The optimization of the voyage routes based on ship operational performance prediction model

Chunyu Jiang

Shanghai Maritime University, Shanghai, China

1185854021@qq.com

Abstract

Under the increasingly competitive shipping market, the proposed navigation optimization aims to reduce the emission of greenhouse gases and improve navigation efficiency, thus enhancing the competitiveness of the shipping trade. Based on the theory of machine learning, this paper realizes the automatic design and optimization of route in the northern Pacific region. To achieve this goal is the premise of accurately predicting the ship maneuvering performance, based on considering the various sea on the impact of environmental factors on ship maneuvering cases, using an improved semi-empirical method to modeling of ship speed, on this basis, and ship fuel consumption calculation model is used to sail on fuel consumption model. Then, the optimal solution set is obtained by using the robust SPEA2 multi-objective optimization algorithm, and the route optimization is realized according to the specific needs. Experimental results show that the host speed model, ship fuel consumption calculation model and SPEA2 multi-objective algorithm of the integrated use of in various aspects, experimental precision and efficiency has a good performance. The study can improve the economic benefits of shipping companies and help them stand out in the fierce shipping market.

Keywords

Energy efficient shipping, Weather routing, Multi-objective optimization.

1. Introduction

Since the 1980s, with the rapid development of economic globalization, the world's regional economic ties are increasingly close, different business areas between the freight demand is extremely strong, leading the world's shipping industry continues to develop, due to join the World Trade Organization, China's shipping Companies are facing fierce competition with rivals from around the world, and the current turmoil in the Middle East, unpredictable fuel prices and climb new highs, fuel costs have become the largest cost of shipping costs, and the proportion of increasing. Therefore, in order to gain the upper hand in the fierce market competition, to maintain its own competitiveness, control fuel cost has become the shipping enterprise cost control of the most important.

Energy-saving shipping is a prerequisite for reducing greenhouse gas (GHG) emissions to the expected level over the next few decades. The continued growth of the world's population and the increase in the number of developing countries have led to an increasing reliance on international trade in the world economy. It is estimated that in 2007, the emissions in the shipping industry were 1.046 billion tons of carbon dioxide, accounting for 3.3% of the global carbon dioxide emissions. International shipping emissions of carbon dioxide in 2007 accounted for 2.7% of global carbon dioxide emissions, international shipping carbon dioxide emissions are expected to reach three times in 2050[1]. These findings have aroused great concern from the International Maritime Organization (IMO) and entered into force on 1 January 2013, the first maritime energy efficiency regulations. The purpose of the regulation is to reduce carbon emissions by reducing fuel consumption. This can be achieved by optimizing the design of the ship, optimizing the speed and route of flight, deploying new energy-saving technologies or improving the operation of the ship. These regulations require new and existing ships to be more than 400GT to develop the Ship Energy Efficiency Management Plan (SEEMP)[2].

2. State of the art

At present, ship navigation optimization as a hot topic in industry and academia has attracted great attention from experts and scholars of domestic and international shipping enterprises, universities and research institutes. All parties are actively engaged in relevant research.

Avgouleas uses an iterative dynamic programming (IDP) algorithm based on bellman's optimal principle to achieve single target route optimization in matlab. And Shao, Zhou et al[3]., solved the ultimate discrete optimization problem of a target function and several constraints using 3D Dynamic Programming (3D Dynamic Programming). Lin, Fang and others have developed a composite influence ship weather routing algorithm based on the multi-dynamic elements, which is used to determine the optimized ship route[4]. The method of 3DMI is used to apply the 3D correction of the floating grid system to the technical and ship tracks. And Debabrata Sena, Chinmaya P. Padhy put forward a general method for determining the optimal route of a ship's weather route, which is the minimum time route[5]. The optimization model is based on the Dijkstra algorithm. The developed algorithm is multi-functional and can consider the actual constraints of all the realities of the ship during the voyage.

3. Model description

In this paper, considering only the two aspects of fuel consumption and sailing time, the objective function of multi-objective optimization algorithm is the function of fuel consumption and sailing time during the navigation. The ship's velocity becomes an important intermediate variable in two objective functions. So to establish the objective function, the first needs to build a good ship speed prediction model, and then on this basis, establish a calculation model of ship engine fuel consumption.

3.1 Speed prediction model

In this paper, a semi-empirical method, the improved Kwon method, is used to model ship maneuverability in consideration of various weather conditions.

$$\frac{\Delta V}{V_1} \times 100 = C_\beta C_\mu C_{Form} \quad (1)$$

$$V_2 = V_1 - \left(\frac{\Delta V}{V_1} \times 100\right) \times \frac{1}{100} V_1 = V_1 - (C_\beta C_\mu C_{Form}) \frac{1}{100} V_1 \quad (2)$$

where,

V_1: Design operating ship speed in still water condition, given in m/s.

V_2: Actual ship speed in the selected weather conditions, given in m/s.

ΔV: Absolute speed loss, given in m/s.

C_β: Direction reduction coeffient, dependent on the weather condition angle and the Beaufort Number(BN).

C_μ: Speed reduction coeffient, dependent on the ship's block coffient C_b.The loading condition and the Froude Number(F_n).

C_{Form}: Ship form coefficient.

Table 1 Ship form coefficient C_{Form} due to ship categories and loading condition.

Type of (displacement) ship	Ship form coefficient
All ships(except container ships) in loaded loading condition	$0.5BN + BN^{6.5}/(2.7 \times \Delta^{2/3})$
All ships(except container ships) in ballast loading condition	$0.7BN + BN^{6.5}/(2.7 \times \Delta^{2/3})$
Container ships in normal loading conditions	$0.7BN + BN^{6.5}/(22 \times \Delta^{2/3})$

Table 2 Speed reduction coefficient C_u due to Block coefficient C_b.

Block coefficient C_b	Ship loading conditions	Speed reduction coefficient Cu
0.55	normal	$1.7-1.4Fn-7.4F_n{}^2$
0.6	normal	$2.2-2.5Fn-9.7F_n{}^2$
0.65	normal	$2.6-3.7Fn-11.6F_n{}^2$
0.7	normal	$3.1-5.3Fn-12.4F_n{}^2$
0.75	loaded or normal	$2.4-10.6Fn-9.5F_n{}^2$
0.8	loaded or normal	$2.6-13.1Fn-15.1F_n{}^2$
0.85	loaded or normal	$3.1-18.7Fn+28.0F_n{}^2$
0.75	ballast	$2.6-12.5Fn-13.5F_n{}^2$
0.8	ballast	$3.0-16.3Fn-21.6F_n{}^2$
0.85	ballast	$3.4-20.9Fn+31.8F_n{}^2$

Table 3 Direction reduction coefficient C_b due to weather direction.

Weather direction	Encounter angle (deg)	Direction reduction coefficient C_β
Head sea (irregular wave) and wind	0–30	$2C_\beta=2$
Bow sea (irregular wave) and wind	30–60	$2C_\beta=1.7-0.03((BN-4)^2)$
Beam sea (irregular wave) and wind	60-150	$2C_\beta=0.9-0.06((BN-6)^2)$
Following sea (irregular wave) and wind	150–180	$2C_\beta=0.4-0.03((BN-8)^2)$

3.2 Model of ship's main engine fuel consumption

Through the above-mentioned ship speed forecasting model, the specific speed situation can be obtained. On this basis, the calculation of fuel consumption of ship main engine is carried out.

$$P_s=\frac{P_E}{\eta_T}=\frac{R_T\times V_s}{\eta_T} \quad (3)$$

$$R_F,R_R\propto V_s^2\times S \quad (4)$$

$$R_T=R_F+R_R+R_A \quad (5)$$

$$R_A\propto V_s^2\times A \quad (6)$$

$$\mathrm{g}(V_s,\Delta)=\alpha\cdot V_s^b\cdot\Delta^c+\delta \quad (7)$$

where,

P_E: Effective power

η_T: Propulsion coeffient

P_s: The main engine power

V_s: Speed through the water

R_T: Ship resistance

R_R: Eddy current resistance and wave resistance

R_A: Air resistance

S: Hull wetted area

R_F: Friction resistance

g: The main engine fuel consumption

a, b, c, η: Unknown parameters

Δ: Displacement

Then, according to the different angles of the voyage, the parameters of the fuel consumption model are solved.

3.3 Application of SPEA2

SPEA2 (Strength Pareto Evolutionary algorithm) is an improved multi-objective optimization algorithm, which has a good performance in error range and compatibility compared with other multi-objective optimization algorithms. The main loop of the algorithm is shown in (from SPEA2,which is the reference for the details of each step).

Input: P_0 *(population size)*

$\overline{N}$ *(archive size)*

T *(maximum number of generation)*

Output: A *(non-dominated set)*

Step 1: *Initialization: generate an initial population* P_0 *and create the empty archive (external set)* $P_0 = \varnothing$. *Set* $t = 0$.

Step 2: *Fitness assignment: calculate all non-dominated individuals* P_t *and* $\overline{P_t}$.

Step 3: *Environmental selection: copy all non-dominated individuals in* P_t *and* $\overline{P_t}$ *to* $\overline{P_{t+1}}$. *If size of* $\overline{P_{t+1}}$ *is less than* $\overline{N}$ *then fill* $\overline{P_{t+1}}$ *with dominated individuals in* P_t *and* $\overline{P_t}$.

Step 4: *Termination: if* $t \geq T$ *or another stopping criterion is satisfied then set* A *to the set of decision vectors represented by the non-dominated individuals in* $\overline{P_{t+1}}$. *Stop.*

Step 5: *Mating selection: perform binary tournament selection with replacement on* $\overline{P_{t+1}}$ *in order to fill the mating pool.*

Step 6: *Variation: apply recombination and mutation operators to the mating pool and set* $\overline{P_{t+1}}$ *to the resulting population. Increment the generation counter* $(t = t+1)$ *and go to Step 2.*

Fig. 1. Main loop of the SPEA2 algorithm

3.4 Optimized route selection

After SPEA2 algorithm, the Pareto front can be obtained. According to the user's requirements, the Hyperplane Strategy Distance (HyStraD) ranking method is adopted to select the optimal route out of Pareto set.

The strategy vector is then defined by the user as S=[$s_1, s_2 \ldots, s_j \ldots s_M$], where s_j indicates the importance assigned to the jth objective. Thus the strategy hyperplane is always passing through the origin of the axes and is defined according to the user strategy vector.

$$s_1 x_1 + s_2 x_2 + \cdots + s_M x_M = 0 \tag{8}$$

Finally, the user defines the weight of each decision variable according to its own requirements.

4. Conclusions

In this paper, taking into account the factors such as navigational fuel consumption and voyage time, this paper uses the ship's speed forecasting model and model of the main engine fuel consumption, and finally uses the multi-objective optimization algorithm to achieve route optimization.

References

[1] Buhaug Ø, Corbett J J, Endresen Ø, et al: Second IMO GHG study 2009, Mepc, 2009.

[2] Lantz J G: Environmental Topics Related to the International Maritime Organization's Development of a Mandatory Code for Ships Operating in Polar Waters; Meeting, Federal Register, 2012.

[3] Shao W, Zhou P, Thong S K: Development of a novel forward dynamic programming method for weather routing, Journal of Marine Science and Technology, 2012, 17(2): 239-251.

[4] Lin Y, Fang M, Yeung R W: The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements, Applied Ocean Research, 2013, 43: 184-194.

[5] Sen D, Padhy C P: An approach for development of a ship routing algorithm for application in the North Indian Ocean region, Applied Ocean Research, 2015, 50: 173-191.