An Adaptive Control Method for Electro-hydrostatic Actuator Based on Virtual Decomposition Control

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***Abstract*—This paper presents an adaptive control method for Electro-hydrostatic Actuator (EHA) based on Virtual Decomposition Control (VDC) under higher-order model, nonlinearities and uncertainties. In the fifth-order dynamic model of EHA, its nonlinear factors make the superior control very difficult. This paper decomposes EHA into four subsystems according to energy conversion, designs the control law for each subsystem, and provides an adaptive control based on VDC. The proposed adaptive controller can solve the problems of multiple uncertainties and nonlinearities in the system and guarantee the stability of EHA. The stability of the subsystems and EHA system are rigorously proven. The simulation results show that the proposed method can effectively control the EHA position and improve the EHA control performance compared with the conventional control method.**

Keywords-Adaptive control; Virtual Decomposition Control (VDC); Electro-hydrostatic Actuator (EHA); servo control

I. INTRODUCTION

EHA is an advanced power-by-wire (PBW) actuator, which has the advantages of small size, high power density, fast response and high reliability. EHA is widely used in aircraft, which is the development trend of more electric aircraft (MEA) in the future [1-2]. But the EHA model is complex and of high order, meanwhile, the system is generally subject to parameter uncertainties such as the compressibility of oil, flow loss of the system and some unknown damping, and nonlinear uncertainties such as dead-zone in motor, nonlinear friction and saturation. The above problems bring great challenges to the precise control of EHA.

To solve the problem of parameter uncertainties and nonlinearities in EHA, fuzzy PID [3], robust [4], sliding model control [5-6] and adaptive backstepping control [7-8] was widely applied. In [5], a Robust Discrete-Time Sliding Model Control (DT-SMC) was designed for EHA system with the effect of varying friction parameters. Zhang [6] proposed a Robust H_∞ Sliding Model Control (RSMC) for a linear EHA system with norm-bounded uncertainty. However, the SMC with a variable structure may generate chattering problem and damage the components of EHA. In [7], an adaptive backstepping control (ABSC) was proposed to solve the uncertainties in pump-controlled EHA. In [8], a modified backstepping algorithm with a special adaptation law was developed, compared with [7], it improved the tracking accuracy of pump-controlled EHA. But the backstepping control can easily lead to differential explosion when apply to high-order systems such as fifth-order EHA system studied in this paper, the above research based on backstepping control [7-8] only studied the third-order pump-controlled EHA system, without considering the motor.

Aiming at the challenge of high-order model, nonlinearities and uncertainties, this paper presents an adaptive control method for EHA system based on VDC. VDC has been widely used in serial systems such as robotic arms in recent years. Because it can virtually decouple complex systems and achieve parallel control law calculation, it has achieved good control results in complex systems with high degrees of freedom [9]. Koivumaki proposed an adaptive and nonlinear control based on VDC for Variable Displacement Axial Piston Pumps (VDAPP), whose dynamic behaviors are highly nonlinear and can be described by a fourth-order differential equation, the experimental results validated the high precision of tracking [10]. In this paper, the fifth-order dynamic model of EHA system is virtually decomposed into 4 subsystems, the control law is designed for each subsystem to solve the problem of model complexity and high order, and avoid the differential explosion. Then the parameter adaptation for the controller is designed to deal with parameter uncertainties and nonlinear uncertainties in EHA. The simulation and comparison results have been provided to verify the effectiveness of proposed method in EHA.

The paper is organized as follows: Section II presents the EHA dynamic model and analyzes nonlinear uncertainties; Section III virtually decomposes the fifth-order dynamic model into 4 subsystems from the perspective of energy conversion; Section IV designs the control law of the EHA; simulation and comparison results are provided in Section V; finally, the conclusion is given in Section VI.

II. EHA DYNAMIC MODEL

This section presents the EHA dynamic model and analyses the nonlinearities in the system.

In this paper, the EHA system includes Brushless DC (BLDC) motor, fixed pump, symmetrical hydraulic cylinder and load. As shown in Fig 1, the BLDC motor drives the fixed pump by changing the control voltage, then the pump changes the pressure difference on both sides of the cylinder to drive the actuator, and finally achieves displacement output.

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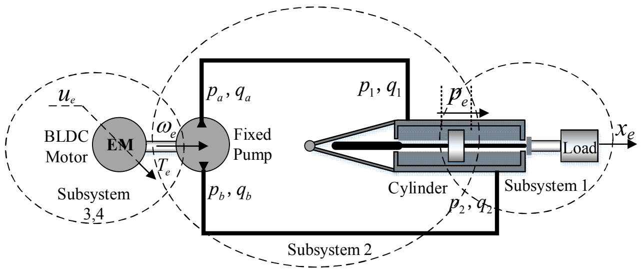

Figure 1. Simplified schematic diagram of an EHA system

A. EHA Dynamics Model

The EHA system fifth-order dynamic model can be written as

$$\begin{cases} u_e = L_e \dot{i}_e + R_e i_e + K_e \omega_e \\ K_m i_e = J_m \dot{\omega}_e + B_m \omega_e + T_e \\ V_P \omega_e = \dfrac{V_e}{4E_e} \dot{P}_e + C_{el} P_e + A_e \dot{x}_e \\ A_e P_e = m_e \ddot{x}_e + B_e \dot{x}_e + F_e + F_f \end{cases} \tag{1}$$

where u_e is the motor control voltage, i_e is the current of the motor, K_e is the Back EMF Coefficient of the motor, ω_e is the speed of the motor, R_e is the armature resistance of the motor, L_e is the armature inductance of the motor, K_m is the Electromagnetic moment constant of the motor, B_m is the total load damping coefficient of the motor and pump, J_m is the total moment of inertia of the motor and pump, and T_e is the output torque of the motor; V is the displacement of the pump, $V_P = V/(2\pi)$; A_e is the effective area of the hydraulic cylinder piston, x_e is the displacement of hydraulic cylinder piston, V_p is the total volume of hydraulic cylinder, C_{el} is the total leakage coefficient of hydraulic cylinder, and E_e is the effective bulk elastic modulus of hydraulic cylinder; m_e is the mass of the load, B_e is the damping coefficient of the load, F_e is force of the load, and F_f is the force of the nonlinear friction.

The EHA system is subject to parameter uncertainties because of the temperature changes and losses in motor, leakage and mechanical expansion of hydraulic cylinders, and compressibility of oil. Meanwhile, the nonlinear uncertainties as section B make the control more challenging.

B. Nonlinear Uncertainties Model

1) Nonlinear dead zone

Dead zone occurs when the motor is commutated, it can be written as

$$T_{em} = DZ(u_e) = \begin{cases} m_p u_e - m_p b_p, u_e \ge b_p \\ 0, \qquad b_n < u_e < b_n \\ m_n u_e - m_n b_n, u_e \le b_n \end{cases} \tag{2}$$

where u_e is the voltage of the motor, T_{em} is the electromagnetic torque of the motor, and m_p , b_p , m_n , b_n are parameters of the dead zone.

The output T_{em} of dead zone is not measurable, and the parameters like m_p are unknown, this brings more challenges to EHA control.

2) Nonlinear friction

The friction in EHA system is a non-linear phenomenon, which is not only related to speed, but also to position, temperature, etc., usually manifested as viscous friction, Coulomb friction, and static friction [11]. The nonlinear friction can be written as

$$F_f(\dot{x}_e) = \left[F_c + (F_s - F_c)e^{-|\dot{x}_e|/\alpha} + K_{vis}|\dot{x}_e|\right] \bullet \mathrm{sgn}(\dot{x}_e) \tag{3}$$

where F_s is maximum static friction, F_c is Coulomb friction, K_{vis} is viscous damping coefficient, α is the value of speed reference, and $\mathrm{sgn}(\ )$ is symbolic function. To make the model continuous, the function is modified with the hyperbolic tangent function as

$$F_f(\dot{x}_e) = \left[F_c + (F_s - F_c)e^{-|\dot{x}_e|/\alpha} + K_{vis}|\dot{x}_e|\right] \bullet \tanh(\dot{x}_e / \beta) \tag{4}$$

where β is the value of speed reference.

III. EHA SYSTEM VIRTUAL DECOMPOSITION

Section III virtually decomposes the fifth-order dynamic model into 4 subsystems from the perspective of energy conversion.

EHA is a system with complex model and high order, and there is a lot of coupling in the system. At present, the traditional backstepping control is mostly used for the control of pump-controlled EHA [7-8]. The existence of differential explosion makes the application of backstepping control to the motor-controlled hydraulic cylinder system more challenging. Different from traditional methods, the control law in this paper is designed for each subsystem, and the subsystems' controllers solve in parallel. Even the fifth-order EHA system studied in this paper will not produce the phenomenon of differential explosion. The virtual decomposition simplifies the dynamic and control of EHA without simplifying the system.

From the perspective of energy conversion, the EHA system is divided into four simple subsystems shown as Figure.2, which makes it more convenient for designing control laws for subsystems.

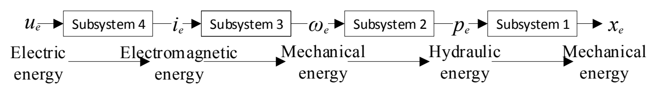

Figure 2. Virtual decomposition diagram of EHA system

IV. CONTROL DESIGN

This section designs the control law of the EHA based on the virtual decomposition in the previous section. The control law is based on the dynamics of each subsystem and the controllers of the four subsystems are connected in series to form the controller of the EHA system to output the final control variable u_e.

In the control law of the nth subsystem, $\forall n \in \{1,2,3\}$, it will appear a stability-preventing term in the time derivative of the non-negative accompanying function, therefore, by placing a feedback term in the control law of the $(n+1)$th subsystem, a stabilizing term is designed in the time derivative of the non-negative accompanying function of the subsystem. The stabilizing terms cancel out all the stability-preventing term in EHA system, this design can rigorously guarantee the stability of the entire EHA system based on Definition 2.4 and Lemma 2.3-2.5 in [9]. This design of control law based on the subsystem dynamics solves the problem of complexity and high order of the EHA system.

Meanwhile, due to the large number of parametric uncertainty and nonlinear uncertainties in the EHA system, parameter adaptation is designed in the control law of each subsystem, adaptive algorithm solves the optimal system parameters in real time and finally identify the accurate system parameters. This design solves the problem of uncertainty, and effectively improve the control accuracy.

The adaptive function P_2 is defined as followed.

DEFINITION 1. Consider a second-order differentiable scalar function $\mathrm{P}_2(s(t),k,a(t),b(t),c,t) \in \mathbb{R}$ defined for $t \geq 0$ such that its time derivative is governed by

$$\dot{\mathrm{P}}_2 = k\left(s(t) + c\kappa_2\right) \tag{5}$$

with

$$\kappa_2 = \begin{cases} a(t) - \mathrm{P}_2, \mathrm{P}_2 \leq a(t) \\ b(t) - \mathrm{P}_2, \mathrm{P}_2 \geq b(t) \\ 0, \text{otherwise} \end{cases}$$

where $s(t) \in \mathbb{R}$ is a scalar variable, $k > 0$ and $c > 0$ are two constants, and $a(t) < b(t)$ holds.

A. Subsystem 1: Actuator Dynamic

The control objective is to make output $\dot{x}_e$ and x_e of the hydraulic cylinder track its desired velocity $\dot{x}_{ed}$ and desired displacement x_{ed}. Based on VDC method, the required velocity $\dot{x}_{er}$ is defined to replace the traditional desired velocity $\dot{x}_{ed}$:

$$\dot{x}_{er} = \dot{x}_{ed} + \lambda\left(x_{ed} - x_e\right) \tag{6}$$

where x_{ed} is desired displacement and $\lambda > 0$ is output displacement feedback.

Based on (1), the control law of the subsystem 1 can be written as

$$\begin{aligned} A_e P_{ed} &= m_e \ddot{x}_{er} + B_e \dot{x}_e + F_e + F_f + k_1\left(\dot{x}_{er} - \dot{x}_e\right) \\ &= \mathrm{Y}_1 \hat{\theta}_1 + k_1\left(\dot{x}_{er} - \dot{x}_e\right) \end{aligned} \tag{7}$$

where p_{ed} is desired pressure of the hydraulic cylinder, $\ddot{x}_{er}$ is required acceleration, and $k_1 > 0$ is the gain for local feedback. $\mathrm{Y}_1\hat{\theta}_1$ is a model-based feedforward compensation term by using the estimated parameters for $\hat{\theta}_1$, $\mathrm{Y}_1 = \begin{bmatrix} \ddot{x}_{er} \\ \dot{x}_e \\ F_e \\ F_f \end{bmatrix}^{\mathrm{T}} \in \mathbb{R}^{1\times 4}$ is regressor vector and $\hat{\theta}_1 = \begin{bmatrix} m_e \\ B_e \\ 1 \\ 1 \end{bmatrix} \in \mathbb{R}^4$ is estimated parameter vector.

The estimated parameter vector $\hat{\theta}_1$ is updated by adaptive algorithm as follow.

$$s_1 = \left(\dot{x}_{er} - \dot{x}_e\right)\mathrm{Y}_1^{\mathrm{T}} \tag{8}$$

Based on (5), the γth parameter of $\hat{\theta}_1$ is updated by P_2:

$$\hat{\theta}_{1\gamma} = \mathrm{P}_2\left(s_{1\gamma}, k_{1\gamma}, \underline{\theta}_{1\gamma}, \overline{\theta}_{1\gamma}, c_{1\gamma}, t\right), \forall \gamma \in \{1,2,3\} \tag{9}$$

where $\hat{\theta}_{1\gamma}$ denotes the γth parameter of $\hat{\theta}_1$, $s_{1\gamma}$ denotes the update function of γth parameter, $k_{1\gamma}$ are update gains, $c_{1\gamma}$ are correction gains, $\underline{\theta}_{1\gamma}$ and $\overline{\theta}_{1\gamma}$ denotes the lower bound and upper bound of $\theta_{1\gamma}$ respectively.

Let the non-negative accompanying function v_{1a} of the subsystem 1 be

$$v_{1a} = \frac{m_e}{2}\left(\dot{x}_{er} - \dot{x}_e\right)^2 + \frac{1}{2}\sum_{\gamma=1}^{3}\frac{\left(\theta_{1\gamma} - \hat{\theta}_{1\gamma}\right)^2}{k_{1\gamma}} \tag{10}$$

Based on (1)(7)(10), the time derivative of v_{1a} can be written as

$$\begin{aligned} \dot{v}_{1a} &= m_e\left(\ddot{x}_{er} - \ddot{x}_e\right)\left(\dot{x}_{er} - \dot{x}_e\right) + \frac{1}{2}\sum_{\gamma=1}^{3}\frac{\left(\theta_{1\gamma} - \hat{\theta}_{1\gamma}\right)^2}{k_{1\gamma}} \\ &\leq \underbrace{A_e\left(P_{ed} - P_e\right)\left(\dot{x}_{er} - \dot{x}_e\right)}_{stability-preventing\ term\ 1} - k_1\left(\dot{x}_{er} - \dot{x}_e\right)^2 \end{aligned} \tag{11}$$

B. Subsystem 2: Cylinder Fluid Dynamic

Based on (1), the control law of the subsystem 2 can be written as

$$\begin{aligned} V_P\omega_{ed} &= \frac{V_e}{4E_e}\dot{P}_{ed} + C_{el}P_e + A_e\dot{x}_e + k_2\left(P_{ed} - P_e\right) + k_3\left(\dot{x}_{er} - \dot{x}_e\right) \\ &= \mathrm{Y}_2\hat{\theta}_2 + k_2\left(P_{ed} - P_e\right) + k_3\left(\dot{x}_{er} - \dot{x}_e\right) \end{aligned} \tag{12}$$

where ω_{ed} is desired rotating velocity of the pump, $k_2 > 0$ is the gain for local feedback, and k_3 is the gain for stabilizing feedback. $\mathrm{Y}_2\hat{\theta}_2$ is a model-based feedforward compensation term by using the estimated parameters for $\hat{\theta}_2$, $Y_2 = \begin{bmatrix} \dot{P}_{ed} \\ P_e \\ \dot{x}_e \end{bmatrix}^T \in \mathbb{R}^{1\times 3}$ is regressor vector and $\hat{\theta}_2 = \begin{bmatrix} V_e / 4E_e \\ C_{el} \\ A_e \end{bmatrix} \in \mathbb{R}^3$ is estimated parameter vector.

The estimated parameter vector $\hat{\theta}_2$ is updated by adaptive algorithm as follow.

$$s_2 = \left(P_{ed} - P_e\right) Y_2^T \tag{13}$$

Based on (5), the γth parameter of $\hat{\theta}_2$ is updated by P_2:

$$\hat{\theta}_{2\gamma} = P_2\left(s_{2\gamma}, k_{2\gamma}, \underline{\theta}_{2\gamma}, \overline{\theta}_{2\gamma}, c_{2\gamma}, t\right), \forall \gamma \in \{1,2,3\} \tag{14}$$

Let the non-negative accompanying function v_{2a} of the subsystem 2 be

$$v_{2a} = \frac{V_e}{8E_e}\left(P_{ed} - P_e\right)^2 + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{2\gamma} - \hat{\theta}_{2\gamma}\right)^2}{k_{2\gamma}} \tag{15}$$

Based on (1)(12)(15), the time derivative of v_{2a} can be written as

$$\begin{aligned} \dot{v}_{2a} &= \frac{V_e}{4E_e}\left(\dot{P}_{ed} - \dot{P}_e\right)\left(P_{ed} - P_e\right) + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{1\gamma} - \hat{\theta}_{1\gamma}\right)^2}{k_{1\gamma}} \\ &\le \underbrace{V_p\left(P_{ed} - P_e\right)\left(\omega_{ed} - \omega_e\right)}_{stability-preventing\ term\ 2} - \underbrace{k_2\left(P_{ed} - P_e\right)\left(\dot{x}_{er} - \dot{x}_e\right)}_{stabilizing\ term\ 1} \\ &\quad - k_3\left(P_{ed} - P_e\right)^2 \end{aligned} \tag{16}$$

C. Subsystem 3: Motor Torque Dynamic

Based on (1), the control law of the subsystem 3 can be written as

$$\begin{aligned} K_m i_{ed} &= J_m \dot{\omega}_{ed} + B_m \omega_e + T_e + k_4\left(\omega_{ed} - \omega_e\right) + k_5\left(P_{ed} - P_e\right) \\ &= Y_3\hat{\theta}_3 + k_4\left(\omega_{ed} - \omega_e\right) + k_5\left(P_{ed} - P_e\right) \end{aligned} \tag{17}$$

where i_{ed} is desired current of the motor, $k_4 > 0$ is the gain for local feedback, and k_5 is the gain for stabilizing feedback. $Y_3\hat{\theta}_3$ is a model-based feedforward compensation term by using the estimated parameters for $\hat{\theta}_3$, $Y_3 = \begin{bmatrix} \dot{\omega}_{ed} \\ \omega_e \\ T_e \end{bmatrix}^T \in \mathbb{R}^{1\times 3}$ is regressor vector, $\hat{\theta}_3 = \begin{bmatrix} J_m \\ B_m \\ 1 \end{bmatrix} \in \mathbb{R}^3$ is estimated parameter vector.

The estimated parameter vector $\hat{\theta}_3$ is updated by adaptive algorithm as follow.

$$s_3 = \left(\omega_{ed} - \omega_e\right) Y_3^T \tag{18}$$

Based on (5), the γth parameter of $\hat{\theta}_3$ is updated by P_3:

$$\hat{\theta}_{3\gamma} = P_2\left(s_{3\gamma}, k_{3\gamma}, \underline{\theta}_{3\gamma}, \overline{\theta}_{3\gamma}, c_{3\gamma}, t\right), \forall \gamma \in \{1,2,3\} \tag{19}$$

Let the non-negative accompanying function v_{3a} of the subsystem 3 be

$$v_{3a} = \frac{1}{2} J_m\left(\omega_{ed} - \omega_e\right)^2 + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{3\gamma} - \hat{\theta}_{3\gamma}\right)^2}{k_{3\gamma}} \tag{20}$$

Based on (1)(17)(20), the time derivative of v_{3a} can be written as

$$\begin{aligned} \dot{v}_{3a} &= J_m\left(\dot{\omega}_{ed} - \dot{\omega}_e\right)\left(\omega_{ed} - \omega_e\right) + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{3\gamma} - \hat{\theta}_{3\gamma}\right)^2}{k_{3\gamma}} \\ &\le \underbrace{K_m\left(i_{ed} - i_e\right)\left(\omega_{ed} - \omega_e\right)}_{stability-preventing\ term\ 3} - \underbrace{k_4\left(P_{ed} - P_e\right)\left(\omega_{ed} - \omega_e\right)}_{stabilizing\ term\ 2} \\ &\quad - k_5\left(\omega_{ed} - \omega_e\right)^2 \end{aligned} \tag{21}$$

D. Subsystem 4: Motor Electrodynamics

Based on (1), the control law of the subsystem 3 can be written as

$$\begin{aligned} u_{ed} &= L_e \dot{i}_{ed} + R_e i_e + K_e \omega_e + k_6\left(i_{ed} - i_e\right) + k_7\left(\omega_{ed} - \omega_e\right) \\ &= Y_4\hat{\theta}_4 + k_6\left(i_{ed} - i_e\right) + k_7\left(\omega_{ed} - \omega_e\right) \end{aligned} \tag{22}$$

where u_{ed} is desired voltage of the motor, $k_6 > 0$ is the gain for local feedback, and k_7 is the gain for stabilizing feedback. $Y_4\hat{\theta}_4$ is a model-based feedforward compensation term by using the estimated parameters for $\hat{\theta}_4$, $Y_4 = \begin{bmatrix} \dot{i}_{ed} \\ i_e \\ \omega_e \end{bmatrix}^T \in \mathbb{R}^{1\times 3}$ is regressor vector, $\theta_4 = \begin{bmatrix} L_e \\ K_e \\ R_e \end{bmatrix} \in \mathbb{R}^3$ is estimated parameter vector.

The estimated parameter vector $\hat{\theta}_4$ is updated by adaptive algorithm as follow.

$$s_4 = \left(i_{ed} - i_e\right) Y_4^T \tag{23}$$

Based on (5), the γth parameter of $\hat{\theta}_4$ is updated by P_2:

$$\hat{\theta}_{4\gamma} = P_2\left(s_{4\gamma}, k_{4\gamma}, \underline{\theta}_{4\gamma}, \overline{\theta}_{4\gamma}, c_{4\gamma}, t\right), \forall \gamma \in \{1,2,3\} \tag{24}$$

Let the non-negative accompanying function v_{4a} of the subsystem 4 be

$$v_{4a} = \frac{1}{2} L_e\left(i_{ed} - i_e\right)^2 + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{4\gamma} - \hat{\theta}_{4\gamma}\right)^2}{k_{4\gamma}} \tag{25}$$

Based on (1)(22)(25), the time derivative of v_{4a} can be written as

$$\begin{aligned} \dot{v}_{4a} &= L_e\left(\dot{i}_{ed} - \dot{i}_e\right)\left(i_{ed} - i_e\right) + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{4\gamma} - \hat{\theta}_{4\gamma}\right)^2}{k_{4\gamma}} \\ &= \left(u_{ed} - u_e\right)\left(i_{ed} - i_e\right) - \underbrace{k_6\left(\omega_{ed} - \omega_e\right)\left(i_{ed} - i_e\right)}_{stabilizing\ term\ 3} \\ &\quad - k_5\left(i_{ed} - i_e\right)^2 + \frac{1}{2}\sum_{\gamma=1}^{3} \frac{\left(\theta_{4\gamma} - \hat{\theta}_{4\gamma}\right)^2}{k_{4\gamma}} \end{aligned} \tag{26}$$

Because the output u_{ed} of the controller is the input voltage u_e of the system motor, then $(u_{ed} - u_e) = 0$, $\dot{v}_{4a}$ can be written as

$$\dot{v}_{4a} \le (u_{ed} - u_e)(i_{ed} - i_e) - \underbrace{k_6(\omega_{ed} - \omega_e)(i_{ed} - i_e)}_{stabilizing\ term\ 3} \tag{27}$$

E. Stability of control design

Let the non-negative accompanying function v_a of the EHA system be

$$\begin{aligned} v_a &= \frac{1}{A_e} v_{1a} + \frac{1}{k_2} v_{2a} + \frac{V_p}{k_2 k_4} v_{3a} + \frac{K_m V_p}{k_2 k_4 k_6} v_{4a} \\ &\ge a_1 (\dot{x}_{er} - \dot{x}_e)^2 + a_2 (P_{ed} - P_e)^2 + a_3 (\omega_{ed} - \omega_e)^2 + a_4 (i_{ed} - i_e)^2 \end{aligned} \tag{28}$$

where $a_1 > 0$, $a_2 > 0$, $a_3 > 0$, and $a_4 > 0$.

The time derivative of v_{4a} can be written as

$$\begin{aligned} \dot{v}_a &= \frac{1}{A_e} \dot{v}_{1a} + \frac{1}{k_2} \dot{v}_{2a} + \frac{V_p}{k_2 k_4} \dot{v}_{3a} + \frac{K_m V_p}{k_2 k_4 k_6} \dot{v}_{4a} \\ &\le -b_1 (\dot{x}_{er} - \dot{x}_e)^2 - b_2 (P_{ed} - P_e)^2 - b_3 (\omega_{ed} - \omega_e)^2 - b_4 (i_{ed} - i_e)^2 \end{aligned} \tag{29}$$

where $a_1 > 0$, $a_2 > 0$, $a_3 > 0$, and $a_4 > 0$.

Based on Definition 2.4 and Lemma 2.3-2.4 in [9]:

$$\dot{x}_{er} - \dot{x}_e \in L_2 \cap L_\infty \tag{30}$$

$$P_{ed} - P_e \in L_2 \cap L_\infty \tag{31}$$

$$\omega_{ed} - \omega_e \in L_2 \cap L_\infty \tag{32}$$

$$i_{ed} - i_e \in L_2 \cap L_\infty \tag{33}$$

$$\dot{x}_{ed} - \dot{x}_e \in L_2 \cap L_\infty \wedge x_{ed} - x_e \in L_2 \cap L_\infty \tag{34}$$

hold, which lead to $(\dot{x}_{er} - \dot{x}_e) \to 0$, $(P_{ed} - P_e) \to 0$, $(\omega_{ed} - \omega_e) \to 0$, $(i_{ed} - i_e) \to 0$, $(\dot{x}_{ed} - \dot{x}_e) \to 0$ and $(x_{ed} - x_e) \to 0$ based on Lemma 2.5 in [9].

V. SIMULATION

In this section, in order to prove the effectiveness of the EHA system controller based on VDC, an EHA dynamics simulation model was established in MATLAB/Simulink, as shown in Figure 6. Table I shows the feedback gains used in controller.

TABLE I. CONTROLLER FEEDBACK GAINS

Feedbacks	Value	Feedback	Value
λ	100	k_4	2×10^{-7}
k_1	10000	k_5	2×10^{-4}
k_2	10^{-12}	k_6	10
k_3	1.5×10^{-5}	k_7	10

Case1: To show the tracking performance of the controller, a sinusoidal signal shown in Figure 3 is selected as desired displacement trajectory. Figure 4 shows the tracking error of actuator's output replacement, as shown in Figure 4, accurate trajectory tracking performance of EHA is achieved.

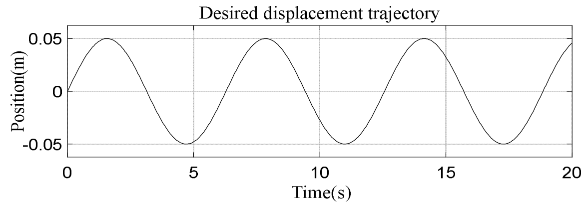

Figure 3. Desired displacement trajectory in case 1 and case 3

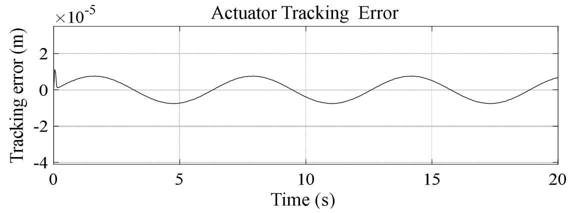

Figure 4. Output replacement tracking error of in case 1

Case 2: Considering the more scenarios to demonstrate the proposed method, a step signal shown in Figure 5 is selected as desired displacement trajectory. As shown in Figure 7, accurate trajectory tracking performance of EHA is achieved.

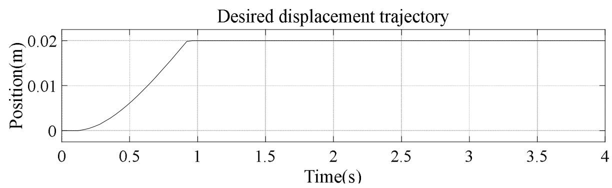

Figure 5. Desired displacement trajectory in case 2

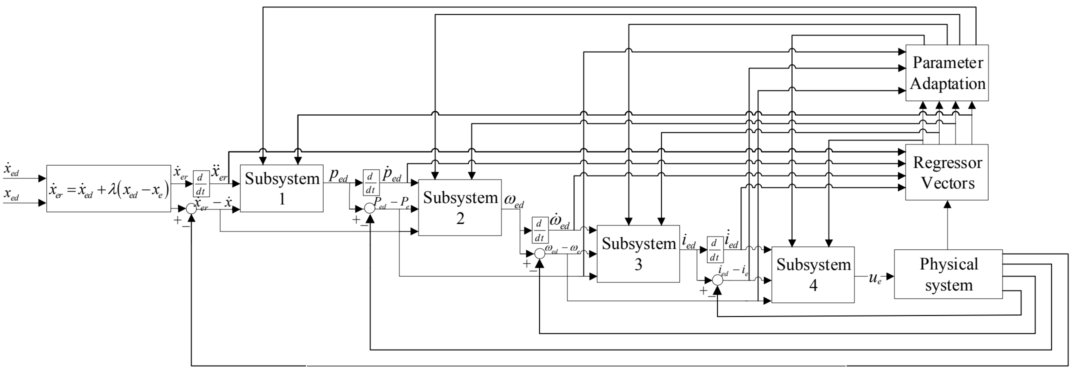

Figure 6. Diagram of the daptive control based on VDC for EHA

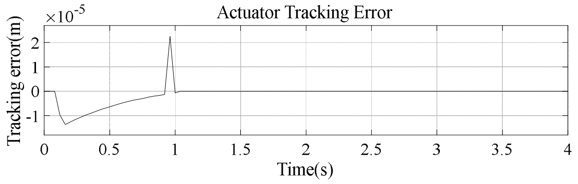

Figure 7. Output replacement tracking error of in case 2

Case 3: To show the tracking performance of the controller in a variable load condition, a random load shown in Figure 8 is generated for a sinusoidal response. The sinusoidal signal is same as case 1. The simulation result shown in Figure 9 proves strongly that the proposed VDC method can maintain robust performance in disturbed conditions.

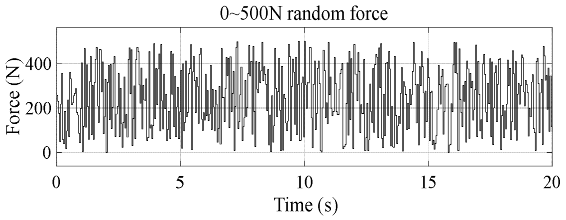

Figure 8. Random force in case 3

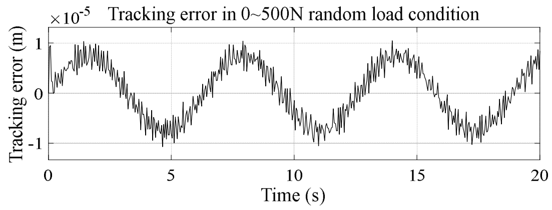

Figure 9. Output replacement tracking error of in case 3

Case 4: In order to prove that the proposed method has better tracking performance, this case is designed to compare with Robust Sliding Model Control (RSMC) for EHA in [4]. The input sinusoidal signal as Figure 10 is same as input in [4] for a more persuasive comparison. As the Figure 11 shows, the proposed VDC method has a better tracking performance than RSMC, and it has higher control accuracy and reliability.

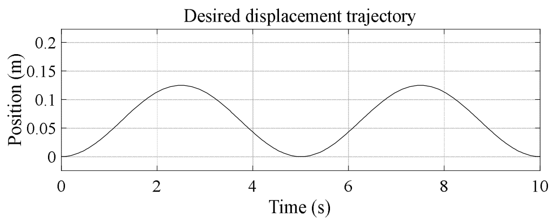

Figure 10. Desired displacement trajectory in case 4 and [4]

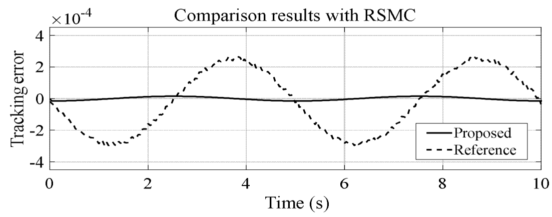

Figure 11. Comparison results with RSMC

VI. CONCLUSION

In this paper, an adaptive control method for EHA system was proposed based on VDC. Through the virtual decomposition, the fifth-order dynamic model of the EHA system was decomposed into four subsystems, and the control law was designed for four subsystems, which made the controller design simpler without simplifying the system, and solved the problem of model complexity and high order. The proposed method designed the parameter adaptation for the controller, dissolved the optimal system parameters in real time through the adaptive algorithm and identified the precise system parameters, which effectively solved the problem of parameter uncertainties and nonlinear uncertainties in the EHA system. The simulation proved the good tracking performance of the controller and the robustness in the disturbed conditions. The comparison results with RSMC verified the effectiveness of proposed method in EHA.

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