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Research on thrust distribution of ship dynamic positioning system based on group search optimization algorithm

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Abstract

With the development of energy utilization, people's demand for the development of marine resources is increasing day by day, which makes the ship propeller system have higher and higher performance to meet people's requirements. On the issue of ship thrust allocation, this paper proposes a ship thrust allocation method based on group search optimization algorithm to solve the problems of local optimum and long iteration time when solving dynamic positioning thrust allocation. A multivariable nonlinear constrained optimization problem is established, which aims at minimizing the energy consumption of the propulsion system and takes the thrust, azimuth working range and change rate of the propeller as constraints. The simulation results show that the group search optimization algorithm can jump out of the local optimization problem to a certain extent, and can effectively reduce the energy consumption, propeller wear and thrust error of the system, which has certain feasibility in solving the ship thrust allocation problem.

Keywords

Dynamic positioning system; Group search optimization algorithm; Thrust distribution.

1. Introduction

With the development of marine resources, the research on ship control methods has been paid attention to, among which dynamic positioning (DP) system has increasingly become a research hotspot. This system relies on the thrust generated by the ship's own propulsion system to offset the interference of the external environment, so as to keep the ship in a certain position and heading, so as to ensure its normal running or operation. DP system mainly includes three systems: position measurement system, control system and propulsion system. The main task of the propulsion system is to distribute thrust and generate force and moment to position the ship at the desired position. The purpose of thrust distribution is not only to determine the thrust and azimuth of each propeller according to the control force and torque needed to resist the interference of marine environment calculated by the controller, but also to minimize the energy consumption, propeller wear and thrust error as much as possible. Therefore, the thrust distribution problem is a multi-objective optimization problem[1-4].

2. Group search optimization algorithm

2.1. Introduction of group search optimization algorithm

GSO algorithm is a new swarm intelligence algorithm based on the intelligent random search of social animals. The algorithm divides group members into discoverers, followers and wanderers. In each iteration, the discoverer is the best member of the group, and the remaining group members are randomly divided into followers and wanderers according to a certain proportion. In the new iteration process, each member will switch among these three roles[5].

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Fig. 1 is an optimization model of GSO algorithm. When modeling GSO algorithm, it refers to the random search behavior of lions, birds, etc. When foraging, and takes the animal visual scanning mechanism as the guiding ideology, it completes the search through the following and wandering behaviors reflected in the process of foraging behavior. Three kinds of members in the population: discoverer, follower and wanderer complete the search by cooperating with each other[6]. Because the optimal solution is randomly distributed, the strategy of changing roles is particularly important for optimizing.

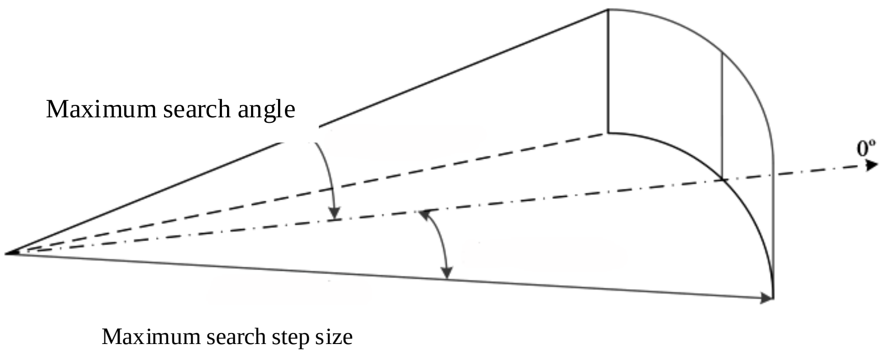

Fig. 1 Spatial scanning model of GSO algorithm

2.2. Group search optimization algorithm steps

In GSO algorithm, a certain number of individuals (Member) form a Group. In the k-th iteration, each individual i has four attributes: Position $X_{\mathrm{i}}^{\mathrm{k}} \in \mathrm{i}^{\mathrm{n}}$. search Angle $\varphi^{\mathrm{k}} = (\mathrm{n}-1\varphi_{\mathrm{i1}}^{\mathrm{k}},\cdots\varphi_{\mathrm{i(n-1)}}^{\mathrm{k}}) \in \mathrm{i}^{\mathrm{n-1}}$, Search direction $D_i^k(\varphi_i^k) = (d_{i1}^k,\cdots,d_{in}^k) \in i^n$ and F Maximum search angle $X_{\mathrm{i}}^{\mathrm{k}}$). $\mathrm{f}_{\mathrm{value}}$ is calculated by the objective function f according to the position of group members $X_{\mathrm{i}}^{\mathrm{k}}$, and the search direction is a unit vector calculated by the search angle. The process is as follows:

$$d_{i1}^k = \prod_{p=1}^{n-1}\cos(\varphi_{ip}^k) \tag{1}$$

$$\mathrm{d}_{ij}^k = \sin(\varphi_{i(j-1)}^k).\prod_{p=i}^{n-1}\cos(\varphi_{ip}^k) \tag{2}$$

$$\mathrm{d}_{in}^k = \sin(\varphi_{i(n-1)}^k) \tag{3}$$

The discoverer starts searching from the current position, then scans the front, left and right sides of the current position in the search space, updates the positions in three directions, and then calculates their fitness, and the three positions are updated according to the following formula.

Sample points in front:

$$X_{\mathrm{z}} = X_p^k + r_1 l_{\max} D_p^k(\varphi_p^k) \tag{4}$$

Sample points on the right:

$$X_{\mathrm{r}} = X_{\mathrm{p}}^k + r_1 l_{\max} D_p^k(\varphi_p^k + r_2\theta_{\max}/2) \tag{5}$$

Sample points on the left:

$$X_{\mathrm{r}} = X_{\mathrm{p}}^k + r_1 l_{\max} D_p^k(\varphi_p^k - r_2\theta_{\max}/2) \tag{6}$$

Calculate the fitness of three positions respectively, select the position with the best fitness to compare with the current fitness, and if this is better than the current fitness, the discoverer's position will be transferred to the position with the corresponding optimal fitness; Otherwise, the discoverer's position does not move, but only changes its search direction as follows:

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$$\varphi^{k+1} = \varphi^{k} + r_2 \alpha_{\max} \tag{7}$$

Other members in the group also move according to certain rules: in the k-th iteration, if the i-th member is a follower whose position is X_i^k and the search angle is φ_i^k, it will move a certain distance to the discoverer in this iteration and update its position according to the following formula:

$$X_i^{k+1} = X_i^k + r_3 (X_p^k - X_i^k) \tag{8}$$

If the i-th member is a wanderer, its search angle will be updated according to formula $\varphi^{k+1} = \varphi^{k} + r_2 \alpha_{\max}$, and a distance $l_i = \alpha . r_1 l_{\max}$ will be randomly selected, so as to transfer to a new position:

$$X_i^{k+1} = X_i^k + l_i D_i^k (\varphi^{k+1}) \tag{9}$$

The addition of rogue effectively solves the problem that the optimization problem falls into local minimum, which makes the advantages of group search algorithm more prominent. In the search process, it is necessary to ensure that the group members search within a limited range. If the search jumps out of the boundary, it will return to the initial position of the search space, and the calculation will be finished after a certain number of iterations. At this time, the fitness of the discoverer is the optimal value of the objective function, and the location of the discoverer is the optimal solution of the optimization problem[7].

3. Mathematical model of ship dynamic positioning

Firstly, a ship nonlinear mathematical model with DP application characteristics is established. For a ship in the horizontal plane with only three degrees of freedom of pitch, roll and head roll[8], the kinematic equation can be expressed as follows:

$$\dot{\eta} = R(\psi) v \tag{10}$$

$$R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{11}$$

The dynamic positioning ship changes slowly when sailing at low speed on the horizontal plane, so the influence of Coriolis centripetal matrix C(v) on ship motion and nonlinear damping matrix are ignored, and a simplified ship low-frequency motion model is obtained:

$$M \dot{v} + Dv = \tau + R^T(\psi) b \tag{12}$$

In the above formula, $\tau = [\tau_u \tau_v \tau_r]^T$ is the force and moment of the ship propulsion system in three degrees of freedom of pitch, roll and head roll; $b = [b_1 b_2 b_3]^T$ represents the interference of external environment; M is the ship mass matrix[9].

Ship thrust allocation can usually be regarded as a multivariable nonlinear optimization problem with constraints. By establishing appropriate objective functions and constraints, the energy consumption of propulsion system, thrust error between control system and propulsion system, propeller wear and other factors can be minimized, and the maneuverability of the ship can be ensured. The commands of the control system can be assigned to each propeller to determine the thrust and azimuth angle of each propeller.

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4. Mathematical model of ship dynamic positioning

4.1. Thrust distribution problem

There are three main requirements for the propulsion system of ships: during the stationary operation of ships, the propulsion system needs to resist the interference caused by environmental changes; In the process of correcting the ship's attitude, it is necessary to ensure sufficient maneuverability of the hull; In the process of long-distance navigation, the propulsion system requires long-term instructions, and it is required to ensure that the sailing direction of the ship will not change suddenly.The function of thrust distribution (TA) is to use redundant propellers to select the optimal solution from propellers, while maintaining the control mapping relationship, so as to improve fault tolerance and maneuverability and reduce power consumption[10]. Therefore, TA problem of azimuth thruster is essentially a constrained nonlinear multi-objective optimization problem.

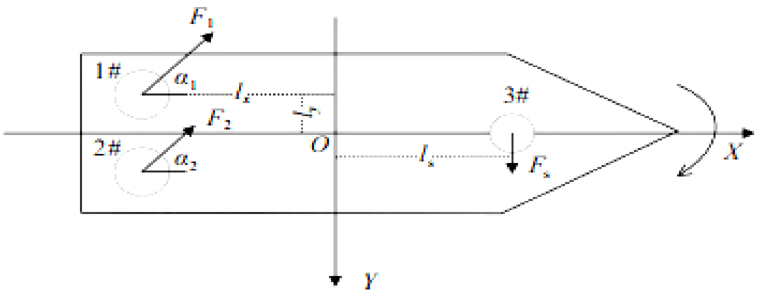

Fig. 2 Propeller arrangement of dynamic positioning ship

4.2. Mathematical model of ship thrust distribution

The main function of the thrust distribution unit is to receive the force and torque commands from the control system, and determine the thrust and thrust angle of each propeller by a certain method. The mathematical description is as follows:

$$\tau = B(\alpha)U \tag{13}$$

$$B(\alpha) = \begin{bmatrix} \cos(\alpha_1) & \cdots & \cos(\alpha_i) \\ \sin(\alpha_1) & \cdots & \sin(\alpha_i) \\ lx1\sin(\alpha_1) - ly1\cos(\alpha_1) & \cdots & lxi\sin(\alpha_i) - lyi\cos(\alpha_i) \end{bmatrix} \tag{14}$$

In addition to satisfying the force balance equation, the constraint conditions of thrust distribution problem also need to consider the performance constraints of thruster itself, such as the extreme value of thruster thrust and azimuth angle, and the variation range of thrust and azimuth angle, that is, the constraint expression is as follows:

$$\begin{cases} U\min \le U \le U\max, \\ \Delta U\min \le U - U_0 \le \Delta U\max, \\ \alpha\min \le \alpha \le \alpha\max, \\ \Delta\alpha\min \le \alpha - \alpha_0 \le \Delta\alpha\max。 \end{cases} \tag{15}$$

Considering energy consumption, thrust distribution error, singular structure and propeller wear, thrust distribution objective function can be expressed by the following formula:

$$\min J(\alpha, U, s) = P\sum_{i=1}^{m}|U|^{\frac{3}{2}} + s^T Q s + (\alpha - \alpha_0)^T \Omega (\alpha - \alpha_0) + \frac{\delta}{\varepsilon + \det\left[B(\alpha)B^T(\alpha)\right]} \tag{16}$$

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5. Conclusion

In this paper, a method to solve the problem of ship thrust allocation by using group search optimization algorithm is proposed. The results show that the application of group search optimization algorithm can make the thrust and direction angle of ship propeller change smoothly, reduce the wear and interaction of propeller, and make the power consumption change of propulsion system hardly fluctuate, and the torque command error of expected thrust and actual thrust can be controlled within a small range. Therefore, this algorithm can better solve the problem of ship thrust allocation and keep the ship heading stable under environmental disturbance.

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