sliding mode control method is reported in this paper. Just within a cycle of acceleration and deceleration, relevant parameters are accurately calculated via the respected HOSLM control input in the tracking of a referenced velocity profile. Further work includes extensive experimental validation on relevant motion control system and applications.

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