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Adaptive backstepping sliding mode control for direct driven hydraulics

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Outline

1. Introduction

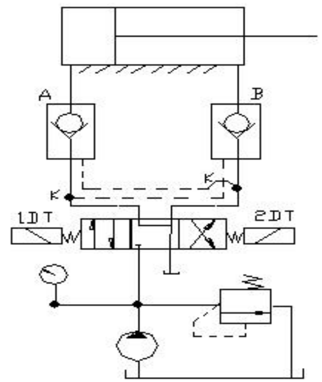
EHA: Electro-hydraulic actuator
DDH: Direct driven hydraulics
ABSMC: Adaptive backstepping sliding mode control
PID: Proportional-integral-differential

1. Introduction

Hydraulic system: Fast response, High power density, Reliability, Robustness

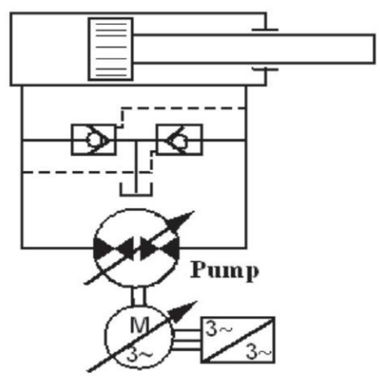
Hydraulic system

Valve-controlled



- High accuracy
- Fast response
- Complex
- Throttling loss
- High calorific value

Pump-controlled



- Higher energy efficiency
- Simple
- High calorific value
- Slow response
- Low accuracy

1. Introduction

Pump-controlled → EHA

(1) Fixed displacement pump and variable speed electric motor

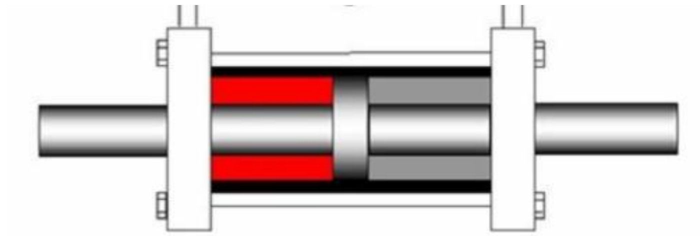
(2) Variable displacement pump and fixed speed motor

(3) Variable displacement pump and variable speed electric motor

Nonlinear friction, parameter uncertainty and unknown external disturbances

The first scheme has a slow dynamic response, but it has the properties of low-cost, simplicity, and high-efficiency

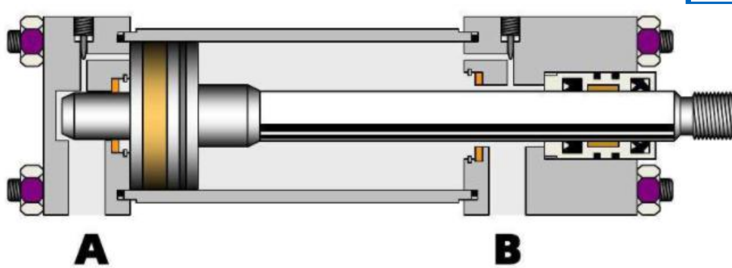
1. Introduction



Pump-controlled

Symmetric cylinder → Started earlier has been mature

Asymmetric cylinder → The flow between the two chambers is asymmetric



Alexander Järf and Tatiana Minav proposed a double-pump direct driven hydraulics (DDH) system.

Purpose

In order to reduce the influence of the parameter uncertainty, nonlinear characteristic and uncertain external disturbance on DDH position control. Improve the position control accuracy of the double-pump DDH

Content

1. Analyze and establish double-pump DDH model
2. Adopting ABSMC method for the DDH
3. Perform simulation and analysis

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2. DDH

2.1. DDH

2.2. Modelling of DDH

2. DDH and Modelling

2.1. DDH

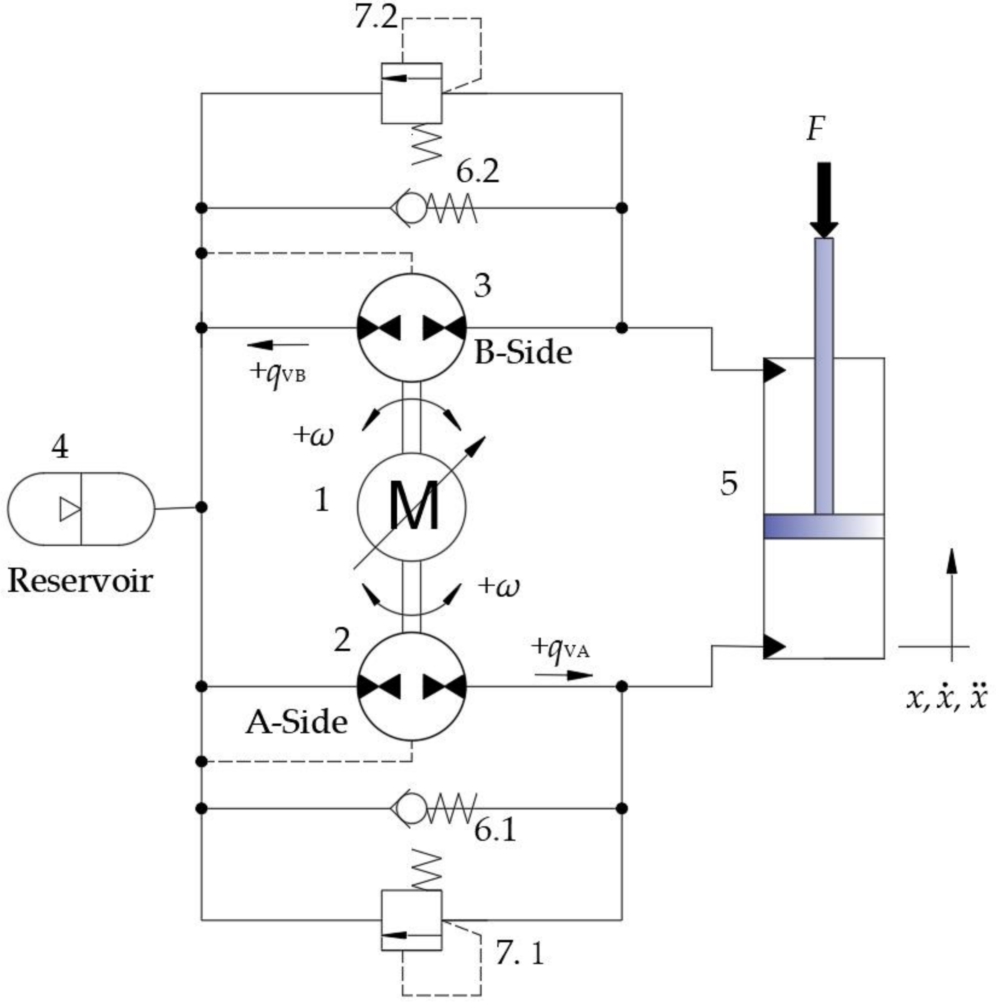

Figure 1. Schematics of DDH.

1: Servo motor,

2: A-side pump,

3: B-side pump,

4: Hydraulic accumulator,

5: Cylinder,

6: Check valve,

7: Relief valve.

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2.2. Modelling of DDH

Cylinder flow

$$q_A = A_A x + c_i(p_A - p_B) + c_e p_A + \frac{V_A}{\beta_e} p_A$$

$$q_B = -A_B x + c_i(p_A - p_B) - c_e p_B - \frac{V_B}{\beta_e} p_B$$

Pump flow

$$q_{VA} = nD_A \eta_A$$

$$q_{VB} = nD_B \eta_B$$

Force balance

$$p_A A_A - p_B A_B = Mx + Bx + kx + F$$

$$x_0 = [x_1 \quad x_2 \quad x_3]^T = [x \quad x \quad x]^T$$

DDH model:

$$\begin{cases} x_1 = x_2 \\ x_2 = x_3 \\ x_3 = r_1 x_3 + r_2 x_2 + b_0 u + f \end{cases}$$

$$r_1 = -\frac{B}{M},$$

$$r_2 = -\frac{\beta_e}{M}\left(\frac{A_A{}^2}{V_A} - \frac{A_B{}^2}{V_B}\right),$$

$$b_0 = \frac{\beta_e}{M}\left(\frac{A_A D_A \eta_A}{V_A} - \frac{A_B D_B \eta_B}{V_B}\right),$$

$$f = -\frac{F}{M}$$

3. Design of ABSMC controller

3.1. Design of ABSMC and the adaptive law of unknown parameters

3.2. Stability verification

3. Design of ABSMC controller

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DDH system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = a_1 x_1 + a_2 x_2 + a_3 x_3 + bu + d \end{cases}$$

where, a_1, a_2, a_3 and b are the unknown parameters, and d is an unknown disturbance.

3. Design of ABSMC controller

3.1. Design of ABSMC and the adaptive law of unknown parameters

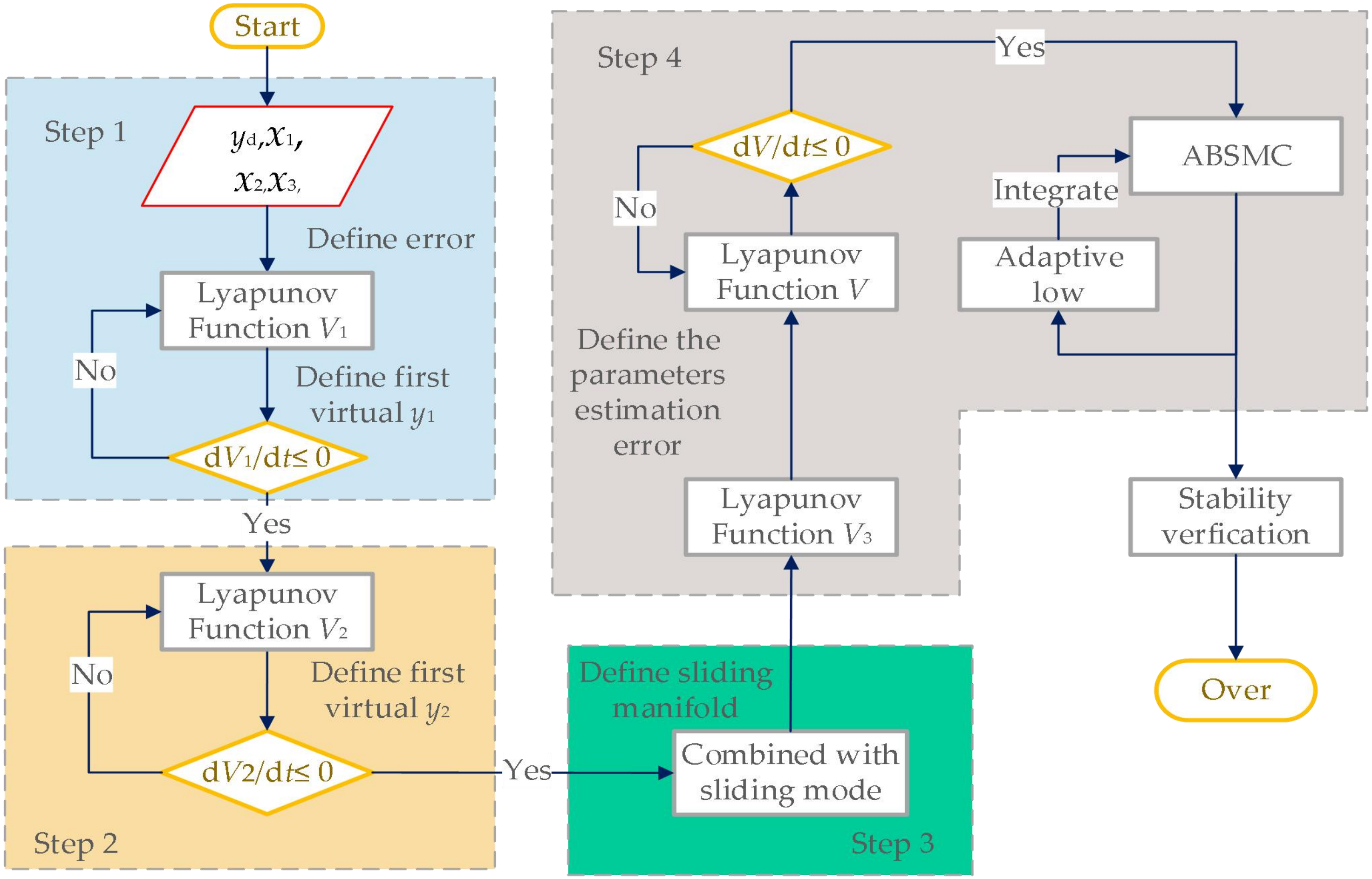

Figure 2. The flowchart of the ABSMC

3. Design of ABSMC controller

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3.1. Design of ABSMC and the adaptive law of unknown parameters

Step 1

$$\begin{cases} e_1 = x_1 - y_d \\ e_2 = x_2 - y_1 \\ e_3 = x_3 - y_2 \end{cases}$$

$$y_1 = -k_1 e_1 + y_d$$

$$V_1 = \frac{1}{2} e_1^2$$

$$\dot{V}_1 = -k_1 e_1^2 + e_1 e_2$$

Step 2

$$y_2 = -k_2 e_2 + \dot{y}_1 - e_1$$

$$V_2 = V_1 + \frac{1}{2} e_2^2$$

$$\dot{V}_2 = -k_1 e_1^2 - k_2 e_2^2 + e_2 e_3$$

Step 3

$$s = c_1 e_1 + c_2 e_2 + e_3$$

$$\dot{s} = c_1 \dot{e}_1 + c_2 \dot{e}_2 + \dot{e}_3$$

$$= c_1 (x_2 - \dot{y}_d) + c_2 (x_3 - \dot{y}_1) + a_1 x_1 + a_2 x_2 + a_3 x_3 + bu + d - \dot{y}_2$$

Step 4

$$\dot{V}_3 = -k_1 e_1^2 - k_2 e_2^2 + e_2 e_3 + s\left[\frac{c_1}{b}(x_2 - \dot{y}_d) + \frac{c_2}{b}(x_3 - \dot{y}_1) + \tau_1 x_1 + \tau_2 x_2 + \tau_3 x_3 + u + \tau_4 - \frac{\dot{y}_2}{b}\right]$$

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 + e_2 e_3 + s[c_1 a_4 (x_2 - \dot{y}_d) + c_2 a_4 (x_3 - \dot{y}_1)] + s[\tau_1 x_1 + \tau_2 x_2 + \tau_3 x_3 + u + \tau_4 - a_4 \dot{y}_2] + \lambda_1 \tilde{\tau}_1 (-\dot{\hat{\tau}}_1) + \lambda_2 \tilde{\tau}_2 (-\dot{\hat{\tau}}_2) + \lambda_3 \tilde{\tau}_3 (-\dot{\hat{\tau}}_3) + \lambda_4 \tilde{\tau}_4 (-\dot{\hat{\tau}}_4) + \lambda_5 \tilde{a}_4 (-\dot{\hat{a}}_4)$$

$$u = -c_1 \hat{a}_4 (x_2 - \dot{y}_d) - c_2 \hat{a}_4 (x_3 - \dot{y}_1) - \hat{\tau}_1 x_1 - \hat{\tau}_2 x_2 - \hat{\tau}_3 x_3 - \hat{\tau}_4 + \hat{a}_4 \dot{y}_2 - h_1 s - h_2 \operatorname{sgn}(s)$$

$$\begin{cases} \dot{\hat{\tau}}_1 = \frac{1}{\lambda_1} s x_1, \quad \dot{\hat{\tau}}_2 = \frac{1}{\lambda_2} s x_2, \quad \dot{\hat{\tau}}_3 = \frac{1}{\lambda_3} s x_3, \quad \dot{\hat{\tau}}_4 = \frac{1}{\lambda_4} s, \\ \dot{\hat{a}}_4 = \frac{1}{\lambda_5} s\left(c_1 (x_2 - \dot{y}_d) + c_2 (x_3 - \dot{y}_1) - \dot{y}_2\right) \end{cases}$$

3. Design of ABSMC controller

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3.2. Stability verification

$$V = -k_1 e_1^2 - k_2 e_2^2 + e_2 e_3 - h_1 s^2 - h_2 |s|$$
$$= -\boldsymbol{E}^{\mathrm{T}} \boldsymbol{Q} \boldsymbol{E} - h_2 |s|$$
$$\boldsymbol{E} = [e_1 \quad e_2 \quad e_3]^{\mathrm{T}}$$
$$\boldsymbol{Q} = \begin{bmatrix} h_1 c_1^2 + k_1 & h_1 c_1 c_2 & h_1 c_1 \\ h_1 c_1 c_2 & h_1 c_2^2 + k_2 & h_1 c_2 - \frac{1}{2} \\ h_1 c_1 & h_1 c_2 - \frac{1}{2} & h_1 \end{bmatrix}$$

$$\begin{cases} k_1 > 0, \quad k_2 > 0, \quad h_1 > 0, \quad h_2 > 0, \\ c_1 > 0, \quad c_2 > 0 \\ k_1 k_2 + k_1 h_1 c_2{}^2 + k_2 h_1 c_1{}^2 > 0 \\ k_1 k_2 h_1 + k_1 h_1 c_2 - \left(k_1 + h_1 c_1{}^2\right)/4 > 0 \end{cases}$$

$$V = -\boldsymbol{E}^{\mathrm{T}} \boldsymbol{Q} \boldsymbol{E} - h_2 |s| \le 0$$
$$\boldsymbol{G} = \boldsymbol{E}^{\mathrm{T}} \boldsymbol{Q} \boldsymbol{E}$$
$$V = -\boldsymbol{E}^{\mathrm{T}} \boldsymbol{Q} \boldsymbol{E} - h_2 |s| \le -G$$
$$\lim_{t \to \infty} \int_0^t G dt \le \begin{bmatrix} V\left(e_1(0), e_2(0), e_3(0)\right) - \\ V\left(e_1(\infty), e_2(\infty), e_3(\infty)\right) \end{bmatrix}$$

Barbalat's theorem

$$\lim_{t \to \infty} G = 0$$
$$\lim_{t \to \infty} e_i = 0 (i = 1,2,3)$$
$$\lim_{t \to \infty} s = 0$$

Stable

4. Simulation and Analysis

4.1. Simulation model

4.2. Load and disturbance

4.3. Simulation analysis

4. Simulation and Analysis

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4.1. Simulation model

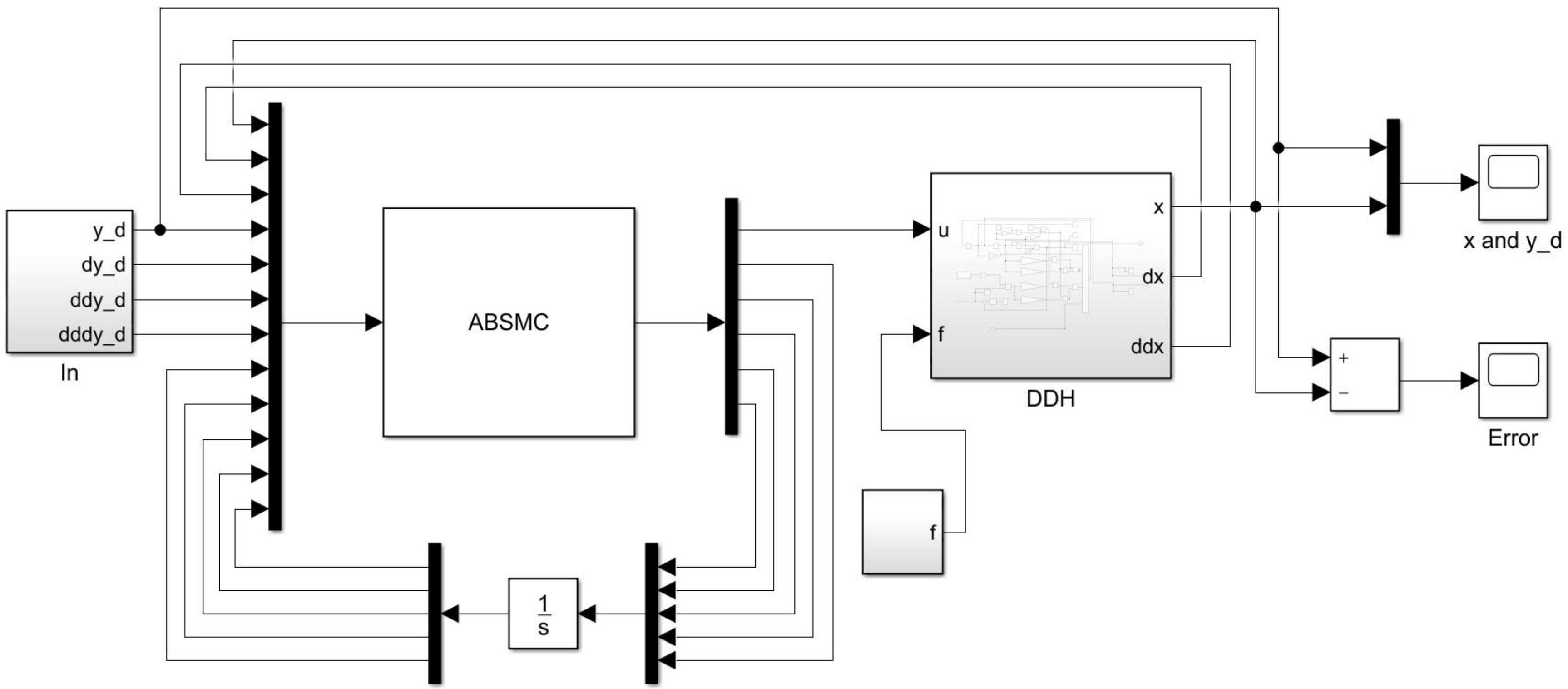
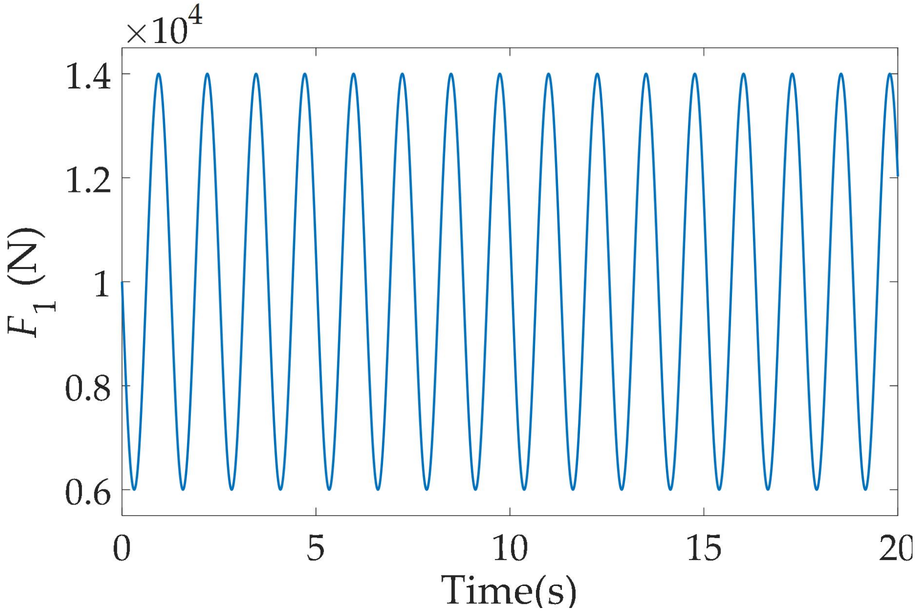
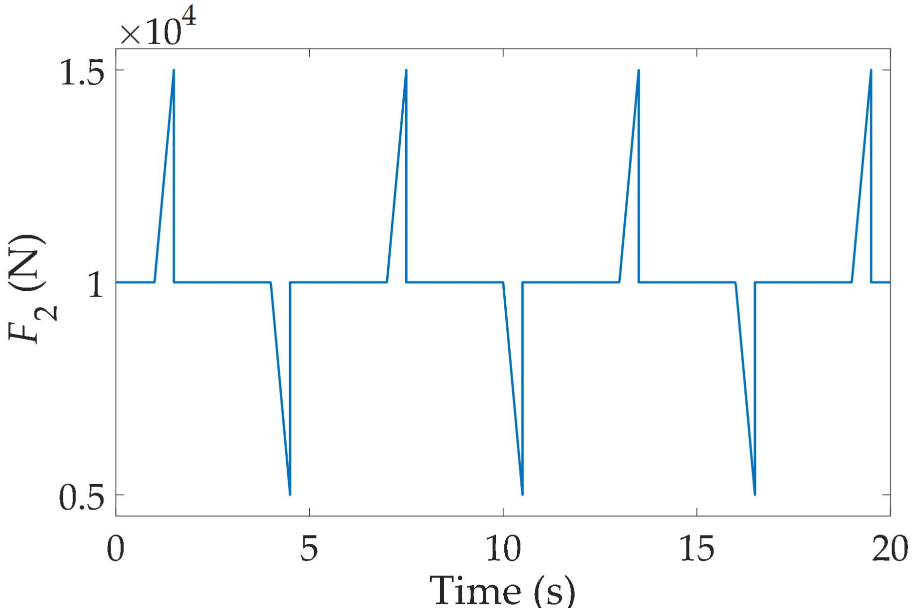


Figure 3. The schematic diagram of the Simulation model of the DDH control system

4.2. *Load and disturbance*



(a) load and disturbance F_1



(b) load and disturbance F_2.

Figure 4. Signal diagram of the sum of load and disturbance F

4. Simulation and Analysis

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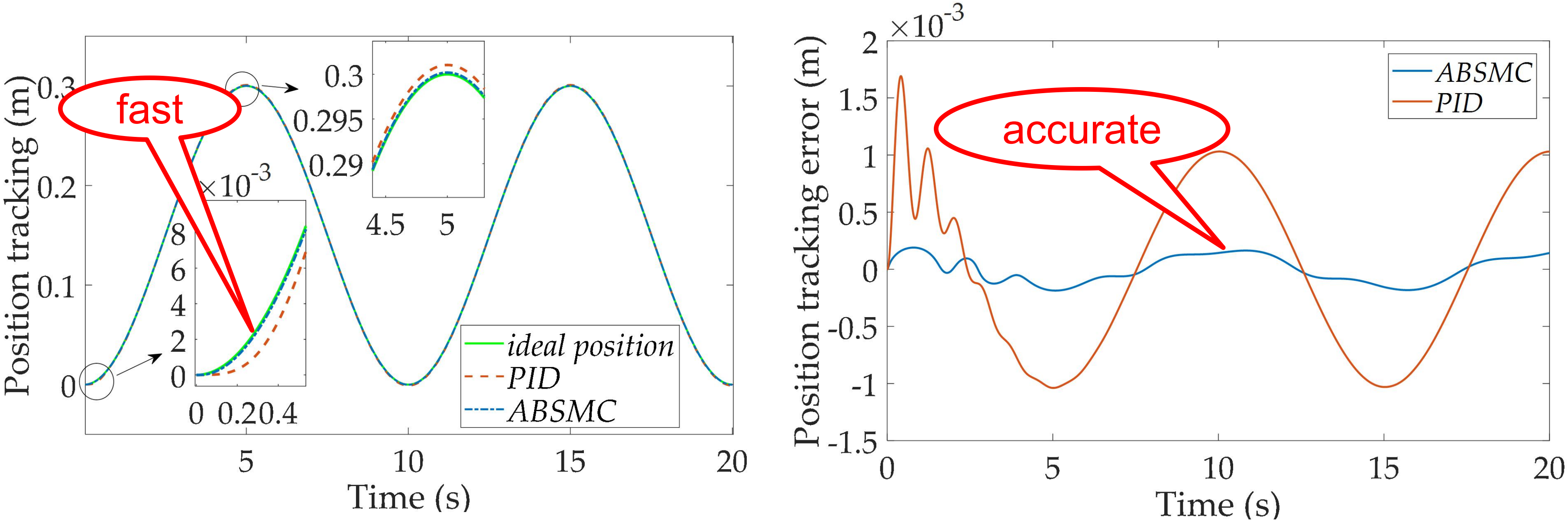
4.3. Simulation analysis

4.3.1. Simple sinusoidal signal

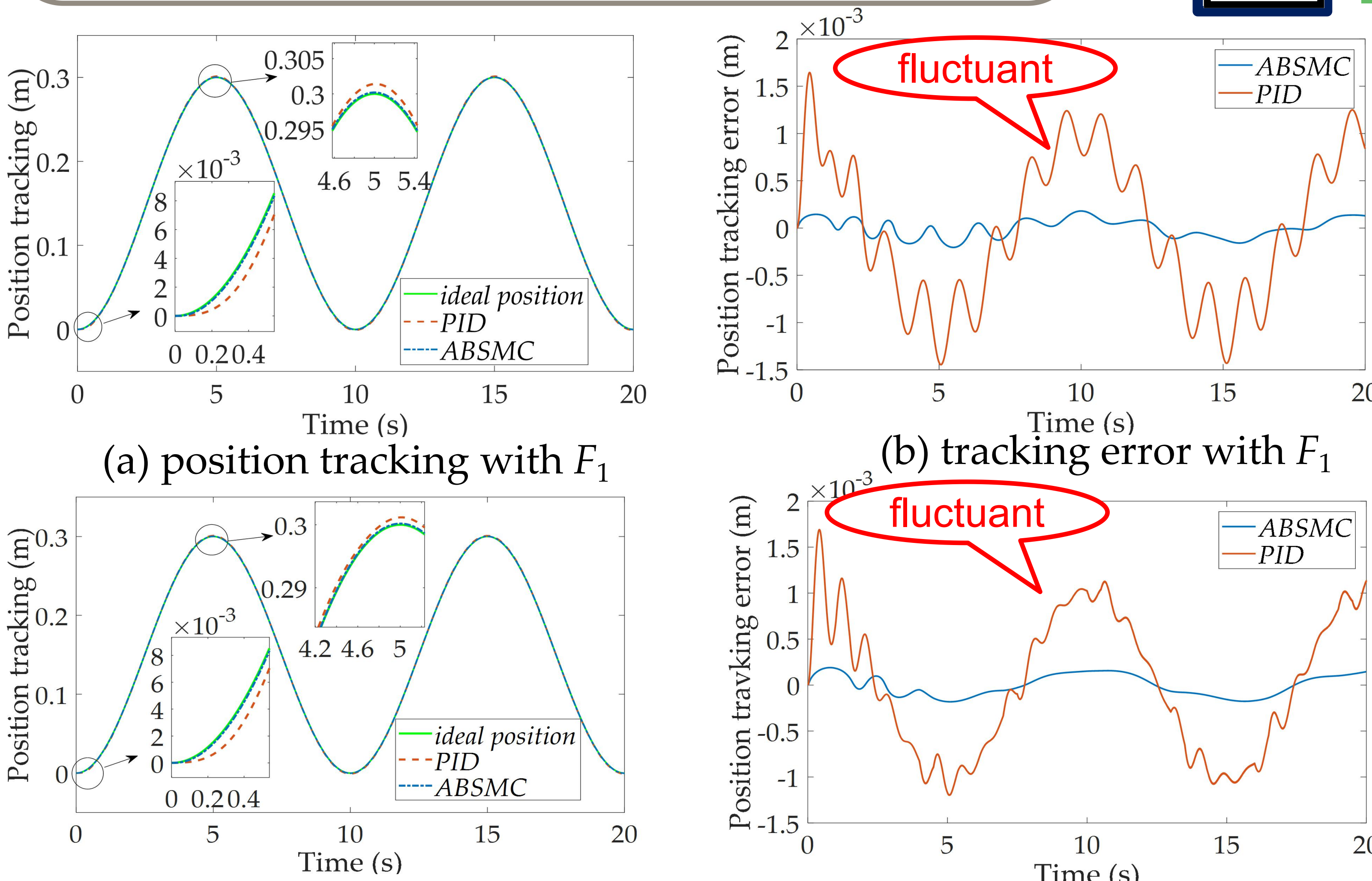
$$x_d = 0.15\sin(\frac{\pi}{5}t - \frac{\pi}{2}) + 0.15$$



(a) position tracking without disturbance (b) tracking error without disturbance.

Figure 5. Simple sinusoidal single responses of double-pump DDH using ABSMC and PID without disturbance

4. Simulation and Analysis



(a) position tracking with F_1

(b) tracking error with F_1

(c) position tracking with F_2

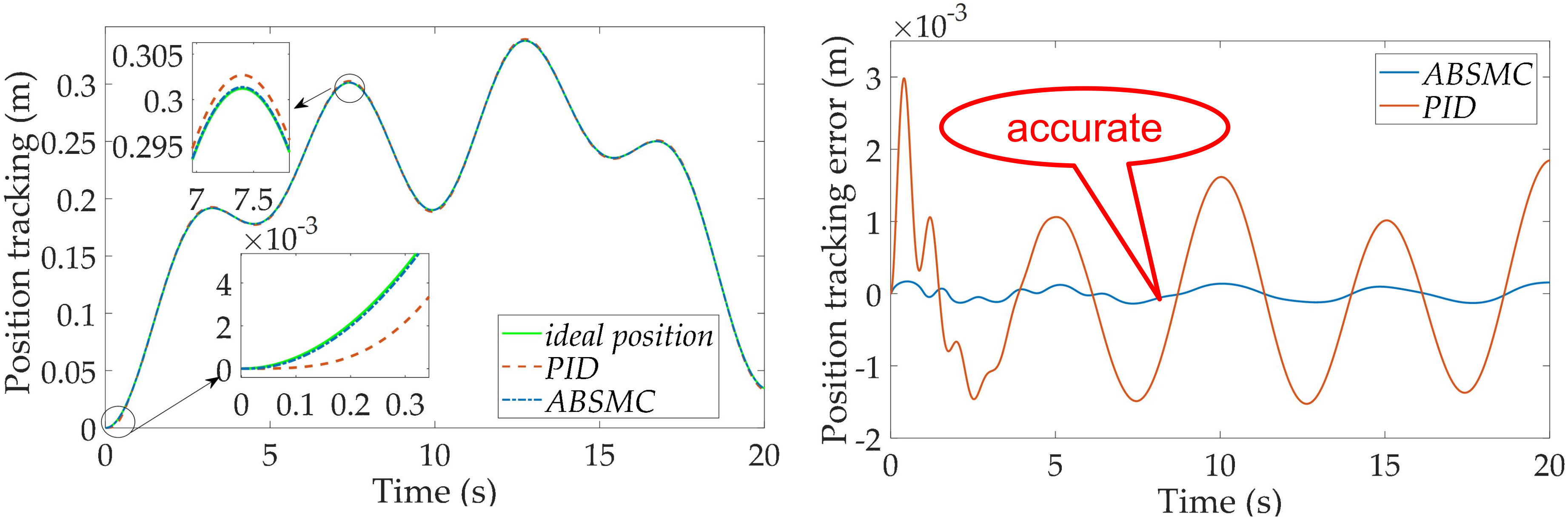
(d) tracking error with F_2

Figure 6. Simple sinusoidal single response of DDH using ABSMC and PID with disturbance

4.3. Simulation analysis

4.3.2. Multi-frequency sinusoidal signal

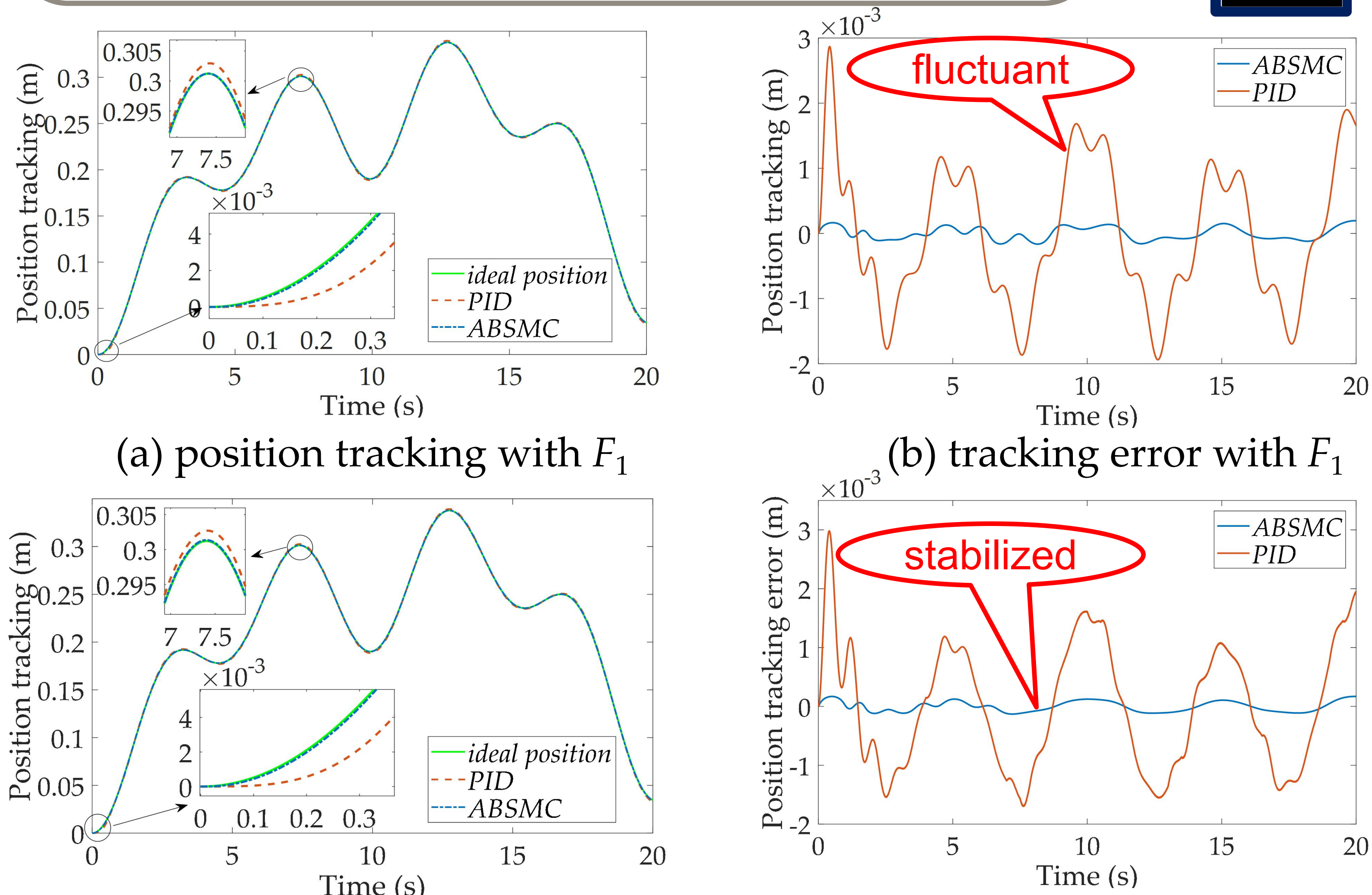
$$y_d = 0.05\left[\sin\left(\frac{2\pi}{5}t-\frac{\pi}{2}\right)+\sin\left(\frac{\pi}{5}t-\frac{\pi}{2}\right)+\sin\left(\frac{\pi}{10}t-\frac{\pi}{2}\right)+\sin\left(\frac{2\pi}{25}t-\frac{\pi}{2}\right)+4\right]$$



(a) position tracking without disturbance (b) tracking error without disturbance.

Figure 7. Multi-frequency sinusoidal single responses of double-pump DDH using ABSMC and PID without disturbance

4. Simulation and Analysis



(a) position tracking with F_1 (b) tracking error with F_1

(c) position tracking with F_2 (d) tracking error with F_2

Figure 8. Multi-frequency sinusoidal single response of the DDH using ABSMC and PID with disturbance

5. Conclusion

5. Conclusion

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A controller adopting ABSMC was proposed for the double-pump DDH

The simulation results show that ABSMC can track the position accurately under varying load disturbances, no matter with simple or complex position reference.It can effectively overcome the influence of the system's nonlinearity and parameter uncertainty, fast and accurate tracking and has strong robustness to parameter changes.

It lacks experimental data for comparison and verification. Therefore, the following research should establish a test bench and conduct experiment to validate the simulation results. In addition, the design process can be innovated.

Thank You !