Trajectory Tracking Active Disturbance Rejection Control of the Unmanned Helicopter and Its Parameters Tuning

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ABSTRACT To solve the problem that the trajectory tracking control system of the unmanned helicopter is limited by the accuracy of the physical model (parameters and dynamic characteristics) and external disturbance of the unmanned helicopter, this paper designs a trajectory tracking control system of the unmanned helicopter based on the linear/nonlinear hybrid Active Disturbance Rejection Control (ADRC). At the same time, this paper proposes a method for tuning the controller parameters based on the Bacterial Foraging Optimization-Flower Pollination Algorithm (BFO-FPA). Finally, the simulation test of spiral climb and “8”-figure climb is applied to verify the controller’s performance. The results show that the controller proposed in this paper can effectively overcome the influence of the unmanned helicopter’s internal and external disturbance, and the controller has the advantages of strong anti-disturbance ability and strong robustness. Simultaneously, the optimization algorithm can obtain the optimal global solution, and can improve the controller’s performance.

INDEX TERMS Unmanned helicopter, linear/nonlinear hybrid control, active disturbance rejection control, control parameter tuning.

I. INTRODUCTION
The unmanned helicopter’s trajectory tracking control system is a system for decoupling control of the multi-input/multi-output (MIMO) nonlinear system, challenging to design [1]. Traditional linear control methods generally rely on accurate mathematical models and the aircraft’s physical parameters [2]–[4]. The internal uncertainty (parameter uncertainty or unmodeled dynamics) and external uncertainty (unknown disturbance of the external environment) of the unmanned helicopter will cause the mathematical model to be inaccurate so that the trajectory tracking accuracy cannot be guaranteed [5]. Therefore, the unmanned helicopter’s flight control system needs to overcome the influence of the uncertainty disturbance. Researchers have applied adaptive control and intelligent control to the unmanned helicopter flight control systems in recent years. Kapoor and Deb et al. [6]–[9] design an adaptive controller for the single main-rotor helicopter and the coaxial rotor helicopter. References [10], [11] apply intelligent control methods to tilt-rotor aircraft and quadrotor aircraft. However, most of these methods only target internal disturbance or external disturbance and cannot wholly overcome uncertainty.

Han [12]–[15] regarded the sum of the system’s internal and external disturbances as total disturbances and proposed Active Disturbance Rejection Control (ADRC). The extended state observer of the ADRC controller estimates the total disturbance and makes real-time compensation. ADRC does not rely on the accurate mathematical model, and ADRC can overcome internal and external disturbances’ uncertainty [16]. Humaidi et al. [17] proposed two ADRC schemes for the position control of a single link flexible joint robot manipulator: Linear Active Disturbance Rejection Controller (LADRC) and Nonlinear Active Disturbance Rejection Controller (NADRC), and a comparison study in terms of transient performances, robustness characteristics and disturbance rejection capabilities has been made based on LADRC and NADRC. They selected the particle swarm
technique (PSO) as an optimal tuner to improve the estimation process and, thereby, to enhance the system performance. Abdul-Adheem et al. [18] designed an ADRC controller based on an improved extended state observer for MIMO systems and achieved good control results. In reference [19], Abdul-Adheem et al. proposed a Novel Active Disturbance Rejection Control (N-ADRC) strategy that replaces the Linear Extended State Observer (LESO) used in Conventional ADRC (C-ADRC) with a nested LESO. Simulations on uncertain nonlinear single-input-single-output (SISO) systems with time-varying exogenous disturbance revealed that the proposed nested LESO could successfully deal with a generalized disturbance in both noisy and noise-free environments. Focusing on the general nonlinear uncertain system, Wang et al. [20] expounded the relationship between the stability, uncertainty, and parameters of LADRC when a disturbance occurs in the control input. Zhang et al. [21] proposed a dual closed-loop LADRC control scheme for the control problems in the quadrotor system, such as nonlinearity, strong coupling, sensitivity to disturbance, etc. Guo and Zhao [22], [23] proved that the active disturbance rejection control is suitable for the SISO system and the MIMO system. Chen et al. [24], [25] obtained the stable region of LADRC and reduced-order LADRC based on the Lyapunov function and the Markus-Yamabe theorem, they also get mathematical proofs of global stability and asymptotic regulation; they also proposed an adaptive method of ADRC parameters based on Q-learning. From the above study, we can find that the ADRC technology is relatively mature and can effectively overcome internal and external disturbance, so ADRC is suitable for the unmanned helicopter. Therefore, this paper designs a trajectory tracking control system of the unmanned helicopter based on the ADRC-LADRC hybrid controller.

Although the ADRC controller’s anti-disturbance performance is excellent, the ADRC controller has many parameters, and it is not easy to obtain better parameters with manual parameter tuning. Therefore, it is necessary to use optimization algorithms to tune controller parameters. In this paper, the Bacterial Foraging Optimization-Flower Pollination Algorithm (BFO-FPA) is used to optimize the ADRC-LADRC hybrid controller’s parameters, which reduces the difficulty of parameter tuning.

Based on the above research background, to enhance the unmanned helicopter’s anti-disturbance ability, this paper proposes a trajectory tracking control system based on the ADRC-LADRC hybrid controller, and the simulation results show that the ADRC-LADRC controller is better than the traditional LADRC controller. At the same time, this paper proposes a parameter optimization algorithm for the ADRC-LADRC hybrid controller based on the BFO-FPA algorithm. The simulation results of the unmanned helicopter’s attitude control show that the BFO-FPA algorithm is superior to the traditional BFO algorithm.

The remaining chapters of this paper are as follows: The second part shows the flight dynamics model of the unmanned helicopter, as well as the design of ADRC and LADRC, and designs the trajectory tracking control system of the unmanned helicopter. The third part shows the controller parameter optimization algorithm based on the BFO-FPA algorithm. The fourth part shows the simulation results and discussions. Finally, the fifth part draws some conclusions for this paper.

II. DESIGN OF TRAJECTORY TRACKING CONTROL LAW

A. FLIGHT DYNAMICS MODEL OF THE UNMANNED HELICOPTER

The flight dynamics equation of the unmanned helicopter with 6-DOF is:

\[ \dot{V} = F - m \vec{v} \]  
\[ \dot{S} = \Gamma^{-1}M - \Gamma^{-1}\Omega IS \]  
\[ \dot{\alpha} = ES \]  
\[ \dot{P} = R_{EB} \vec{V} \]

where, \( V = [u \ v \ w]^T \) is the linear velocity; \( S = [p \ q \ r]^T \) is the angular velocity; \( \alpha = [\phi \ \theta \ \psi]^T \) is the Euler angle of roll, pitch and yaw; \( P = [X \ Y \ Z]^T \) is position vector in ground coordinates; \( m \) is the mass of the whole machine; \( F \) and \( M \) are the forces and moments of the components of the whole machine (rotor, tail rotor, fuselage, vertical tail, flat tail, etc., including gravity); \( I \) is the moment of inertia matrix, \( \Omega \) is the angular rate antisymmetric matrix, \( R_{EB} \) is the conversion matrix from airframe coordinates to ground coordinates, and \( E \) is the conversion matrix from airframe angular velocity to Euler angular velocity, namely:

\[ \Omega = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \]

\[ R_{EB} = \begin{bmatrix} C_\phi C_\psi & S_\theta S_\phi C_\psi - C_\phi S_\psi & S_\theta C_\phi C_\psi + S_\phi S_\psi \\ C_\phi S_\psi & S_\theta S_\phi S_\psi + C_\psi C_\phi S_\psi & S_\theta C_\phi S_\psi - S_\phi C_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{bmatrix} \]

\[ E = \begin{bmatrix} 1 & S_\theta T_\theta & T_\theta C_\phi \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{bmatrix} \]

B. ADRC CONTROL FEATURES

ADRC consists of tracking differentiator (TD), extended state observer (ESO), and state error nonlinear control law (SENCL), as shown in Fig. 1. TD can quickly obtain the tracking signal and differential signal of the input signal. ESO is used to estimate the extended state formed by internal uncertainty and external disturbances. The nonlinear combination of the state error is used as the control output to realize the unmanned helicopter’s effective control.
The following is the discrete form of the nonlinear tracking differentiator of the second-order system [14]

\[
\begin{align*}
    x_1 (k+1) &= x_1 (k) + hx_2 (k), \\
    x_2 (k+1) &= x_2 (k) + h \text{fst} (x_1 (k) - v (k), x_2 (k), r, h), \\
    \text{fst} (x_1, x_2, r, h) &= \begin{cases} \\
        - r \text{sign} (a), & |a| > d, \\
        r \frac{y}{a}, & |a| \leq d, \\
    \end{cases}
\end{align*}
\]

where, the state variable \(x_1 (k)\) is the tracking signal of the input signal \(v (k)\), the state variable \(x_2 (k)\) is its differential signal, \(k\) is the \(k\) time of signal sampling, \(h\) is the discrete sampling time step, \(r\) is the speed factor, \(h\) and \(r\) are adjustable, which determine the speed of signal tracking.

2) EXTENDED STATE OBSERVER (ESO)

The expression of the nonlinear equation of the controlled plant is as follows

\[
\begin{align*}
    x_1 &= x_2 + a_0 - d \text{sign} (y), \\
    x_2 &= \frac{y}{h}, \\
    d &= rh, \\
    a_0 &= \sqrt{d^2 + 8r |y|}, \\
    y &= x_1 + x_2 h,
\end{align*}
\]

Extended state variable \(z_3\) is the estimated value of the sum of the controlled plant’s internal and external disturbances, and \(z_3\) is used to compensate the control quantity, thereby effectively suppressing the disturbance’s influence.

Let \(u = u_0 - \frac{z_0}{b_0}\), then

\[
\begin{align*}
    \dot{x}_1 &= x_2, \\
    \dot{x}_2 &= x_3 + b_0 \left( u_0 - \frac{z_0}{b_0} \right), \\
    y &= x_1
\end{align*}
\]

\(b_0\) is a constant term for the controller gain. The expanded state observer of the expanded system (13) is [12-14]

\[
\begin{align*}
    e &= z_1 - y, \\
    \dot{z}_1 &= z_2 - \beta_1 e, \\
    \dot{z}_2 &= z_3 - \beta_2 \text{fal} (e, \lambda_1, \zeta) + b_0 u, \\
    \dot{z}_3 &= -\beta_3 \text{fal} (e, \lambda_2, \zeta)
\end{align*}
\]

where, \(\lambda_i > 0 (i = 1, 2, 3)\), \(\beta_i (i = 1, 2, 3)\) is the gain and \(\zeta\) is the step size; \(\text{fal} (\cdot)\) is a nonlinear function, then the output variables of the extended state observer (14) can track the state variables of the system (13), namely

\[
\begin{align*}
    z_1 \rightarrow x_1, z_2 \rightarrow x_2, z_3 \rightarrow x_3
\end{align*}
\]

The part of the system (12) that is different from the standard integral series is regarded as the total disturbance (including internal disturbance and external disturbance), thereby forming an integral series system with disturbance (13). ESO uses the system’s input and output information to estimate the total disturbance and then compensates the total disturbance through the control law, thereby transforming the system (13) into a standard integral series system (18).

Given the second-order controlled plant system model

\[
\begin{align*}
    \dot{x}_1 &= x_2, \\
    \dot{x}_2 &= x_3 + b_0 u, \\
    \dot{x}_3 &= g (t), \\
    y &= x_1
\end{align*}
\]

\(u_0\) is the output of SENCL. Through the compensation of the expanded state estimate, the system becomes an integral series linear system, namely

\[
\begin{align*}
   \dot{x}_1 &= x_2, \\
   \dot{x}_2 &= b_0 u_0, \\
   y &= x_1
\end{align*}
\]
FIGURE 2. The observation effect of ESO.

in Fig. 2, \( z_1, z_2, z_3 \) are the state estimate of ESO, \( x_1, x_2 \) and \( x_3 \) are the state variables and expansion state of the controlled system (13). The estimated output value of ESO can well track the system’s state variables and the extended state variables formed by disturbances.

3) STATE ERROR NONLINEAR CONTROL LAW (SENCL)
SENCL is formed by the nonlinear combination of state deviations corresponding to TD and ESO, namely:

\[
\begin{align*}
e_1 &= v_{11} - z_1 \\
e_2 &= v_{21} - z_2 \\
u_0 &= \beta_{01}\text{fal}(e_1, \alpha_1, \xi) + \beta_{02}\text{fal}(e_2, \alpha_2, \xi) 
\end{align*}
\] (20)

where, \( \beta_{01}, \beta_{02} \) are adjustable gains. \( \text{fal} \) function can effectively suppress the occurrence of signal chattering and has good filtering effect.

FIGURE 3. Second order LADRC block diagram.

C. LADRC CONTROLLER AND ITS PARAMETERS
Construct a linear extended state observer (LESO) for the system (13), namely

\[
\begin{align*}
e &= y - z_1 \\
\dot{z}_1 &= z_2 + \beta_{11}e \\
\dot{z}_2 &= z_3 + \beta_{12}e + b_0u \\
\dot{z}_3 &= \beta_{13}e \\
\check{y} &= z_1 
\end{align*}
\] (21)

where, \( z_1, z_2 \) and \( z_3 \) are the observed values of the LESO respectively; \( \beta_{11}, \beta_{12} \) and \( \beta_{13} \) is selected as \( \begin{bmatrix} \beta_{11} & \beta_{12} & \beta_{13} \end{bmatrix} = \begin{bmatrix} 3w_0 & 3w_0^2 & w_0^3 \end{bmatrix} \), \( w_0 \) is the observer bandwidth[22].

LESO (20) is expressed as follows

\[
\dot{z} = A\check{z} + Bu
\] (22)

and

\[
\begin{align*}
A &= \begin{bmatrix} -3w_0 & 1 & 0 \\
-3w_0^2 & 0 & 1 \\
-3w_0^3 & 0 & 0 \\
0 & 3w_0 & 0 \\
b_0 & 3w_0^2 & 0 \\
0 & w_0^1 & 0 \\
\end{bmatrix} \\
B &= \begin{bmatrix} 0 \\
b_0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\end{align*}
\] (23)

where, \( u = [u_y]^T \) represents the input and output of the controlled plant.

The control law is designed as follows [26]

\[
u = \frac{u_0 - z_3}{b_0} \quad u_0 = w_c^2(v - z_1) - 2w_cz_2
\] (24)

where, \( w_c \) is the controller bandwidth. The LADRC controller can be constructed without TD, as shown in Fig. 3. The parameters to be tuned are simplified to \( w_c, b_0 \) and \( w_0 \). Compared with the second-order ADRC controller, the LADRC controller has fewer parameters.

D. TRAJECTORY TRACKING CONTROL LAW
The block diagram of the trajectory tracking controller for the unmanned helicopter is shown in Fig. 4. It is composed of the attitude control loop, the velocity control loop, and the position control loop from inside to outside. The order of ADRC or LADRC involved in the control loop is determined according to the relevant dynamic model’s order.
According to the above analysis, design the longitudinal controls $\delta_{\text{lon}}$ in the pitch loop as follows

$$
\begin{align*}
\dot{e} &= \theta - z_1 \\
\dot{z}_1 &= z_2 + \beta_{\delta_1} e \\
\dot{z}_2 &= z_3 + \beta_{\delta_2} e + b_{\delta_0} \delta \dot{\theta} \\
\dot{z}_3 &= \beta_{\delta_3} e \\
u_0 &= w_c^2 (\theta_r - z_1) - 2w_c z_2 \\
\delta_{\delta_0} &= b_{\delta_0} \\
\delta_{\text{lon}} &= \delta_{\delta_0} + \delta_{\text{trim}}
\end{align*}
$$

(29)

where, $\theta_r$ is the output signal of longitudinal velocity loop; $\theta$ is the pitch angle signal; $\delta_{\text{trim}}$ is the longitudinal control trim; $b_{\delta_0}$ is the control gain; $[\beta_{\delta_1}, \beta_{\delta_2}, \beta_{\delta_3}] = [3w_0, 3w_0, w_0^3]$.

The design of the roll loop control $\delta_{\text{lat}}$ and the yaw loop control $\delta_{\text{TR}}$ are similar, and will not be repeated.

2) VELOCITY CONTROL LOOP

Formula (1) can be expressed as

$$
\dot{V} = F_4 (\alpha, S, \dot{V}, w)
$$

(30)

Define the disturbance $\ddot{V} = F_4 (\alpha, S, \dot{V}, w) - B_{0\text{V}} \alpha$, then

$$
\ddot{V} = \ddot{V} + B_{0\text{V}} \ddot{\alpha}
$$

(31)

where, $B_{0\text{V}}$ is the velocity control gain matrix, and the system (30) is a first-order dynamic system, so design the corresponding first-order ADRC controller, as shown in Fig. 6. $\ddot{V}$ is the virtual control quantity, which forms a single input single output system corresponding to the longitudinal, lateral and vertical velocity $V$, the velocity control loop is shown in Fig. 7. The output of the position control loop is the speed command, and forms the desired commands $[\theta_r, \phi_r, \delta_{\text{col}}]$.

Design the control output $\theta_r$ in the longitudinal velocity loop as follows

$$
\begin{align*}
\dot{v}_1 &= -hf_{\text{st}} (v_1 - u_r, r, h) \\
\dot{e} &= z_{11} - u \\
\dot{z}_{11} &= z_{12} - \beta_{1\text{fal}} (e, 0.5, \zeta) + b_{u_0} \theta \\
\dot{z}_{12} &= -\beta_{2\text{fal}} (e, 0.25, \zeta) \\
\dot{e}_1 &= v_1 - z_{11} \\
u_0 &= \beta_{0\text{fal}} (e, 2, \zeta) \\
\theta &= u_0 - \frac{z_{12}}{B_{0\text{V}}} \\
\theta_r &= \theta + \theta_{\text{trim}}
\end{align*}
$$

(32)
where, \(v_1\) is the tracking signal from TD, \(u_r\) is the output of longitudinal position loop; \(\theta^{trim}\) is the bias value of longitudinal velocity; \(b_{i0}\) is the control gain.

The design of latitudinal velocity loop and vertical velocity loop are similar, and will not be repeated.

### 3) POSITION CONTROL LOOP

Equation (4) can be expressed as

\[
\hat{P} = F_5(\alpha, w) V
\]  

(33)

Define the disturbance \(\tilde{P} = (F_5(\alpha, w) - B_{0P})V\), then

\[
\hat{P} = \tilde{P} + B_{0P}V
\]  

(34)

where, \(B_{0P}\) is the position control gain matrix. The system (33) is a first-order system. Design the corresponding first-order ADRC controller (as shown in Fig. 6). \(V\) is the virtual control of \(P\). The three-position control loops also use a first-order ADRC controller to form the three-axis position control loop, as shown in Fig. 8. The position command is a preplanned trajectory input. The control output is the input of the velocity control loop \([u_r, v_r, w_r]\).

Design the control output \(u_r\) in the longitudinal position loop as follows

\[
\begin{align*}
V_1 &= -hfst(v_1 - X_r, r_1, h_1) \\
e &= z_{11} - u \\
z_{11} &= z_{12} - \beta_{12}fal(e, 0.5, \varphi_r) + b_{i0} R_{EB}u \\
z_{12} &= -\beta_{12}fal(e, 0.25, \varphi_r) \\
e_1 &= v_1 - z_{11} \\
u_0 &= \beta_{02}fal(e, 2, \varphi_r) \\
u &= R_{EB}\left(u_0 - \frac{z_{12}}{b_{i0} R_{EB}}\right) \\
u_r &= u + \theta^{trim}
\end{align*}
\]  

(35)

where, \(X_r\) is the tracking signal from TD, \(\theta^{trim}\) is the longitudinal position bias; \(b_{i0}\) is the control gain.

The design of the latitudinal position loop and the vertical position loop are similar, and will not be repeated.

### III. CONTROL PARAMETER TUNING

#### A. PARAMETER TUNING PRINCIPLE

The controller parameters have different effects on the performance of ADRC and LADRC controllers. Table 1 lists the parameters and their functions.
TABLE 1. ADRC/LADRC hybrid controller tuning parameters.

| Parameter | Description |
|-----------|-------------|
| LADRC $w_0$ | To eliminate the steady-state error, if $w_0$ is too large, it will cause oscillation, if $w_0$ is too small, it will cause poor tracking effect |
| $w_0$ | Increasing $w_0$ can shorten the rise time, but if the value of $w_0$ is too large, it will cause oscillation |
| $b_0$ | Increasing $b_0$ can suppress the oscillation, but if the value of $b_0$ is too large, it will cause the rise time to be too long |
| $r$ | The larger the value of $r$, the faster the tracking speed of $TD$, but the more pronounced the noise amplification effect of $TD$ |
| $h$ | The larger the value of $h$, the better the filtering effect of $TD$, but the more serious the phase loss of $TD$ tracking signal |
| TD $\beta_1$ | Increasing $\beta_1$ to suppress the overshoot of the system, but if the value of $\beta_1$ is too large, it will lead to a longer rise time of the system |
| $\beta_2$ | Increasing $\beta_2$ can reduce the lag of $ESO$'s estimation of the total disturbance of the controlled system |
| $\zeta_1$ | If $\zeta_1$ is too large, $ESO$ can not estimate the total disturbance of the system well |
| SENCL $\beta_{01}$ | If the value of $\beta_{01}$ is too large, the overshoot of the system will increase, but the rise time will be shorter |
| $\zeta_2$ | Same as $\zeta_1$ |

FIGURE 10. BFO-FPA flow chart.

1) PARAMETER INITIALIZATION
Including migration times $N_{ed}$, reproduction times $N_{re}$, chemotaxis times $N_{ce}$; migration probability $P_{ed}$; switching probability $P_{d}$, etc.

2) INITIALIZE THE BACTERIA’s LOCATION
That is to initialize the parameters of the ADRC-LADRC controller. Formula (36) is the position initialization, and formula (37) is the calculation of bacterial fitness.

$$X = x_{min} + rand \cdot (x_{max} - x_{min}) \quad (36)$$

$$J = \sum_{i=1}^{H} \int_{0}^{\infty} \left| e_i(t) \right| Q_i(t) \, dt \quad (37)$$

In the formula, $rand$ is a random number between [0,1]; $x_{min}$ and $x_{max}$ are the upper and lower boundaries of the parameters; $|e(t)|$ represents the absolute value of the difference between the expected input and actual output of the control system; $H$ represents the number of loops of the control system; $Q_i(t)$ represents the input signal of the control loop. The smaller the fitness value, the better the solution.

3) CHEMOTAXIS CYCLE
1) Flip: use formula (37) to update the position of bacteria

$$P_{i,j+1,k,l} = P_{i,j,k,l} + C_{i} \mu_{i} \quad (38)$$
\[ \mu(i) = \frac{(i)}{\sqrt{T(i) \Delta(i)}} \]  

(39)

where, \(C(i)\) is the step length of the selected direction; \((i)\) is the arbitrary direction vector generated in the direction change; \(\mu(i)\) is the unit step length vector selected after the direction adjustment; \(P(i, j, k, l)\) represents the space vector position of the \(i\)-th bacterium, that is, it is in the \(j\)-th chemotaxis cycle, the \(k\)-th reproduction cycle, and the \(l\)-th migration cycle.

2) Swimming: If the fitness value of bacteria decreases after flipping, swimming in the direction after flipping, otherwise swimming remains unchanged. The swimming operation adopts the FPA algorithm; the specific process is as follows

2-1) Find the optimal solution \(g_\star\) and its fitness value \(f(g_\star)\) in the current bacteria (pollen) population.

2-2) If \(\text{rand} < Pd\), use formula (40) (global optimal solution search) for cross-pollination, otherwise use formula (42) (local optimal solution search) for self-pollination.

\[ x_{i}^{j+1} = x_{i}^{j} + L \left( x_{i}^{j} - g_\star \right) \]  

(40)

\[ L \sim \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi^{\lambda/2}} \frac{1}{s^{1+\lambda}} \quad (s \gg s_0 \gg 0) \]  

(41)

\[ x_{i}^{j+1} = x_{i}^{j} + \epsilon_h \left( x_{im}^{j} - x_{in}^{j} \right) \]  

(42)

where, \(x_{i}^{j}\) is the position of pollen \(i\) in \(j\)-th iterations; \(L\) is the pollination intensity, and it is a random step that obeys Levy distribution; \(\Gamma(\lambda)\) is the standard gamma function; \(\epsilon_h\) is a random number with uniform distribution on \([0,1]\); \(x_{im}^{j}, x_{in}^{j}\) are two pollen positions from the same pollen at different time.

2-3) Evaluate the new solution. If fitness value \(f\left(x_{j+1}^{j}\right) < f\left(x_{j}^{j}\right)\), then update the solution in the population.

2-4) Compare the new solution \(x_{\text{new}}\) with \(g_\star\), if \(f\left(x_{\text{new}}\right) < f\left(g_\star\right)\), replace the optimal pollen \(g_\star\) with \(x_{\text{new}}\).

2-5) If the current pollen is not the last pollen of the population, go back to step 2-3), otherwise output the population containing the best pollen individual.

(4) The reproduction cycle. After the chemotaxis cycle, each bacteria’s fitness values were accumulated and sorted according to the fitness values. Remove bacteria with high fitness from the population, leaving half of the bacteria with low reproduction fitness.

(5) Migration cycle. After completing the replication cycle, choose a random probability \(\text{rand}\). If \(\text{rand} < Pd\), bacteria will migrate and initialize according to formula (36).

(6) Judge whether the algorithm meets the end conditions and output the optimization result if it meets it.

C. VERIFICATION OF BFO-FPA ALGORITHM

Taking the attitude control loop as an example to verify the BFO-FPA algorithm. Table 2 shows the BFO-FPS algorithm parameters, and Figure 11 shows the process curves of the attitude response of the BFO-FPA and BFO algorithms. The attitude commands are all \(5^\circ\) step signals. Figure 12 shows the convergence process of the respective algorithms’ fitness.
calculation, and Table 3 shows the tuning results of the two optimization algorithms. The results show that the BFO-FPA algorithm is better than the BFO algorithm alone. The BFO algorithm has obvious chattering in the pitch and roll loops, and the BFO-FPA algorithm has a shorter adjustment time in the attitude loop.

IV. TRAJECTORY TRACKING CONTROL AND SIMULATION RESULT ANALYSIS
The following will carry out the spiral ascending trajectory tracking and the “8” shaped ascending trajectory tracking simulation experiment. The control system selects the ADRC-LADRC controller, LADRC controller, and PID controller, respectively. Table 4 shows the parameters of the controlled device. The model includes a gust model, and

TABLE 2. BFO-FPA algorithm parameters.

| Parameter | Description          | Value |
|-----------|----------------------|-------|
| NG        | Number of iterations | 400   |
| sizepop   | Population size      | 20    |
| Nm        | Number of migrations | 5    |
| Nc        | Number of chemotaxis | 50   |
| Nre       | Number of reproduction | 10  |
| Pm        | Migration probability | 0.25 |
| Pd        | Switching probability | 0.6  |
the response of the output trajectory consists of an external disturbance of Gaussian noise with an intensity of 0.003db. Table 2 shows the parameters of the BFO-FPA algorithm.

### A. SPIRAL ASCENT TRACKING CONTROL

When the unmanned helicopter model has only external interference, Figures 13 and 14 show the spiral trajectory tracking control simulation results. Table 5 shows the ADRC-LADRC hybrid controller parameter values tuned by the BFO-FPA algorithm. Figure 14 is a three-dimensional trajectory diagram. The control effect of the ADRC-LADRC controller is better than that of the LADRC controller and the PID controller, with faster tracking speed and better control accuracy. Fig. 13 is the time response curve of the tracking error in the three-axis direction. The greater the curvature of the trajectory, the greater the error of the LADRC controller. The results show that the trajectory tracking and anti-disturbance effect of the ADRC-LADRC controller is better than that of the LADRC controller. It can achieve high-precision spiral trajectory tracking control.

The external interference remains unchanged, but the unmanned helicopter’s parameter values in the new simulation experiment have changed. Table 6 shows the parameter values of the new unmanned helicopter. This paper uses parameter changes to represent the controlled plant’s internal uncertainty and keeps the controller parameter values in Table 5 unchanged. Figure 15 is the new spiral ascending trajectory tracking control simulation. The results clearly show that the ADRC-LADRC hybrid controller and the LADRC controller can still ensure good trajectory tracking accuracy even if the controlled model changes. But, the tracking accuracy of the ADRC-LADRC is better than that of the LADRC controller. The tracking control error of the PID controller is significant. It shows that the ADRC-LADRC hybrid controller has strong anti-disturbance and robustness.

### B. “8” SHAPE CLIMBING TRAJECTORY TRACKING CONTROL

Compared with the spiral ascent trajectory tracking control, the “8” type climbing trajectory tracking control is more complicated. It can better test the trajectory tracking ability of the ADRC-LADRC controller. The simulation conditions remain unchanged, and Table 7 shows the controller parameter values.
FIGURE 16. Trajectory tracking response and error in X, Y and Z (“8” shape climbing trajectory tracking).

TABLE 5. ADRC-LADRC hybrid controller parameter value (spiral rising trajectory).

| loop    | Parameter | Value | loop    | Parameter | Value | loop    | Parameter | Value |
|---------|-----------|-------|---------|-----------|-------|---------|-----------|-------|
| Roll angle | $w_{c1}$ | 492   | Y velocity | $\beta_{c1}$ | 101   | Y position | $\beta_{x1}$ | 97   |
|          | $w_{c2}$ | 5.2   |         | $\beta_{c2}$ | 4.7   |          | $\beta_{x2}$ | 5.9   |
|          | $b_{01}$ | 9.3   |         | $\beta_{d01}$ | 2.2   |          | $\beta_{y01}$ | 1.8   |
|          | $w_{c2}$ | 1320  |         | $\beta_{d1}$ | 73    |          | $\beta_{y1}$ | 91    |
| Pitch angle | $w_{c2}$ | 4.2   | X velocity | $\beta_{c2}$ | 3.9   | X position | $\beta_{z2}$ | 6.4   |
|          | $b_{02}$ | 2.7   |         | $\beta_{d02}$ | 1.7   |          | $\beta_{y02}$ | 1.6   |
|          | $w_{c3}$ | 309   |         | $\beta_{d1}$ | 197   |          | $\beta_{y1}$ | 107   |
| Yaw angle | $w_{c2}$ | 4.2   | Z velocity | $\beta_{c2}$ | 5.2   | Z position | $\beta_{z2}$ | 2.3   |
|          | $b_{03}$ | 0.35  |         | $\beta_{d03}$ | 2.9   |          | $\beta_{y03}$ | 3.7   |
TABLE 6. Modification parameters of unmanned helicopter.

| Parameter                  | Unit | Value |
|----------------------------|------|-------|
| Mass                       | kg   | 6.8   |
| Rotor speed                | rad/s| 135   |
| Tail rotor speed           | rad/s| 810   |
| Rotor swinging inertia coefficient | kg m² | 0.031 |
| Inertia coefficient $I_x$  | kg m²| 0.15  |
| Inertia coefficient $I_y$  | kg m²| 0.27  |
| Inertia coefficient $I_z$  | kg m²| 0.22  |

TABLE 7. ADRC-LADRC hybrid controller parameter value ("8" shape climbing).

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $w_{01}$  | 487   | $\beta_{P1}$ | 97    | $P_{X1}$  | 105   |
| $w_{C1}$  | 5.5   | $\beta_{P2}$ | 4.6   | $P_{X2}$  | 5.7   |
| $b_{01}$  | 8.9   | $\beta_{P3}$ | 1.9   | $P_{X3}$  | 1.6   |
| $w_{02}$  | 1272  | $\beta_{P4}$ | 3.7   | $P_{Y1}$  | 94    |
| $w_{C2}$  | 4.3   | $\beta_{u1}$ | 71    | $P_{Y2}$  | 7.1   |
| $b_{02}$  | 2.5   | $\beta_{u2}$ | 1.7   | $P_{Y3}$  | 1.8   |
| $w_{03}$  | 311   | $\beta_{w1}$ | 201   | $P_{Z1}$  | 94    |
| $w_{C3}$  | 4.6   | $\beta_{w2}$ | 5.1   | $P_{Z2}$  | 2.2   |
| $b_{03}$  | 0.39  | $\beta_{w3}$ | 43.2  | $P_{Z3}$  | 3.9   |

V. CONCLUSION

It is difficult to predict the internal and external uncertainty when designing the unmanned helicopter’s trajectory tracking control system. The design of attitude and trajectory loop parameter values. Figures 16 and 17 show the simulation results. Fig. 17 indicates that the control accuracy of the PID controller has dropped significantly. In contrast, the ADRC-LADRC controller still has higher control accuracy, and the control effect is more robust than that of the LADRC controller. Fig. 16 shows trajectory tracking response and error in X, Y, and Z. The ADRC-LADRC controller has apparent advantages. The x-axis error is in the range of $-0.25$ to $0.25$, which is better than the LADRC controllers $-0.5$ to $0.4$ range. The other axes are similar.

Also, in constant external disturbance, the plant model parameters are changed to simulate parameter uncertainty, shown in Table 6. The controller parameter values remain unchanged, seen in Table 7. Figure 18 shows the simulation results. Figure 18 reflects that the tracking trajectory of the PID controller has completely deviated from the predetermined course. In contrast, the ADRC-LADRC hybrid controller and the LADRC controller can still maintain high tracking accuracy. But, the tracking accuracy of the LADRC controller decreases more obviously. It shows that the ADRC-LADRC hybrid controller proposed in this paper has apparent advantages as a trajectory tracking controller, which can effectively overcome the internal and external interference of unmanned helicopters, has good robustness and high tracking accuracy.
control law using ADRC technology can effectively solve the above problem. The main results of this paper are as follows

(1) When the unmanned helicopter changes structure parameters or is interfered with by external disturbance, the ADRC-LADRC controller has better robustness than the LADRC controller. The anti-disturbance performance of the PID controller is lower than the ADRC-LADRC controller. BFO-FPA algorithm can effectively optimize the ADRC-LADRC controller's parameters and enhance the controller's performance. Compared with the traditional BFO algorithm, BFO-FPA has better optimization ability.

(2) In the future research work, we can consider integrating adaptive neural network into ADRC to improve the adaptive ability of the controller and reduce the difficulty of parameter tuning.

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