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| **Depth control for a deep-sea self-holding intelligent buoy system based on active-disturbance rejection control method** |
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| **Abstract**：The net buoyancy of the deep-sea self-holding intelligent buoy (DSIB) will change with depth due to pressure hull deformation in the deep submergence process. The net buoyancy changes affect the hovering performance of the DSIB. To make the DSIB have better resistance to the external disturbances caused by the net buoyancy and water resistance, a depth controller was proposed to improve the depth positioning based on the active disturbance rejection control (ADRC). Firstly, a dynamic model was established based on the motion analysis of the DSIB. In addition, the extended state observer (ESO) and nonlinear state error feedback controller were designed based on the Lyapunov stability principle. Besides, semi-physical simulations for the depth control process were made by using the ADRC depth controller and traditional PID depth controller separately. The results of the semi-physical simulations indicate that the depth controller based on the ADRC can achieve the predefined depth under the external disturbances. Compared with the traditional PID depth controller, the overshoot of the ADRC depth controller is 1.74%, and the depth error is within 0.5%. It has a better control capability to restrain the overshoot and shock caused by the external disturbances. The research of this control method has certain significance in improving the DSIB's intelligence under the depth-following task．**Keywords**：deep-sea self-holding intelligent buoy (DSIB)；active disturbance rejection control (ADRC)； depth control；buoyancy change；pressure hull deformation |

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**0 Introduction**

Recently, with the development of exploration in deep ocean, applications of the deep-sea self-holding intelligent buoy (DSIB) have experienced a substantial increase, which mainly due to the tasks arising from various commercial and scientific needs. As a efficient mobile sensor platform, the DSIB has broad application prospects in ocean monitoring, exploring and detection, for both civilian and military purposes. such as scientific sampling, undersea search and mining, observation of the ocean environment, hydrographic surveys and biological surveys, building of military affairs and national defense and so on[1-3].

The DSIB has the virtues of extensive scope of activity, small volume, convenient in operation, good maneuverability, strong security, intelligence, etc, which

can carry on various kinds of dangerous tasks instead of human. To achieve the aforementioned tasks, a control method for depth positioning of the DSIB is indispensable. Depth positioning is an important function of a float. However, the dynamics of the DSIB have nonlinear relation with the environmental disturbances. Several control methods for nonlinear depth positioning have been proposed, which, however, render the depth positioning method difficult to design [4-5]. Many researchers have extensively investigated various linear control approaches as well, and their achievements have been acknowledged in the current Refs. [6-10].

A cascade PID controller was designed to conduct the double closed-loop depth control on the float [6]. The float reached a depth of 7 m with the depth error within 2.85%. However, this controller was expensive in terms of energy consumption. Other studies available in Ref.[7] is related to the state–space feedback control algorithm. The control algorithm proposed in Ref.[7] was used not only to increase the accuracy of the float dynamics model, but also to accomplish the control procedure for depth positioning and altitude trajectory. However, this method had to be combined with empirical motor efficiency data so that the tradeoffs between the efficiency and the performance could be studied. In addition, a intelligent control strategy based on the ocean model was used to design the depth positioning strategy of the DSIB [8]. Nevertheless, the algorithm presented in Ref.[8] was dependent on a large-scale ocean model. Considering the nonlinear and strong coupling characteristics of the DSIB motion model, a fuzzy PID controller based on a dual closed-loop was proposed to achieve the depth control[9]．By simulation, the overshoot of the fuzzy PID controller is 2.0%, and the depth error is within 1.0%．However, the implementation of this method needs to be further verified by the experiments. Based on the principle of trial-and-error method and the unique design of the characteristic curve function, an automatic bathymetric depth control method for a class of the DSIB without propellers was proposed [10]. The float hovered at a depth of 5 m with an average depth tracking error of less than 1m. But, the relevant dynamic model was not established in the application of this method, so it was difficult to optimize the bathymetric control method. A model-free feedback control method was used to achieve the depth control with the depth error within 5% [11]. Although the depth control was realized by the model-free feedback method, the optimal effect of the depth control process had not been achieved. This method needs to be further optimized.

The DSIB ascends or dives at a certain speed from the initial depth to the target depth. But, the external disturbances caused by the pressure hull deformation and water resistance may lead to unavoidable disturbances in the depth control process. However, the external disturbances affect the effect of the depth positioning. The influence factor is not taken into account in the aforementioned Refs. [6-10]. Because ADRC method is based on the poor dynamic quality of tracking control caused by the internal and external uncertainties of the controlled object [12]. ADRC depth controller is suitable for solving the depth control problem under the external disturbances. Thus, based on the research of depth control in Ref. [9], a deep control strategy based on ADRC technology is proposed. Firstly, based on the pressure hull deformation, the dynamic model of the DSIB was modeled. Then，the nonlinear tracking differentiator (TD) is used to extract the differential signal for the transition process of the depth tracking; Extended state observer (ESO) is designed to estimate the DSIB system state and integrate DSIB system disturbances and make compensation according to the external disturbances；A nonlinear state error feedback controller (NLSEF) is designed to control the buoyancy regulating system of the DSIB. Finally, the simulation experiment and comparative analysis of the proposed ADRC depth control strategy are carried out by the semi-physical simulation system, which verifies the effectiveness of the control method in the depth control process.

**1 DSIB motion modeling in vertical plane**

**1.1 Deformation of spherical pressure hull under external pressure**

In our study, a spherical pressure hull is used in the pressure-proof structure of the DSIB. Only the volume changes induced by the deformation with increasing seawater pressure are considered. The deformation of the spherical pressure hull under seawater pressure condition slightly reduces the active buoyancy of the float. Thus, the deformation of the spherical pressure hull cannot be ignored in deep sea. The spherical pressure hull deformation at different pressures is expressed as [13]

 (1)

where *r* is the radius of the spherical pressure hull (0.216 m), *λ* is the Poisson’s ratio (0.2), *E* is the modulus of elasticity on the spherical pressure hull (63 GPa), *δ* is the thickness of the spherical pressure hull (0.0135 m), and *Pz* is the pressure at the target depth *z* (*P*z=*ρgz, g=9.8m/s2*). The material used for the spherical pressure hull is glass. Substituting the values for the above parameters in Eq.(1), we obtain

 (2)

where**.

**1.2 Drag analysis**

The drag force on the DISB is assumed to be a quadratic drag law and is expressed as[3]

 (3)

where *R* is the drag force*, A* is the effective cross-sectional area of the float, and *Cd* is the drag coefficient. The effective cross-sectional area can be obtained by the projection of the 3D model onto the vertical plane. In the current study, *A* is calculated to be 0.301 m2, by using Eq. (3). Through CFD simulation analysis, the drag coefficients of the DSIB in the ascending and diving processes are respectively calculated to be Cd-up=0.73, and Cd-down=0.66.

Equation (3) shows that the drag force is nonlinear, which can be approximated to a linear expression at the velocity equilibrium point. The velocity component of the drag term is expressed asinstead of *v2*. Considering the current velocity, *u*, the drag can be linearized as

 (4)

The relationship between the quadratic and linearized drags is shown in Fig.1. The horizontal axis is the motion velocity of the DSIB, and the vertical axis is the drag force. The drag law is approximately quadratic as indicated by the red solid line, and the linearized drag is represented by the blue solid line. Finally, the linearization velocity of the float () under the current disturbances, is represented by the green point.



**Fig.1 Relationship between quadratic drag and linearized drag**

**1.3 Kinematic equation of deep-sea intelligent float**

The dynamic model of the float in disturbing currents is considered to be nonlinear and coupled in the vertical plane. However, a linearized dynamic model can be used in this study with linear techniques. Therefore, simplifying them at the operating point based on special assumptions is necessary.

1. The total mass of the DSIB is constant. The center of mass and the center of buoyancy are axially collinear. The float is regarded as a spherical entity in the vertical plane, and the direction of its movement is also vertical.
2. The current is not negligible in the vertical plane, and the drag force is considered to be linear.

Based on these special assumptions, the dynamic model of the DSIB is established under the current disturbances in the vertical plane. The DSIB ascends or descends at a velocity v from the initial depth to the target depth. In the above process, the relevant forces and relevant velocity vectors acting on the float include buoyancy ***F***, gravity ***G***, drag ***R***, and motion velocity of the float ***v***, as illustrated in Fig. 2. The floating (ascending) process is represented by the region marked solid line, and the submerging (diving) process is represented by the region dotted line.



**Fig.2 Significant forces acting on DSIB during floating and submerging processes**

Based on the assumption that the DSIB reaches the predefined target depth *h*, where *h* is a fixed value; the associated depth error is set as, where *z* is the displacement of the DSIB in the ascending and diving process. Different displacement of the DSIB in the vertical plane are produced by the hydraulic oil volume of the external bladder. When the DSIB hovers at a target depth, . The floating and submerging processes of the DSIB are represented by the following force equilibrium Eqs. (5) and (6), respectively,

(5)

(6)

Table 1 presents the non-dynamic parameters of the DSIB.

**Table 1 Non-dynamic parameters of DSIB**

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| --- | --- | --- | --- |
| Parameter | Value | Unit | Description |
| *M* | 52.39 | kg | Total mass of DSIB |
| *g* | 9.8 | m/s2 | Acceleration due to gravity |
| *Vf* | 0.0504 | m3 | Volume of DSIB |
| *Cd-up* | 0.77 |  | Drag coefficient as DSIB ascending |
| *Cd-down* | 0.7 |  | Drag coefficient as DSIB diving |
| *A* | 0.301 | m2 | Projected area of hull  |
|  |  | kg/m3 | Seawater density at a set depth scope |
| *Q* |  | m3 | Hydraulic oil volume of external bladder |

According to Eqs. (5) and (6), the state-space equation of the DSIB system can be obtained as

 (7)

Let ,,,, where *x*1 and *x*2 are depth error and motion velocity of the DISB respectively，*u* denotes control input. Thus, Eq. (7) is expressed as

 (8)

where *b* is control gains, ；*f*(*x*1*,x*2) is the unknown nonlinear dynamics of the DISB,；∆1 isunknown nonlinear disturbance of DISB, *∆*1=R5.

**2 Design of active disturbance rejection depth controller**

Active disturbance rejection controller (ADRC) is an applied control improved the shortage of PID control in many aspects and has good disturbance rejection ability and robust ability [14]. The schematic diagram of the ADRC is shown in Figure.3. TD is the tracking differentiator for the expected response；ESO is an extended state observer for estimating general disturbances and object output；NLSEF is a kind of non-linear state error feedback which uses the error and its derivatives to achieve the good control performance in a non-linear way [15].



**Fig.3 Schematic diagram of ADRC depth controller**

**2.1 Design of Tracking Differentiator**

The noise amplification effect of the classical differentiator is overcame by the steepest tracker for the tracking differentiator. A transition process is arranged for a given signal so that the given signal is tracked without overshooting. The DSIB system is controlled by the error with the feedback amount so as to avoid the DSIB system overshoot caused by the excessive initial control force. Let i=w1-w0, the second-order tracking differentiator is designed as[16]

 (9)

where *w*(t) is a given signal；*w*1 and *w*2 are the tracking signal and differential tracking signal, respectively; *r* is a fast factor; *h* is the simulation step. *fhan(.)* is the fastest control synthesis function, the specific expression is [15]

 (10)

**2.2 Design of extended-state observer**

The extended state observer can be used to estimate the nonlinear part of the DSIB system. The nonlinear disturbance part is continuously differentiable and bounded. Then the extended state system of the DSIB system is defined as

 (11)

where *λ* is the derivative of *x*3，*η* is the derivative of *∆*1，*λ* and *η* are bounded in practice. Defining *e*1=*z*1-*x*1，According to equation (11)，the extended-state observer of the system is represented as

 (12)

where *z*1，*z*2，*z*3 are observations of *w*1，*w*2，*w*3；α1，α2，α3 are observer gains；*σ*1=0.5，*σ*2=0.25，the role of the saturation function *fal*(*e, σ, δ*) is to suppress signal chattering, and it is defined as [15]

 (13)

Considering systems (11) and (12), we get the following error system as

 (14)

**Theorem 1:** For error system（14），there exist appropriate α1, α2 and α3 guaranteeing error system variables to converge 0. That is, the extended state observer (12) estimates state variables of system (11) effectively.

In order to prove the convergence of the extended state observer, the Lyapunov function needs to be defined as

 (15)

The derivative of V1 is given as

****where *η* is the derivative of *∆*1，and is bounded in practice. Note that fal(.) is an odd function and monotonically increasing. There exists a big enough parameter *α*1, proper parameters *α*2, *α*3 such that.That is, the convergence of the extended state observer (15) is shown.

**2.3 Design of nonlinear error feedback controller**

The system uncertainty and total disturbance are measured through the extended state observer (ESO). It is the core of ADRC. Error signals between the tracking differentiator and the extended-state observer are defined as

 (16)

where *w1* and *w2* are the given position and velocity, respectively, and *z1* and *z2* are the observations of the corresponding output. The nonlinear state error feedback controller *u* is given as

 (17)

where *β*1 and *β*2 are two gains of the nonlinear controller, and z3/b0 is compensation for DSIB system (8). In order to analyze the stability of the DSIB closed-loop system, the errors between the given and the output is presented as

 (18)

Furthermore, the error system can be defined as

 (19)

where *w3* is the derivative of *w2*, and it is continuous and bounded. From (16) and (18), it is easy to get the following expression as

 (20)

Moreover, we have

 (21)

**Theorem 2:** Considering the closed-loop system (19) with the error feedback controller (17), choosing appropriate controller gains *β1* and *β2* in controller (17), the closed-loop system (19) is stable. That is, output x1 and x2 converge to input w1 and w2, respectively.

Construct a Lyapunov function as

****(22)

**** Let *β*1=*β*2=*β*≥0 for simplified analysis, we have

****

According to Ref.[9]，the function fal(•) is an odd function that is monotonically increasing.Thus, *σ*1*fal*(*σ*1,γ1,δ1)≥0 and *σ*2*fal*(*σ*2,γ2,δ2)≥0. To get the sign of expression (*σ*1+*σ*2)(*fal*(*σ*1,γ1,δ1)+*fal*(*σ*2,γ2,δ2))，we let γ1=γ2=γ，δ1=δ2=δ，the following analysis is given.

1) If σ1 < 0，σ2 < 0, we get *fal*(*σ*1,γ,δ)<0，*fal*(*σ*2,γ,δ)<0. Then，(*σ*1+*σ*2)(*fal*(*σ*1,γ,δ)+*fal*(*σ*2,γ,δ))>0.

2) If σ1≥0，σ2≥0, we get fal(σ1,γ,δ)≥0，fal(σ2,γ,δ)≥0. Then, (σ1+σ2)(fal(σ1,γ,δ)+fal(σ2,γ,δ))≥0.

3) If σ1<0≤σ2，σ2≥|σ1|, we get fal(σ2,γ,δ)≥0>fal(σ1,γ,δ), fal(σ2,γ,δ)≥|fal(σ1,γ,δ)|.

Then, (σ1+σ2)(fal(σ1,γ,δ)+fal(σ2,γ,δ))≥0.

4)If σ1<0≤σ2，σ2<|σ1|, we get fal(σ2,γ,δ)≥0>fal(σ1,γ,δ), fal(σ2,γ,δ)<|fal(σ1,γ,δ)|.

Then, (σ1+σ2)(fal(σ1,γ,δ)+fal(σ2,γ,δ))>0。

In a similar way，if σ1≥0>σ2,

(σ1+σ2)(fal(σ1,γ,δ)+fal(σ2,γ,δ))>0。

In conclusion, we obtain that

(*σ*1+*σ*2)(*fal*(*σ*1,γ,δ)+*fal*(*σ*2,γ,δ))≥0 (23)

Let ,

Note that *w*3 is the derivative of *w*2, it denotes the given acceleration of the DSIB, and it is continuous and bounded;. denotes the seawater density at a target depth range which is also bounded, *∆*1 is also bounded in practical; Due to the fact that the convergence of the extended-state observer has been proved, we have proved that e1, e2, and e3 are bounded. The error between input signal and output signal is also bounded in practice. It is also obtained that G is also bounded.

Therefore, we have

 (24)

Because the function fal(•) is an odd function and it is monotonically increasing，fal(σ1, γ1, δ1) and fal(σ2, γ1, δ2) are bounded. It holds that  if (24) holds. It is easily shown that (24) must hold if *β* is large enough. That is, by choosing appropriate nonlinear controller gains *β1* and *β2*, there exists .

Thus, the designed nonlinear error feedback controller (17) guarantees the stability of the closed-loop system (19) by selecting appropriate controller parameters *β1* and *β2*.

**3 Semi-physical simulation experiment for depth control process of DSIB**

**3.1 Principle of semi-physical simulation test platform**

In order to verify the effectiveness and robustness of the designed ADRC depth controller, the DSIB system was selected as the research object in this study, and the simulation test was performed under the semi-physical simulation condition (as shown in Figure 4). The semi-physical simulation test platform was used to simulate the marine environment more realistically and provided a reliable reference value for the sea trial of the DSIB.

Without considering the effects of the changes in salinity, temperature, and gravity acceleration, the seawater pressure can be approximately considered as 40 MPa at the depth of 4000 m in this study. Therefore, the pressure change of the piston cylinder in the semi-physical simulation platform was used to simulate the depth change in the actual sea conditions. The experimental research on the depth tracking of the DSIB during the ascending and diving process was realized.

The floating and diving processes of the DSIB were performed by the buoyancy regulating system of the DSIB. The oil draining and oil returning stages were performed in the simulation experiment. When the DSIB ascends from 4 000 m underwater to the sea surface, the seawater pressure gradually decreases from 40 MPa to 0 MPa in the ascending process. If the pressure on the side of the rodless chamber for the 60 MPa hydraulic cylinder was reduced in the experimental platform. Hydraulic oil was discharged from the external bladder by the buoyancy regulating system. In this case, the DSIB is in the floating process. When the float dives from the sea surface to 4 000 m, the seawater pressure gradually increases from 0 MPa to 40 MPa in this process. Hydraulic oil is allowed to flow from the external bladder back into the buoyancy regulating system by the external seawater pressure. In the test platform, the pressure of the 60 MPa hydraulic cylinder without the rod cavity was increased. In this case, the float is in the diving process. If the DSIB hovers at a target depth, the pressure on the side of rodless chamber of 60 MPa hydraulic cylinder was remained constant at this time. The 60 MPa high-pressure accumulator was regarded as the external seawater pressure in the deep-sea environment for pressure-holding test.

The workflow of the semi-physical simulation experiment platform was as follows:

Firstly, the DSIB prototype was placed on the semi-physical test platform. The piston of 60 MPa hydraulic cylinder was placed at one side near the DSIB, and hydraulic oil was allowed to flow from the external bladder back into the buoyancy regulating system.

1) The electric pump was turned on, the pressure of 60 MPa relief valve A was adjusted to 10 MPa, and the pressure of 60 MPa relief valve B was adjusted to 5 MPa (the purpose was to ensure that the piston was finally at the leftmost end in the 60MPa hydraulic cylinder). After the system is stable, the electric pump is turned off；

2) The DSIB was connected to the rod cavity side of the 60MPa hydraulic cylinder. For the computer control system, the seawater pressure, dynamic model parameters and the control parameters of the PID depth controller and the ADRC depth controller were set according to the predefined hovering depth.

3) The pressure of 60 MPa relief valve B was adjusted to a certain value (more than 40 Mpa). The hydraulic oil was began to drained by the buoyancy regulating system. The actual pressure value of the detected 60 MPa hydraulic cylinder side was coupled back to the computer control system by the pressure sensor in real time. According to the difference between the specified pressure value and the actual pressure value, the working pressure of the rodless chamber side was adjusted by the computer control system so that the pressure value can track the input specified seawater pressure value. The pressure closed-loop control simulation was realized.

4) Similarly, the hovering depth was set in the computer control system for the diving process, and then oil returning was conducted to simulate the diving process of the DSIB. The pressure value corresponding to the predefined diving depth was tracked by the side of the 60MPa hydraulic cylinder.



**Fig.4 Schematic of semi-physical simulation test platform for depth control process of DSIB**

The non-dynamic parameters of the DSIB for simulation were shown in Table 1. For the ADRC depth controller, the desirable parameters were as follows:

1) TD parameters: r=1, d=0.1;

2) ESO parameters: *α*1=200, *α*2=100, *α*3=200,*δ*=0.05;

3) NLSEF parameters：*γ*1=0.85，*γ*2=1.5，*β*1=1.75，*β*2=10，b=1.07，*δ*1=*δ*2=5.

Relevant simulations have been conducted to validate the proposed depth control method compared to that of a standard PID controller. For the PID depth controller, the desirable parameters were as follows: *K*p=5, *K*i =2, *K*d=25.

In order to fully verify the control performance of the ADRC depth controller for the DSIB in the South China Sea, the test is divided into shallow water area and deep water area with the depth of 2000 m as the demarcation point. The DSIB was always affected by the net buoyancy change caused by the pressure hull deformation and water resistance.

**3.2 Experimental verification**

The simulation scenario of the shallow water area was as follows: Assumed that the DSIB ascends at a certain initial speed from 800 m deep water, and hovers at a target depth of 600 m. The depth control results for the ADRC controller and PID controller were illustrated in Figure 4. As shown in Figure 4, The DSIB was affected by the net buoyancy change caused by the pressure hull deformation and water resistance during the floating process. Under such circumstances, depth control is achieved by both the ADRC controller and PID controller. For the ascending process, the ADRC algorithm settling time was minimal, only 346 s, and overshoot was less than 1.67%, which was much smaller than the PID algorithm, for which settling time was more than 696 s and overshoot exceeded 5.3%. the depth errors of the PID controller was ±5 m, which was much larger than the ADRC controller's ±1 m, and so the control effects were also worse than the ADRC controller. Figure. 5 shows the depth tracking curves of the PID depth controller and the ADRC depth controller when the DSIB ascended to 600m and 400m respectively. It can be found that the aforementioned two depth controllers can achieve tracking effect on the different depths of the relatively shallow water area. Compared with PID controller, ADRC controller has a smaller overshoot and better tracking effect in the depth control process. In order to verify the stability of the PID depth controller and ADRC depth controller, when hovering at a predefined depth, external disturbance is added to the established simulation model at a certain moment, so as to observe the influence of external disturbance on the hovering motion of the DSIB. As shown in Figure. 6, when the DSIB hovered at a depth of 600m, an external disturbance of 50N is added at 970s, the settling time of the ADRC algorithm was less than that for the PID algorithm with 585s.Therefore, compared to the PID depth controller, the designed ADRC depth controller was better able to suppress the overshoot caused by the transient interference.



**Fig.4 Depth control curve under different controllers in relatively shallow water**



**Fig.5 Multi depth hovering curve under different controllers in relatively shallow water**



**Fig.6 Anti interference curve under different controllers in relatively shallow water**

The simulation scenario of the deep water area was as follows: Assumed that the DSIB dives at a certain initial speed from 2 500 m deep water, and hovers at a target depth of 2 800 m. Figure.7 shows the depth control results for the ADRC controller and PID controller. The results are similar to the floating process. The DSDC-ADRC had a shorter settling time at 685 s and a smaller overshoot at 1.74%. In contrast, the PID’s settling time was 1 030 s, and overshoot was more than 5.37%. Analogously, the depth errors of ADRC was less than PID, the corresponding comparison results was ±1.5 m vs. ±6.5 m. Fig.8 shows the depth tracking curves of the PID depth controller and the ADRC depth controller when the float dove to 2 800m and 3000m respectively. It can be seen from the simulation results that the ADRC algorithm had good control precision and low overshoot with less settling time for the different depths of the deep water area. According to the anti-interference depth tracking curve in Figure. 9, when the DSIB hovered at a target depth of 2800 m, a transient external disturbance of 50N is added at 980s, and the PID depth controller and the ADRC depth controller were used to suppress the external disturbance. the ADRC controller showed a good performance of 516s settling time. The PID controller’s performances was 605s. Thus, for the same external disturbance, ADRC depth controller had a better anti-interference ability and stability than the PID depth controller.



**Fig.7 Depth control curve under different controllers in relatively deep water**



**Fig.8 Multi depth hovering curve under different controllers in relatively deep water**



**Fig.9 Anti interference curve under different controllers in relatively deep water**

In conclusion, by comparing the two methods, it can be found that the ADRC has smaller adjustment time, overshoot and depth error than the PID control method under the same external disturbance conditions. The ADRC performs better than the standard PID controller in the depth control process. For the dual closed-loop fuzzy PID depth control method [9], the overshoot of the fuzzy PID controller is 2.0%, and the depth error is within 1.0%. Compared to the fuzzy PID depth control method [9], the overshoot of the ADRC depth controller is 1.74%, and the depth error is within 0.5%. Thus, the depth positioning of the DSIB can be achieved by the ADRC method with high accuracy and fast response. The experimental results verified the effectiveness of the proposed depth controller.

4 **Conclusion**

In this study, a buoyancy-driven deep-sea intelligent float was the object of research interest. Based on the pressure hull deformation of the DSIB, the dynamic model of the DSIB was modeled. In order to realize depth control process from the initial depth to the target depth, a depth control strategy based on ADRC method was proposed. The stability of the designed ADRC depth controller was proved by Lyapunov stability principle. Finally, the designed depth controller was verified by the semi-physical test platform. The depth controller based on ADRC method has better response ability and anti-jamming effect in comparison to the PID algorithm. The designed depth controller provides a stable operation condition of the marine sensors carried by the DSIB, and ensures the high-precision data acquisition of the DSIB on the ocean environment observation of a target depth. Since ADRC depth controller has various parameters and complicated setting process, the optimization method of ADRC needs to be further studied. In addition, the designed depth controller can be applied to the actual experiments to further verify the effectiveness of the method.

**References**

1. Hennon T D , Riser S C , Alford M H. Observations of internal gravity waves by argo floats. Journal of Physical Oceanography, 2014, 44(9):2370-2386.
2. Kubryakov A A , Bagaev A V , Stanichny S V, et al. Thermohaline structure, transport and evolution of the Black Sea eddies from hydrological and satellite data. Progress in Oceanography, 2018, 167 (6):44-63.
3. Xu L , Li P , Xie S P, et al. Observing mesoscale eddy effects on mode-water subduction and transport in the North Pacific. Nature Communications, 2016, 7(10):105-115.
4. D'Asaro E A, Farmer D M. A lagrangian float. Journal of Atmospheric & Oceanic Technology, 1996, 13(13): 1230-1246.
5. Le Reste S, Dutreuil V, André X, et al. “Deep-arvor”: A new profiling float to extend the argo observations down to 4000-m depth. Journal of Atmospheric and Oceanic Technology, 2016, 33(5): 1039-1055.
6. Barker L. Closed-loop buoyancy control for a coastal profiling float. MBARI International Reports, 2014, 2014(8): 1-15.
7. Mcgilvray B , Roman C. Control system performance and efficiency for a mid-depth Lagrangian profiling float[C]// Oceans 2010 IEEE, Sydney, 2010, 978(4):1-10.
8. Smith R N, Huynh V T. Controlling buoyancy-driven profiling floats for applications in ocean observation. IEEE Journal of Oceanic Engineering, 2013, 39(3): 571-586.
9. Zhang H L, Li X F, Yang S B, er al. Dual closed-loop fuzzy PID depth control for deep-sea self-holding intelligent buoy. Information and Control, 2018, 48(2): 202-208, 216.
10. Shi X P, Chad L. Research and application of the depth control technology for a class of underwater autonomous drifting floats. Journal of Ocean Technology, 2014, 33 (5): 13-17.
11. Sun Q G, Zheng R, An J Y, et al. Study on the AUV depth and hovering control based on variable system. Journal of Ocean Technology, 2017, 36(6): 33-37.
12. Han J Q. Active disturbance rejection controller and its application．Control and Decision, 1998，13(1) : 19-23．
13. Wu J G, Xu H X, Liu J. Research on the buoyancy change of deep-sea autonomous underwater vehicle in diving process. Robot, 2014, 36(4): 455-460.
14. Bai J G, Pang Y J, Wan L, et al. Underactuated AUV's bottom-following control based on self-adaptive method. Electric Machines and Control, 2017, 21(06): 83-88.
15. Han J Q. Active disturbance rejection control technique. Beijing: National Defense Industry Press, 2008: 1-45, 243-295.
16. Shi X C, Zhao J P, Zhou J J, et al. Hydrodynamic coefficients estimation for UUV and ADRC to its diving control. Chinese Journal of Scientific Instrument, 2014, 35(s2):1-6.

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| **基于自抗扰方法的深海自持式智能浮标的定深控制研究** |
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| **摘 要：**深海自持式智能浮标在下潜过程中，随着深度增加将会引起浮标壳体形变，使得浮标的自身净浮力产生变化，而浮标净浮力的变化将会影响浮标的定深性能。为了使浮标在实际定深工作中更好地抵抗净浮力和水阻力所构成的外部干扰，提出基于自抗扰控制方法设计定深控制器以提高深度定位效果。首先，通过分析浮标的运动过程，建立了动力学模型。然后，基于李雅普诺夫稳定性原理来设计扩张状态观测器和非线性状态误差反馈控制器。将所设计的自抗扰深度控制器与基于传统的PID方法的定深控制器进行了半实物仿真实验对比。仿真实验结果表明，基于自抗扰控制技术的深海智能浮标深度控制方法能够实现准确定深跟踪控制，同时，相比于传统PID控制器，自抗扰深度控制器的超调量为 1.74%，深度误差控制在 0.5%以内。自抗扰深度控制方法能够更有效地抑制净浮力和水阻力共同干扰下所造成的超调和震颤等现象，具有更优的控制效果。该控制方法的研究对提高深海自持式智能浮标在进行深度跟踪任务时的智能性具有一定意义。**关键词：**深海智能浮标；自抗扰技术；深度控制；浮力变化；耐压壳体形变引用格式：QIU Zu-rong，WANG Qiang，YANG Shao-bo，et al. Depth control for a deep-sea self-holding intelligent buoy system based on active-disturbance rejection control method. Journal of Measurement Science and Instrumentation, 2020, 11(1): 00-00. [doi:10.3969/J.ISSN.1674-8042.2020.01.000] |