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The Comprehensive Optimization Analysis of a Hydrofoil Sliding USV's Intelligent Propulsion System

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Abstract. Adopting the improved fuzzy control rules and chaos optimization algorithm to build the mathematical model of optimal allocation for the parameters in the intelligent propulsion system considering rapidity and controlling characteristics. The step is to build the model for optimizing and simulating realized by Matlab, compare the simulating and optimizing results of different solutions of controlling parameter, discuss the optimized propulsion controlling parameter, and finally prove that the real-time configuration of controlling parameter based on optimization has good adaptability in different conditions .Meanwhile ,it provides a certain reference value to the designation of the intelligent propulsion system of ship .

Introduction

Unmanned surface vehicle [1]is the important part in the modern unmanned combat system[2],which has a feature of small volume ,quick speed ,strong mobility ,and able to cooperate with UUV ,UAV to complete the operational mission such as intelligence gathering, antisubmarine ,anti-mine, investigating , detecting and precise strike. It can also load with a variety of modules according to the mission, which means a better cost-benefit ratio, avoidance of casualty. For the civilian purpose, USV can operate the function of meteorological watch, hydrographic surveying and charting, searching and rescuing in water with a fairly broad application prospects.

The key technology of USV is independent decision-making and control technique, where the intelligent propulsion system plays an important role and is the foundation for the specific requirement of Autonomous path planning, finding the optimal path, the real-time performance meeting, and ,the solution for local collision avoidance planning under the dynamic target threat etc. *Gao shuang*[3], aware of the problem of high-nonlinearity for the USV propelled by water jet ,which is hard to control by traditional control method ,using the Neural networks winding as identifier and fuzzy-PID controller for controlling for simulation of system in matlab, proves that the neural network and fuzzy PID controller can realize the precise and real-time controlling. *Cui Jian*[4] etc, build the platform of simulating and optimizing for the USV intelligent propulsion system ,discuss, analysize the real-time optimal configuration and simulation in the model [5] ,and finally summarize the effect of different initial speed which has a reference value to the designation of the USV intelligent propulsion system.

In this paper, the author uses hydrofoil USV[6] as the model, water jet propulsion as propulsion mode, fuzzy control as the rule for controlling, chaos optimization algorithm as optimization method to further research the optimal selection of the various parameters in the intelligent propulsion system through the simulating and optimizing system in matlab, which lays a foundation and provides some reference value to the design of the intelligent propulsion system.

Establishment of mathematical model

2.1The propulsion system of high-speed unmanned vehicle

1)The translational equation:

$$\left(M+M'\right)\frac{dV_s}{dt}=T_e-R_t \tag{1}$$

Where M is the quality of hull, M' is added mass, V_s is the speed of ship; T_e is the effective thrust of propeller, R_t is the real-time resistance forced in hull.

2) rotary equation: $2\pi I \frac{dn}{dt} = M_d - M_p$ (2)

Where I is rotational inertia, M_d is torque provided by main engine, M_p is the torque acting on propeller.

2.2Water jet propulsion model

The thrust of the water pump and the absorption torque of rotary equation are: $T_p = \rho Q(V_a - V_e), M_p = \frac{P_D}{2\pi n}$

Where T_p is effective thrust, ρ is the density of water ,Q is the flow of pump , V_a is the flow rate out , V_e is the flow rate in , $V_e = V_s$, P_D is the shaft power needed by pump, n is pump rotate speed.

2.3Fuzzy control

1)The theoretical domain of input and output linguistic variables and the determination of membership function .

Input variable

speed deviation: $E = V_s - V_0$;Theory of domain [-1.2,1.2] ,k n

Deviation change: $EC = dV_s / dt$; Theory of domain：[-1.2,1.2] , k n/s

Output variable

The speed of the propeller or pitch: $U = n$ or p ; Theory of domain: [-1 2,1 2] ,r/s or m

Range of linguistic variables of input and output value :{ NB,NM, N S,O,P S,P M, P B}

The author adopts the triangular membership function and the Mamdani controlling rule.

2)The design of the fuzzy controller rule

The author defines the controlling rule according to the experts' controlling experience as shown in table 1 and uses gravity method to defuzzy

Table 1. Fuzzy control rules of the propulsion system

	U			E				
		NB	NM	NS	O	PS	PM	PB
	NB	PBB	PBS	PMB	PMS	PSB	PSS	O
	NM	PBS	PMB	PMS	PSB	PSS	O	NSS
	NS	PMB	PMS	PSB	PSS	O	NSS	NSB
EC	O	PMS	PSB	PSS	O	NSS	NSB	NMS
	PS	PSB	PSS	O	NSS	NSB	NMS	NMB
	PM	PSS	O	NSS	NSB	NMS	NMB	NBS
	PB	O	NSS	NSB	NMS	NMB	NBS	NBB

2.4 Optimized mathematical model

Application of Chaos optimization algorithm (COA). It has the features of easy implementation, short execution time and robust mechanisms of escaping from the local optimum, is a promising tool for the engineering applications. It is a kind of characteristic which has a bounded unstable dynamic behavior and exhibits sensitive dependence on its initial conditions. An essential feature of the chaotic systems is that small changes in the parameters or the starting values for the data lead to the vastly different future behaviors. Due to the non-repetition of the chaos, the COA can carry out overall searches at higher speeds than stochastic ergodic searches that depend on the probabilities.

Design variables

The parameter selection for the Intelligent propulsion system(which adopts the Adjustable pitch) of the high speed unmanned vessel include: design speed, propeller diameter ,disk ratio, the three proportionality coefficient for speed controlling of the fuzzy controller ,the three proportionality coefficient for pitch controlling of the fuzzy controller, 9 parameters in total. we design the variables based on these 9 parameters, its vector expression is as follow:

$$X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9\}^T = \{V_o, D_o, k_q, K_1, \ \ K_2, K_3\}^T$$

Objective function

1) Speedability

We choose the Quickness horizontal factor C corresponding with the admiralty coefficient as the quickness indicator, the expression is: $C_{sp} = P_{\mathrm{E}}\Delta^{-1}V_S^{-2} / (\eta_0\eta_H\eta_R\eta_S) = R_t\Delta^{-1}V_s^{-1} / (\eta_0\eta_H\eta_R\eta_S)$

Where Δ is displacement, P_E is effective power, R_t is resistance forced on hull, $\eta_{0,}\eta_H, \eta_R, \eta_S$ are efficiency factor related to water jet propulsion.

$f_1(X) = \frac{1}{T}\int_0^T C_{sp}dt$, Where T is time of simulation.

2) Controlling property

A good controlling property is indispensable in the process of ship sailing, the controlling objective function is introduced as follow: $f_2(x) = J = \frac{1}{T}\int_0^T (V - V_x)^2 dt$

Where V_x is the expected speed, T is the controlling time.

3)General objective function

As for the function made up of several objective functions, we use the method of weighted sum to get the general objective fuction, and choose the weight without limit. For the high speed unmanned vessel, the product of two objective functions is adopted as the general objective function.

$$\min F(x) = f_1(x) \times f_2(x)$$

Constraint condition

1)Determination of the design varibles range according to the Threshold conditions.

2)The restriction of the propulsion system equation according to translational equation (1) and rotary equation (2).

3) Propeller design meets the requirement of cavitation. the Keller equation is as follow:

$$\frac{1.3 + 0.3Z}{(P_c - P_s)D^2}T_0 + K - \frac{A_e}{A_0} \le 0$$

Introduction of simulation and optimization platform

1) Platform interface

The author build the platform for the simulation and optimization for the intelligent propulsion system for USV when keeping a watch eye on the establishment of mathemetic model and optimization algorithm, and also designs the interface through GUIDE, which makes it become a completed application software with higher reliability and practicability. In addition, the feature of the interface mainly pursuits the simple and serious style, which ensures good interaction with the user.

Fig. 1 and Fig. 3 show the interface of the optimization of USV’s intelligent propulsion system. Users can choose different ship forms, propulsion modes, controlling methods and optimization methods to enter into the sub interface, then match with the corresponding ship form parameters and optimizing parameters, thus make it convenient for simulation. The author chooses water jet propulsion, fuzzy control method and chaotic algorithm optimization method for the hydrofoil sliding USV.

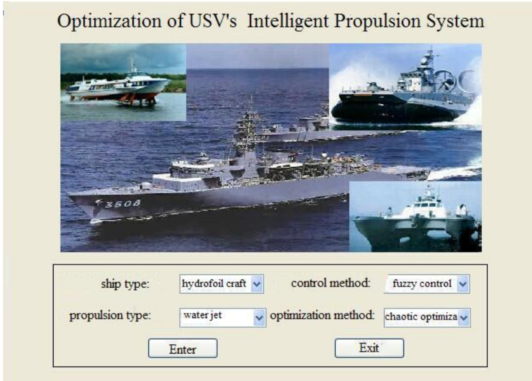


Fig.1. Main interface for optimization

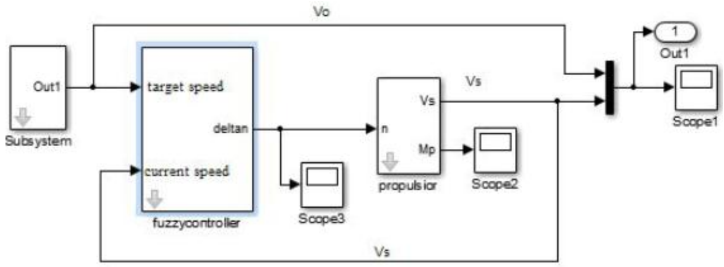


Fig. 2. The fuzzy control model

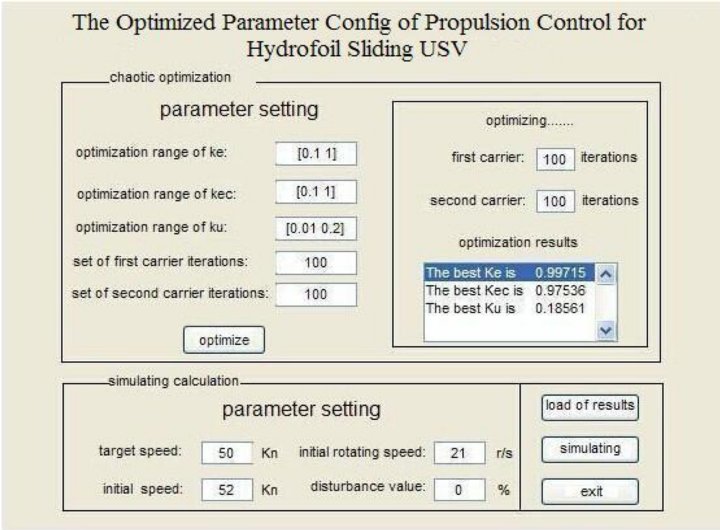


Fig. 3. Optimization analysis interface

2) The fuzzy control model

The author avail of the simulation tool in Matlab/ simulink to build the simulating model of controller according to the mathematic model as shown in Fig. 2.

Test and analysis

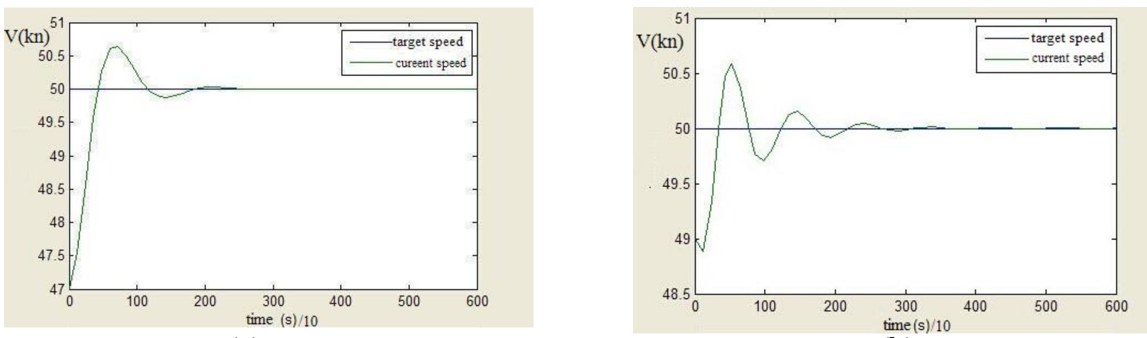
4.1 The simulated test and analysis

Implement of simulation for the hydrofoil sliding USV with water jet propulsion system, the principle dimension is as below in table 2:

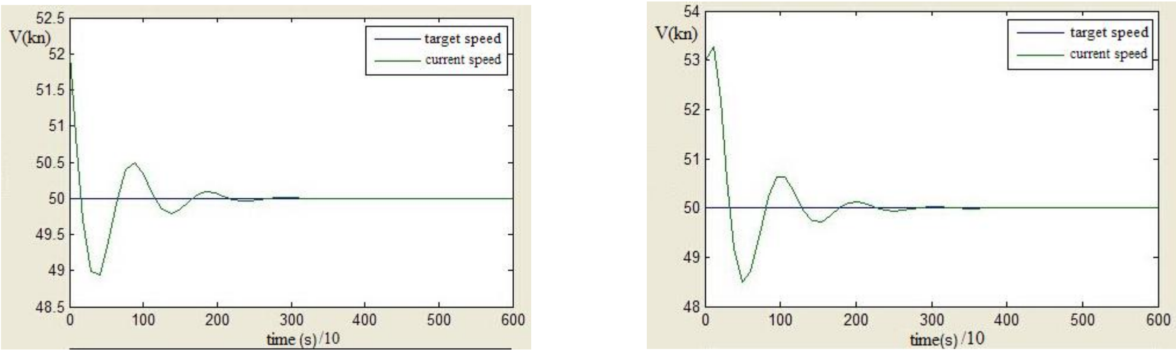
Table 2 the principle dimension of a hydrofoil sliding USV

Displacement Δ / t	Waterline L/m	Width B/m	Draught T/m
84	26.458	4.788	1.386

The simulation results of the optimized calculation for parameter config based on optimization for the propulsion control of Hydrofoil sliding USV in condition of no turbulence are shown in Fig. 4.



(a) (b)



(c) (d)

Fig. 4 Simulated results of control effect with different initial speed

Table 3.Simulation results

Target speed(kn)	50	50	50	50
Initial speed(kn)	47	49	52	53
Speed overshoot(kn)	0.65	0.6	1.1	1.5
Settling time(s)	25	27	23	28

Preliminary conclusions can be drawn from the data in Table 3 that :

1) The overshoot decreases as the speed gap reduces when initial speed approaches to the target speed in the same direction(from low to high ,or high to low).

2)The overshoot of speed is amplified when the initial speed is higher than the target speed.

3)The settling time for controlling is between 23-28s.

4.2 Comparison of simulation results and optimization results

The optimization results of the intelligent water jet propulsion system of hydrofoil sliding USV are shown in Fig. 8, 9and10 as below

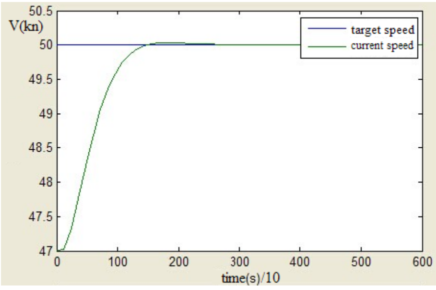


Fig. 8. Control effect in condition of no turbulence

It shows the intelligent control effect of hydrofoil sliding USV with initial speed of 47kn, target speed of 50kn and no turbulence, as comparing with simulation results which shows in table 4:

Table 4. Comparison of simulation and optimization results

Hydrofoil-sliding USV	Simulation	Optimization
Initial speed(kn)	47	47
Target speed(kn)	50	50
Speed overshoot(kn)	0.65	0.028
Settling time(s)	22	21

Preliminary conclusions can be drawn from the data in Table 4 that in condition of 47kn of initial speed, the overshoot of the optimization result is 95.69% lower than that of the simulation results ,so is the settling time, for 4.5%lower.

4.3 The anti-interference analysis of the optimization result

We choose the interference value of 5% and 15%, while keeping the initial speed of 47kn to separately implement the optimization and simulation calculation, and get the results as shown in Fig. 9 and 10.

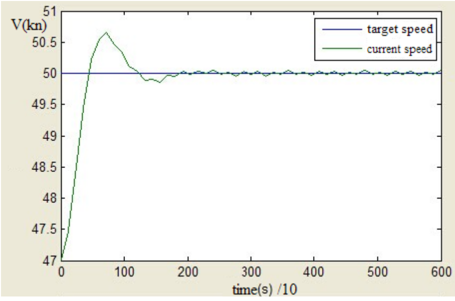


Fig. 9 Control effect with 5% turbulence

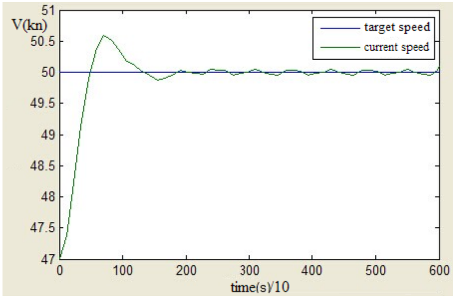


Fig. 10. Control effect with 15% turbulence

Table 5. Simulation for optimized results

Turbulence	5%	15%
Initial speed(kn)	47	47
Target speed(kn)	50	50
Speed overshoot(kn)	0.67	0.60
Settling time(s)	20	20
Fluctuation(kn)	±0.0510	±0.0519

It can be analyzed from table 5 that: The anti-interference performance of optimization result is better. In condition of 47kn initial speed with 5% or 15% of turbulence, the overshoot speed of both is lower than 0.7, the Interference fluctuation is also low with the value of 0.0510 or 0.0519 in relevant condition of 5% or 12% turbulence .

Conclusion

The authors build the optimized mathematic model of hydrofoil sliding USV for the optimal parameter config for the intelligent propulsion and control system with good rapidity and controlled characteristic on the Matlab platform, then choose different initial speed and different value of interference to compare with the simulation results without optimization, analysis and summaries the effect made by different value of initial speed which verify the feasibility of the optimization results. The analysis results have certain reference value to the design of the propulsion system as for the choice of main influencing parameters: ke, kec, ku for the optimization of USV's intelligent propulsion system.

Acknowledgements

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