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Initial considerations for operational parameters intended to minimize fuel consumption by ships in real weather conditions

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Abstract

The paper presents the concept of modeling a ship's operating parameters in order to minimize the fuel consumption in real weather conditions. This is an important innovation because, in ship theory, fuel consumption and speed are usually expressed by average values over longer periods of time, which is a significant limitation. This article presents selected topics of the proposed research such as state-of-the-art, general objectives, scientific and technical expectations, scientific and economic extensions, and environmental impacts. The article also proposes an original method of the research.

Introduction

The literature describes various methods for reducing the fuel consumption of ships in service (Aligne, Papageorgiou & Ramos, 1997; Christiansen, 1999; Tsujimoto & Tanizawa, 2006; Fagerholt, Laporte & Norstad, 2010; Yiyo, 2010; Norstad, Fagerholta & Laportec, 2011). Many of these methods are based on minimizing the time when the ship is in weather conditions that require the consumption of large quantities of fuel. To this end, a variety of methods to optimize shipping routes are used (Wiśniewski, Medyna & Chomski, 2009; 2013). The result is that the route of the ship is determined by estimating (predicting) the fuel consumption over the entire journey or over large portions of it. These methods of calculating total fuel consumption usually assume calm water, sometimes taking wave action into account.

The approach presented here makes use of an analysis of the ship's overall efficiency (Figure 1), which consists of the following elements: engine efficiency, propeller efficiency, and hull efficiency (Logan, n.d.). In ship theory, these items are separately modeled using the characteristics of the engine, propeller and the propulsion system. For this purpose, calculations are made in the theoretical design phase. There are various models of analytical, statistical and computational fluid dynamics.

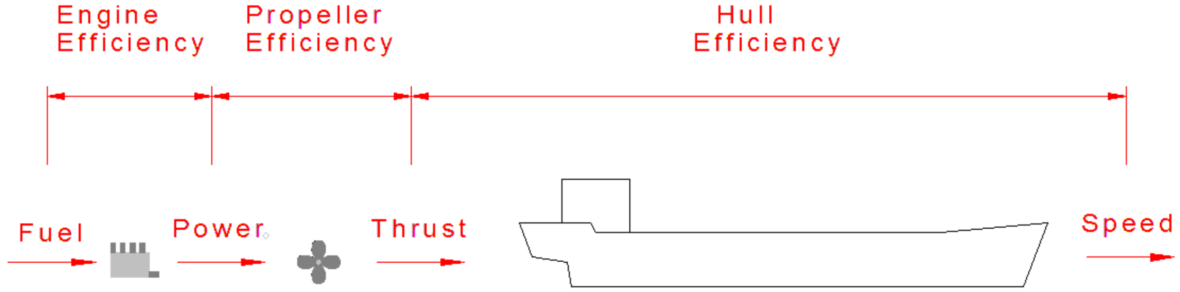

Figure. 1. Overall ship efficiency (Logan, n.d.)

The problem is that it is difficult to describe the characteristics of a ship's overall efficiency as an entire unit. In particular, it is difficult to predict propeller cooperation with the ship's hull.

Based on theoretical estimates of ship resistance including considerations of hull performance, the efficiency of the propulsion system, and the efficiency of the engine, the fuel consumption and speed of the vessel can be theoretically estimated. Only on the basis of sea trials it is possible to verify the efficiency and characteristics of the whole system. However the sea trials are carried out in a short period of time, in a narrow range of draft and trim changes and usually in good weather conditions.

The short duration of sea trials therefore leaves knowledge gaps reflecting the impact on the speed and fuel consumption of operational factors such as: wind, waves, drafts and trim, shallow water, propeller fouling, hull fouling, and poor maintenance. Among the operating parameters special attention should be paid to the impact of drafts and trim to reduction of speed and fuel consumption.

Despite the development of ship theory and the development of computational methods for computational fluid dynamics, modern science has not been able to describe the precise relationship between trim, draft, and the reduction of the speed.

It is generally accepted that the standard trim of the ship is 1 foot on the stern before sailing. But observations carried out onboard show that this standard is wrong. There are often the situations in which ships operated at a different trim have a smaller reduction in the speed and lower fuel consumption.

The impact of the actual conditions of the marine environment is provided by the "wave added resistance nn" methods. The problem is that the resistance added by waves is calculated by theoretical methods (Maruo, 1957; Gerritsma & Beukelman, 1972; Hosoda, 1973; Szelangiewicz, Wiśniewski & Żelazny, 2014) which do not adequately account for actual physical conditions.

These methods allow for an approximate calculation of the average values of the resistance added by waves, the so-called "statistical wave". These methods and their limitations are described in a number of papers (Aligne, Papageorgiou & Ramos, 1997; Tsujimoto & Tanizawa, 2006). These methods do not allow for the assignment of a temporary increase in resistance, reduction of the speed, and increase in fuel consumption. These methods are applicable only to the design analyses. The use of theoretical models in weather routing do not allow for an exact calculation of the instantaneous fuel consumption of vessels navigating in real conditions. Only theoretical fuel consumption based on the characteristics of the engine, rotation (RPM), engine load and efficiency of the drive system is calculated.

These theoretical models do not take into account changes in weather conditions in the technical characteristics of the vessel at the time of operation, for example, hull fouling, reducing the efficiency of the engine, propulsion and the hull. Existing methods are used mainly to project analysis (Cepowski, 2008a; 2008b; 2009; 2010; 2011). Additionally, due to the fact that there is no accurate method, the above methods are sometimes used for different navigation route optimization systems for example (Wiśniewski, Medyna & Chomski, 2013).

In summary, there are no accurate methods to calculate the instantaneous fuel consumption of a ship sailing under varying weather conditions in real time. Moreover, there are no methods to specify optimal vessel speed reductions during changing weather conditions. To test the impact of independent variables on the dependent variables, linear and sometimes nonlinear regression techniques are employed.

General objectives

Improving the efficiency of ship operation and reducing environmental impacts are priority research objectives in the field of maritime technology. The prescribed operational efficiency of a ship can be obtained by:

- Minimizing fuel consumption on route;
- Minimizing voyage duration for a fixed fuel consumption rate.

Reducing environmental impact mainly entails reducing emissions and fuel consumption. Therefore, the general objective of the research is modeling the operational parameters of the vessel during real time weather conditions such that:

- Fuel consumption is reduced;
- Speed reduction is minimized.

Fuel consumption and vessel speed in real weather conditions are influenced by various factors, including:

- Factors related to the technical characteristics of the ship, such as engine efficiency, propulsion system efficiency, and the frictional resistance of the hull;
- Factors related to the operating conditions of the ship, such as the weight of the vessel and its draft, trim, and the rotational speed of the

propeller, as well as the parameters of waves, wind and sea currents;
- Factors related to the deterioration of the technical characteristics of the vessel during the operation, such as the engine, propeller fouling, hull fouling, and deformation of the shell.

Operational factors that affect fuel consumption and speed of a vessel with fixed technical properties as a function of actual weather conditions include the following:

- Factors related to the ship:
  - The number of revolutions of the propeller;
  - The weight of the ship;
  - Draft and trim.
- Environmental conditions including waves, wind, and current;
- The effects of wave impacts on the ship including impacts on the ship's motion, and secondary effects such as slamming and screw surfacing,

This leads to the following scientific problems:

- Existing methods of prediction of fuel consumption and vessel speed under real conditions are inaccurate, and fail to account for the impact of weather related factors;
- It is not known how these factors affect the instantaneous fuel consumption and speed of the ship under real operating conditions.

Therefore, the specific scientific objectives of the research are:

1) To determine which factors have a significant impact on the instantaneous fuel consumption and instantaneous speed of the vessel under real operating conditions;
2) To develop an approximating function for instantaneous fuel consumption and vessel speed as a function of relevant operating parameters under actual operating conditions.

The practical aim of the research is to develop technical guidelines and instructions and software to determine the optimum operating parameters of the ship for fuel consumption and speed under real operating conditions for a particular vessel.

Research methods

To achieve the aim of the research, it is planned to carry monitor ship operation parameters for a group of vessels within over a few years' time. The data gathered by the monitoring will be analyzed to:

- Determine which of the operating parameters have a significant impact on the instantaneous fuel consumption and instantaneous speed of the vessel under real weather conditions;
- Develop functions approximating the instantaneous fuel consumption and speed of the vessel under real weather conditions based on relevant operating parameters.

The key element of the research is to determine functions f_1 and f_2 approximating the instantaneous fuel consumption IFC and instantaneous speed of the vessel ISV based on operating parameters X_1, X_2, … X_n:

$$\text{IFC} = f_1\,(X_1, X_2, \ldots, X_n) \tag{1}$$

$$\text{ISV} = f_2\,(X_1, X_2, \ldots, X_n) \tag{2}$$

where:

IFC – approximate instantaneous fuel consumption;
ISV – approximate instantaneous vessel speed;
$X_1, X_2, \ldots X_n$ – operating parameters including:

- Parameters describing the loading condition;
- Parameters describing the ship propulsion system;
- Parameters of ship roll and pitch;
- Parameters describing the environmental conditions;
- The life of the ship.

f_1, f_2 – functions for approximating the instantaneous fuel consumption IFC and the instantaneous speed of the vessel ISV.

The functions f_1 and f_2 can be determined according to the following formulae:

$$X_1, X_2, \ldots, X_n \xrightarrow{f_1} IFC \tag{3}$$

$$X_1, X_2, \ldots, X_n \xrightarrow{f_2} ISV \tag{4}$$

where:

X_1, X_2, … X_n – registered values of operating parameters on the ship in real time operation;
IFC – registered values of the instantaneous fuel consumption on the ship in real time operation;
ISV – registered values of the instantaneous speed of the vessel on the ship in real time operation.

In order to determine functions f_1 and f_2 in equations (3) and (4), use can be made of statistical methods or methods based on artificial neural networks.

The studies described in the literature (Drozd, 2006; Abramowski, 2008) indicate the possibility of using artificial neural networks for modeling technical processes in various fields related to the operation and design of ships. In this case, artificial neural networks are mainly used to develop the required relationships.

Therefore, to achieve the scientific and technological objectives set forth, the following method are proposed:

1. The registration values of parameters: X_1, X_2, …, X_n, IFC and ISV for group of vessels in real weather conditions during the service time;
2. Statistical analysis in order to determine which of the X_1, X_2, …, X_n parameters have a significant impact on the speed ISV and fuel consumption IFC of the vessels based on the registered values;
3. The development of mathematical relationships (3) and (4) between the operating parameters X_1, X_2,…, X_n, and fuel consumption IFC, and the speed of the ship ISV.

There following areas circumscribe the following main tasks of the research:

1. Installation of measuring equipment, installation of equipment for registering and transfer of data on ships and onshore server.
2. Performance of measurements and statistical analyses, the selection of relevant independent variables, and the development of mathematical models (1) and (2) for the vessels researched.
3. Develop advices, guidelines, and computer software to determine the optimum service parameters of the ship for fuel consumption and speed under real weather conditions.

Scientific and technical expectations

This research is expected to lead to information on the following scientific issues:

1) Determination of which operating parameters have a significant impact on fuel consumption and vessel speed under real weather conditions;
2) Development of the approximating functions of fuel consumption and vessel speed on the basis of the relevant operating parameters under real weather conditions;
3) Possibility of determining the relationship between the ship's geometrical parameters, operating parameters, and speed reductions caused by waves.

Perhaps further studies will determine the influence of geometrical parameters of the hull on speed and fuel consumption. In this case, trials can be continued on a larger group of vessels in order to explore such relationships.

Moreover mathematical functions can be developed to verify the theoretical methods used in the ship theory that address estimation of added wave resistance or speed reduction of the ship. Such advancements will significantly improve the theory of ship design.

The research will lead to the following technical objectives:

1) Development of guidelines for determining the optimum operating parameters as a function of vessel fuel consumption and speed;
2) Development of computer software to predict fuel consumption and speed based on the operating parameters of ships;
3) Determination of the possibility of developing computer software to predict the vessel speed reduction based on the geometric parameters of the hull and real time operating and environmental conditions.

Scientific and economic continuation

Achieving the goals of research allows developing a mathematical model of predicting the instantaneous speed impact and fuel consumption based on the operating parameters of the ship. This model can be used to conduct research on:

- Optimization of instantaneous ship motion parameters in rough weather conditions in terms of voyage time and fuel consumption;
- Multi-criteria optimization of shipping routes in terms of long- and short-term planning.

The results of this research will be used to develop the self-learning computer system based on artificial intelligence. The computer system will automatically develop the approximating functions for fuel consumption and speed reduction as a function of data measured on the ship. The development of the automatic system and its implementation will significantly increase the accuracy of fuel consumption predictions and speed reduction estimates under real weather conditions.

The economic benefit of this research will be to reduce fuel consumption and voyage time. The models can then be used to reduce the operating costs of analyzed ships by:

- Reducing average fuel consumption for the entire route of the ship;
- Temporary reduction in fuel consumption under real operating conditions over a part of the route;
- Reducing voyage time.

An important economic advantage of continuing this research is an analysis of the costs of the operation of vessels along different routes, and then selecting the following options:

- The most economical ship for the shipping route;
- The most economical route for a vessel.

This will reduce energy costs and reduce environmental pollution.

Environmental impact

The practical effect of the research will be to reduce fuel consumption, thereby reducing emissions and pollution. These effects are consistent with the IMO in terms of pollution prevention. For this purpose IMO has developed energy efficiency measures. The proposed study is consistent with the following from the above measures (IMO, 2015):

- Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI);
- Energy Efficiency Design Index (EEDI);
- Model Course for energy efficient operation ships.

A Recent IMO research MEPC58/INF.21 presented in (Green, Winebrake & Corbett, 2008) indicated that weather routing reduces fuel consumption by 2–4%, and as much as a 50% improvement can be achieved through operational measures such as speed reduction and fleet planning.

The objective of the proposed research is to reduce the fuel consumption and thus reduce GHG emissions. Therefore, the study has a significant impact on the reduction of environmental pollution.

In turn, the increase in the operating efficiency of the ship can affect employment and improve working conditions.

Conclusions

The issues presented in the paper are the basis for research on modeling the operational parameters of the vessel for fuel consumption and speed reduction. The article contends that there is a strong necessity of modeling ship service parameters under real weather conditions. Effects of the proposed research will have a significant impact on the development of the science and theory of the ship design and operation, and it will bring economic benefits for the maritime economy and reduce negative environmental impacts. Overall, the outcome of this research will increase the energy efficiency of a ship, resulting in:

- Reduction of the cost of service of ships, which will help increase the competitiveness of European shipping companies;
- Reduction of emissions which, in turn, will result in a global reduction of environmental pollution.

Moreover, mathematical functions can be used to verify the theoretical methods used in the ship theory, such as estimating added wave resistance or speed reduction of the ship.

Moreover, the research results will be used to develop a self-learning computer system based on artificial intelligence. The computer system will automatically develop the approximating functions of fuel consumption and speed reduction on the basis of data measured on the ship. The development of the automatic system and its implementation significantly increases the accuracy of prediction fuel consumption and speed reduction under real weather conditions.

Abbreviations

ANN – Artificial Neural Network
CFD – Computational Fluid Dynamics
DWT – Deadweight
EEDI – Energy Efficiency Design Index
EEOI – Energy Efficiency Operational Indicator
GHG – Greenhouse Gas
IMO – International Maritime Organization
MEPC – Marine Environment Protection Committee
SEEMP – Ship Energy Efficiency Management Plan

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