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Dynamic optimization of ship energy efficiency considering time-varying environmental factors

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ABSTRACT

Nowadays, optimization of ship energy efficiency attracts increasing attention in order to meet the requirement for energy conservation and emission reduction. Ship operation energy efficiency is significantly influenced by environmental factors such as wind speed and direction, water speed and depth. Owing to inherent time-variety and uncertainty associated with these various factors, it is very difficult to determine optimal sailing speeds accurately for different legs of the whole route using traditional static optimization methods, especially when the weather conditions change frequently over the length of a ship route. Therefore, in this paper, a novel dynamic optimization method adopting the model predictive control (MPC) strategy is proposed to optimize ship energy efficiency accounting for these time-varying environmental factors. Firstly, the dynamic optimization model of ship energy efficiency considering time-varying environmental factors and the nonlinear system model of ship energy efficiency are established. On this basis, the control algorithm and controller for the dynamic optimization of ship energy efficiency (DOSEE) are designed. Finally, a case study is carried out to demonstrate the validity of this optimization method. The results indicate that the optimal sailing speeds at different time steps could be determined through the dynamic optimization method. This method can improve ship energy efficiency and reduce CO_2 emissions effectively.

1. Introduction

Waterway transportation plays a key role in the international trade. The total trade volume of world seaborne shipments is more than 10 billion tons making over 80% of the total world merchandise trade in 2015 (UNCTAD/RMT). However, the induced problems including high energy consumption and serious environmental pollution could not be neglected. Accounting for more than 60% of the total operational costs, ship fuel expenses lead to a huge impact on the competitiveness of shipping companies. On the other hand, according to the research by the International Maritime Organization (IMO), maritime transport emitted 938 million tons of CO_2 constituting 2.6% of the world's total emissions in 2012 and it will increase by 150–250% by 2050 if no further measures are taken (Marine Environment Protection Committee, 2014). Inland waterway transport also has this problem. Take the Yangtze River as an example, there are about 60,000 ships sailing on it, achieving 1.92 billion tons of cargo transportation in 2013 (Yan et al., 2011). The

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consumed energy of this large number of ships results in up to 5.27 million tons of CO_2 emissions, which should arouse wide concern for the shipping industry (Yan et al., 2010).

According to the IMO regulation, energy efficiency operational indicator (EEOI), which expresses the operation efficiency in terms of CO_2 emissions per unit of transport work, is used for measuring ship energy efficiency, as expressed in the following equation (International Maritime Organization, 2010). In which, j represents fuel type; FC_j is the total fuel consumption on the voyage, C_{carbon} is the carbon content of the fuel j; m_{cargo} is the mass of transported cargo; Dis is the voyage distance. For a given voyage, the fuel type, cargo capacity and the sailing distance is relatively fixed. Therefore, one method to reduce EEOI is to cut down the fuel consumption of the ship during the whole voyage.

$$EEOI = \frac{\sum_j FC_j \times C_{carbon}}{m_{\text{cargo}} \times Dis} \tag{1}$$

In order to improve ship energy efficiency, IMO has proposed some relevant measures including technical and operational measures, such as new energy applications (Beşikçi et al., 2016), propulsion system optimization design (Zhao et al., 2016), ship navigation optimization (Wang et al., 2015b, c) etc. In the case of in-service ships, a lot of research on speed optimization has been performed in order to improve energy efficiency (Corbett et al., 2009; Chang and Wang, 2014; Chang and Chang, 2013; Psaraftis and Kontovas, 2013; Psaraftis and Kontovas, 2014; Magirou et al., 2015; Fagerholt et al., 2010). Norstad et al. (2011) suggested that taking variable speed into consideration can significantly improve profit. Lindstad et al. (2011) studied the impact of speed reduction on the CO_2 emissions and transportation cost, and concluded that the shipping industry has much potential to reduce CO_2 emissions. Ronen (2011) focused on the determination of the ship speed and the number of ships for a container line by establishing a cost model to reduce the operating cost of the route. Recently, research on the optimization of ship energy efficiency has paid more and more attention to the large influence of navigational environment on the ship fuel consumption (Wang et al., 2015a; Chen et al., 2013; Lu et al., 2015; Beşikçi et al., 2015). Meng et al. (2016) focused on modeling the relationship between the fuel consumption rate and its determinants, including sailing speed, displacement, and weather conditions by using the shipping log data. Wang and Meng (2012) found that the fuel consumption even under the same sailing speed is different because of the different weather conditions and sea conditions. Furthermore, they established a mixed-integer nonlinear programming model to determine the optimal sailing speed for container ships.

In general, these methods only study the speed optimization of sea-going ships from the perspective of maritime logistics. In contrast, few studies have been done on the speed optimization of inland river ships (Sun et al., 2013; Yan et al., 2015; Wang et al., 2017b). The complex navigational environment of the inland waterway makes it rather difficult to decide the best sailing speeds for the inland river ships. Sun et al. (2013) calculated and analyzed the EEOI of an inland river ship under different working conditions based on experimental data. They demonstrated the huge impact of sailing speed and environmental factors on the energy efficiency of inland river ships. Yan et al. (2015) conducted a sensitivity analysis about the effect of environmental factors on ship energy efficiency by adopting a neural network method. On this basis, Wang et al. (2017b) proposed a quasi-static optimization method of engine speed through route division based on the statistical analysis of big environmental data, which took a step forward in the optimization of ship energy efficiency considering various navigational environments.

The above-mentioned speed optimization methods considering navigational environment are based on the static/quasi-static information on weather conditions from the weather forecast. In fact, weather forecast becomes less accurate over a long period of time due to inherent time-variety and uncertainty associated with these environmental factors. These static/quasi-static optimization algorithms could not ensure the real-time optimal energy efficiency during the entire voyage, due to the continuously varying environment. Therefore, it is better to develop a dynamic optimization and control method to improve ship energy efficiency considering the real-time updated environmental information. MPC is an on-line optimization-based control technique which updates decision making in response to real-time information over a given horizon (Negenborn and Maestre, 2014). The main characteristic of MPC is to use the rolling optimization strategy and can compensate for the disturbance caused by uncertainties of continuously varying parameters. Due to this advantage, it already has wide applicability in maritime transportation such as energy-efficient container handling and control of waterborne AGVs (Xin et al., 2015; Zheng et al., 2017; Negenborn and Maestre, 2014; Zheng et al., 2016). Therefore, MPC can also be used to deal with the dynamic optimization problem of ship energy efficiency considering time-varying environmental factors in this paper. In addition, the particle swarm optimization (PSO) algorithm is used to solve the established dynamic optimization model to obtain the optimal sailing speed under the real-time environment because of its ability to explore the problem's search space with lower computational complexity, especially in cases of complicated and non-linear objective functions or constraints (Kornelakis, 2010). Compared with the genetic algorithm, PSO has the advantage of faster convergence and fewer control parameters, and it has been widely used in some optimization problems (Wang et al., 2016b; 2017a). Thus; we apply this method to determine the optimal sailing speeds under different environmental conditions.

The objective of this paper is to achieve the dynamic optimization of ship energy efficiency considering time-varying environmental factors. By the adoption of MPC strategy, the optimal sailing speeds at different time steps can be determined to compensate for the disturbance caused by changing environmental factors. The decision and control method can assist the operators to fully tap the potential of ship operation energy efficiency optimization. The contributions of this study are twofold. From the perspective of theory, we establish the ship energy efficiency model considering time-varying environmental factors, so that it can effectively describe the ship energy efficiency under time-varying weather conditions. From the practical perspective, we extend the static and/or quasi-static method to a dynamic optimization method based on real-time updated environmental information. We demonstrate