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Estimation of ship speed loss and associated CO_2 emissions in a seaway

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ABSTRACT

A reliable prediction of attainable ship speed at actual seas is essential from economical and environmental aspects. A methodology for estimating the attainable speed in moderate and severe sea is proposed. The irregular sea is handled as a series of regular waves with different amplitudes and frequencies. The added resistance in regular waves is obtained by either a direct pressure integration method or an asymptotic small wavelength formula. The in-and-out-of-water-effect and ventilation of a propeller in severe seas is accounted for by a quasi-steady averaging of experimental data for different propeller submergences. The propulsion results for regular waves are used in simulating results in irregular waves. It is shown that for higher sea states this effect has much more influence on the speed loss than the added resistance in waves. The speed loss is calculated by taking into account the engine and propeller performance in actual seas as well as the mass inertia of the ship. The attainable ship speed is obtained as time series. Correlation of speed loss with sea states allows predictions of propulsive performance in actual seas. The expected CO_2 emission for a containership is estimated for the Northern route of North Atlantic.

1. Introduction

The ship behaviour in actual weather condition is currently one of the major concerns for designers and ship owners as well as for ship officers. Each one of them has their own preoccupations. From the designer's point of view, the competition between design offices has stimulated the effort of more accurate ship performance evaluation. Ship officers want a fast and safe ship with good performance in actual seas. On the other hand, ship owners are oriented to achieve the highest possible profit in given conditions and restrictions. In this respect the accurate calculation of attainable ship speed at higher sea states is essential from economical and also environmental aspects. A reliable speed loss calculation allows a more accurate prediction of the power increase and fuel consumption as well as gas emissions from ships. Following the increasing awareness of the environmental and human health concerns of shipping, legislative actions have been taken on global and national levels. Internationally, ship emissions are restricted by the International Maritime Organization (IMO). Current regulations about air pollution from ships are covered in MARPOL Annex VI which was put into force in May 2005 (IMO, 2006) but does not include effective regulatory scheme for greenhouse gases (GHG) emissions. Nowadays this issue becomes very important because of the problem of global warming. The Marine Environment Protection Committee (MEPC) of IMO states that carbon dioxide (CO_2) and other GHG emissions from shipping are rising at an alarming rate due to the increase in the global trading of goods (IMO, 2008) and appealing for immediate measure to prevent and reduce this pollution. Many interested partners in global shipping put an effort to reduce the air pollution from oceangoing vessels and to get prepared for possible policy measures, but the process is loomed by the recent economic recession. Although lower economic activity due to the financial crisis will reduce CO_2 emissions, in the longer term the drying up of funding for lower-carbon energy solutions is likely to have far greater adverse impact on emissions.

Progress towards developing a mandatory regime to control GHG emissions from international shipping was made during the first meeting of IMO's Working Group on GHG Emissions from Ships, held in Oslo, Norway (23 to 27 June 2008). The session was tasked with developing the technical basis for reduction mechanisms that may form part of a future IMO regime to control GHG emissions from international shipping. Besides establishing a global levy scheme on marine bunker fuel to achieve GHG emission reductions, other short-term measures for further consideration include improvement related to fuel consumption and use of other energy means, voluntary/mandatory requirements to report CO_2 Index values, vessel speed reduction and measures to improve traffic control, fleet management, cargo handling operations and energy efficiency. The longer-term measures identified

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by the Working Group and approved by the committee for further development include technical measures for ship design, use of alternative fuels, a CO_2 Design Index for new ships, a unitary CO_2 Operational Index limit, combined with penalty for non-compliance.

MEPC has considered indexes expressing the GHG efficiency of the design of a ship in great detail. The fundamental principle that has been agreed is that the emission index expresses the ratio between the cost (i.e., emission) and the benefit that is generated, which is expressed as transport work capacity (IMO, 2009; CE Delft et al., 2006). The Energy Efficiency Design Index (EEDI) expresses the emission of CO_2 from a ship under specified conditions (e.g., engine load, draught, wind, waves, etc.) in relation to a nominal transport work rate. The Energy Efficiency Operational Indicator (EEOI) is related more to operational efficiency. Unlike the EEDI, the EEOI changes with operational conditions. The EEOI may thus be calculated for each leg of a voyage and reported as a rolling average or periodically. Recently, MEPC (IMO, 2010) has considered introducing those indexes as mandatory measures, possibly as amendments to MARPOL Annex VI Regulations for the prevention of air pollution from ships. The type and size of vessel to which they shall apply have also to be agreed on. The unit for both indexes is grams of CO_2 per capacity-mile, where "capacity" is an expression of the cargo-carrying capacity relevant to the cargo that the ship is designed to carry. For most ships, capacity will be expressed as deadweight tonnage.

The EEDI is being developed as a means to determine how efficient a given ship design would be in reducing emissions. An important aspect for improvement in this respect still lays in hull optimization based on ship performance in actual sea. In past years researchers and designers have put a significant effort in the development of optimum hulls in calm water. It may therefore be reasonable to think that there is no much potential left for improvement. However, the experience (IMO, 2000) obtained from model experiments at MARINTEK indicate that reduction of power in the order of 20% may still be gained by relatively minor changes to the bow and/or stern of a vessel. So, there is still a significant potential for power savings by good hull design. These measures could effectively be combined with several other operational measures, such as weather routing and voyage planning, in order to ensure that fuel consumption and GHG emissions from ships are minimized on every voyage.

We have focused our attention to develop a reliable methodology for estimating the attainable ship speed in moderate and severe seas. At higher sea states the ship is subjected to very strong environmental forces and consequently experiences several additional dynamic effects which affects her speed. The relative vertical motion could be very pronounced and the consequence is that propeller operates too close to the surface of the water or even periodically operates out of the water. In these cases, the propeller will obviously behave differently than in calm water or small seas. Since this phenomenon is very difficult to solve numerically, we tried to capture the effect by implementing a thrust loss model using available experimental data (Smogeli, 2006). The calculation of added resistance in regular waves is carried out by a direct pressure integration method in the wavelength range of non-negligible ship motions together with a small-wavelength asymptotic formula (Faltinsen et al., 1980). The irregular sea is approximated by a decomposition of irregular wave time trace into a series of regular wave parts. Then these values are used in performing calculation in regular waves. Accounting for the effect of still water resistance and added resistance as well as for thrust loss in waves, the attainable ship speed for a constant engine torque is obtained by accounting for the mass inertia of the ship (Prpić-Oršić and Faltinsen, 2009). As a result we obtained time trace of ship speed on specific sea state. According to calculated mean speed at specific sea state the increase of CO_2 emission at sea could be estimated. The effect of air resistance and the ship steering are presently not included, but ought to be considered in the future.

2. Hull resistance calculation

The still water resistance is calculated according to Holtrop and Mannen's method (Holtrop and Mennen, 1982; Holtrop, 1984), which is an approximate procedure widely used at the initial design stage of a ship. The method is based on regression analysis of random model experiments and full-scale data, available at the Netherlands Model Basin.

The calculation of added resistance in waves in the ship-motion range of wavelengths is carried out by the direct pressure integration procedure developed by Faltinsen et al. (1980). The method is developed for calculation of added resistance, transverse drift force and mean yaw moment on a ship in regular waves of any wave direction that are functions of the linear time-dependent velocity potential which in our case calculated by the strip theory by Salvesen et al. (1970). When the wavelength – to ship length ratio is lower than 0.5, asymptotic expressions presented by Faltinsen et al. (1980) are used.

3. In-and-out-of-water effect and ventilation of the propeller

In extreme conditions the propeller works in a very hostile environment and the additional dynamic loads due to ventilation and in-and-out-of water effects can be severe. If a propeller operates too close to the water surface, the localized low pressure created by the blades can draw air under the water and cause ventilation effects. Ventilation is most likely to occur either when the ship operates in high seas with severe ship motions causing high amplitudes of propeller relative motion, or when the ship operates in a very light displacement condition or have a large negative trim.

In this research, the in-and-out-of-water effect on thrust value is roughly taken into account by an approximation of thrust losses due to the effect of ventilation and loss of propeller disc area at severe sea states. The ventilation thrust loss model for an open propeller is proposed by Smogeli (2006), as a function of relative shaft speed n/n_{bp} (propeller shaft speed – propeller bollard pull shaft speed ratio) and relative submergence h/R (propeller shaft submergence – propeller radius ratio) of propeller in calm water. The model is adapted to a time domain simulation and the thrust loss values are obtained for any combination of shaft speed and relative submergence of practical importance. The thrust loss coefficient values were estimated by simplifying experimental results. The results of open water tests, performed by Smogeli (2006) in the Marine Cybernetics Laboratory (MCLab) at Norwegian University of Science and Technology (NTNU), are used for this purpose. A quasi-steady time averaging over one encounter period is then used to consider the effect of regular waves. The results for regular waves are used in simulating results in irregular waves.

The wave effect on wake and the thrust deduction factor as discussed by Faltinsen et al. (1980) are neglected. The change in propeller torque with the immersion is not taken into account.

4. Voluntary speed reduction

When the ship encounters the storm or heavy sea, the master will probably voluntarily reduce the ship speed in order to avoid severe consequences. He or she decides to slow down