Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2018
June 17-22, 2018, Madrid, Spain

OMAE2018-78514

UNCERTAINTIES OF SHIP SPEED LOSS EVALUATION UNDER REAL WEATHER CONDITIONS

Jasna Prpić-Oršić
Faculty of Engineering, University of Rijeka
Rijeka, Croatia
Centre for Autonomous Marine Operations and Systems (AMOS)
Trondheim, Norway

Kenji Sasa
Department of Maritime Sciences, Kobe University
Kobe, Japan

Marko Valčić
Faculty of Maritime Studies Rijeka
University of Rijeka
Rijeka, Croatia

Odd Magnus Faltinsen
Centre for Autonomous Marine Operations and Systems (AMOS)
Trondheim, Norway

ABSTRACT

A correct assessment of the ship speed loss in conditions of exploitation is becoming increasingly important for ship owners as well as ship designers. We are witnessing the increasing concern for the environment and awareness of the necessity to preserve it as much as we could. The ship speed drop in the real environmental conditions can cause the increased fuel consumption as well as increased emissions of CO_2 and other GHG (greenhouse gases) from ships. Decrease of the ship speed in real conditions is a consequence of the added resistance due to the impact of weather conditions, i.e. waves and wind, and due to aggravated working conditions of propeller, i.e. engine system. Moreover, the solution estimation of this problem is very affected by human factors. Ship master, concerning for safety, can make a judgment that, under certain adverse weather loads, it is necessary to slow down or change ship's course to moderate or bypass the worst condition. In addition, the loading condition of the ship is constantly changing which govern the basic parameters of the ship: the mass and mass moment of inertia, draft and trim and, consequently, the ship behavior at sea.

All these parameters affect the assessment of ship speed and it is necessary to be conscious of the intensity of their impact on the final value. At the same time, they cannot be predicted with absolute certainty so the purpose of this analysis is to estimate the impact of weather and operational uncertainties on the actual speed of the ship in real operating conditions.

INTRODUCTION

Improving the energy efficiency of the ship means increasing profits and reducing the adverse impact on the environment. Following the increasing awareness of the environmental and human health concerns of shipping, legislative actions have been taken on global and national levels making mandatory (from January 1, 2013) that new ships over 400 gross tonnage, to comply with the regulations, should have emissions of CO_2 under some limiting value. From the navigational and marine hydro-dynamic point of view, the accurate calculation or at least reliable estimation of attainable speed of ship under real environmental conditions allows a more accurate prediction of the power increase and fuel consumption as well as gas emissions from ships. On the other hand, technological enhancements like improved hull designs as well as improvement in power and propulsion systems could potentially reduce CO_2 emission up to 35 %. These measures could effectively be combined with several other operational measures, such as optimal weather routing and voyage planning for ships, to ensure that fuel consumption and CO_2 emissions from ships are minimized on every voyage.

The ship behavior in actual weather conditions 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 towards achieving 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 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.

However, the choice of the methodology of attainable ship speed estimation and related parameters significantly affects the calculated speed values which are reflected on the energy efficiency evaluation of ship as well as on the level of environmental compatibility.

ENERGY EFFICIENCY OF SHIP

Internationally, ship emissions are restricted by the International Maritime Organization (IMO), which works towards developing a comprehensive regulatory regime aimed at effectively protecting the environment from pollution caused by ships. Current regulations about air pollution from ships are covered in MARPOL Annex VI, which was put into force in May 2005 [1] and since recently include effective regulatory scheme for greenhouse gas (GHG) emissions [2]. The Marine Environment Protection Committee (MEPC) has considered indexes expressing the GHG efficiency of the design of a ship in detail. The fundamental principle that has been agreed on 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. 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 adopted measures were added to MARPOL Annex VI through a new Chapter 4 entitled "Regulations on energy efficiency for ships", making mandatory the EEDI for new ships and the Ship Energy Efficiency Plan (SEEMP) for all ships. The regulations apply to ships above 400 gross tonnage and have entered into force on 1 January 2013.

The idea of new regulations is to reduce GHG and other air pollution emissions by requiring new ships to reduce their EEDI from an existing baseline EEDI. The EEDI is a calculation based upon a ship's technical characteristics, such as hull dimensions and form, propeller design, propulsion system, fuel usage, and other factors. IMO developed EEDI values for the existing international fleet by type of ship. A "reference line value" was determined by fitting a curve through the data for the fleet. The mathematical formula for the curve determines the reference line value. The formula uses the deadweight of the ship and numerical factors based on her type.

The regulations establish a "Required EEDI", which is the reference line value reduced by a percentage. The percentage of reduction from the reference line value is planned to be increased through four phases (from phase 0 to phase 3) during next twelve years. So, the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. At Annex 8 of MEPC resolution the *Guidelines on the method of calculation of the Attained EEDI for new ships* is adopted. An "Attained EEDI" is a measure of a ship's energy efficiency and must be calculated for each new ship or each ship that has undergone a major conversion [3, 4, 5]. The unit for EEDI is grams of CO_2 per capacity-mile and is calculated by a formula based on the technical design parameters for a given ship. The "capacity" is an expression of the cargo-carrying capacity relevant to the cargo that the ship is designed to carry. For most ships, capacity is expressed as deadweight tonnage. To comply with the regulations, the Attained EEDI must be lower than or equal to the Required EEDI. If the design of a ship belongs to more than one of the ship type category, then the Required EEDI for the ship shall be the most stringent value.

Still optional is the calculation of so-called Attained $EEDI_{weather}$, which can be calculated by dividing Attained EEDI by weather factor f_w, the non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed. As an option to applying a weather factor of 1.0, EEDI can be determined by conducting the ship-specific simulation on its performance at representative sea conditions in which case "Attained $EEDI_{weather}$" is assigned to the ship.

Apparently, future research efforts will be directed toward appropriate measures and strategies that can enable further reduction of EEDI, which naturally leads to decrease of fuel consumption and GHG emissions.

However, these strategies involve models and methodologies that are a source of numerous uncertainties.

UNCERTAINTY OF ATTAINABLE SHIP SPEED ESTIMATION

To assess the reliability associated with attainable ship speed estimation, it is essential to understand and quantify uncertainty involved. For the design of a safe ship, it is necessary to assess the reliability of seakeeping analysis and wave load estimation as well as operational conditions in which the ship should perform its mission [6]. The same uncertainties are associated with the procedure of attainable speed prediction. However, those uncertainties are strongly coupled with the uncertainties of engine and propulsion system performance as shown in Figure 1.

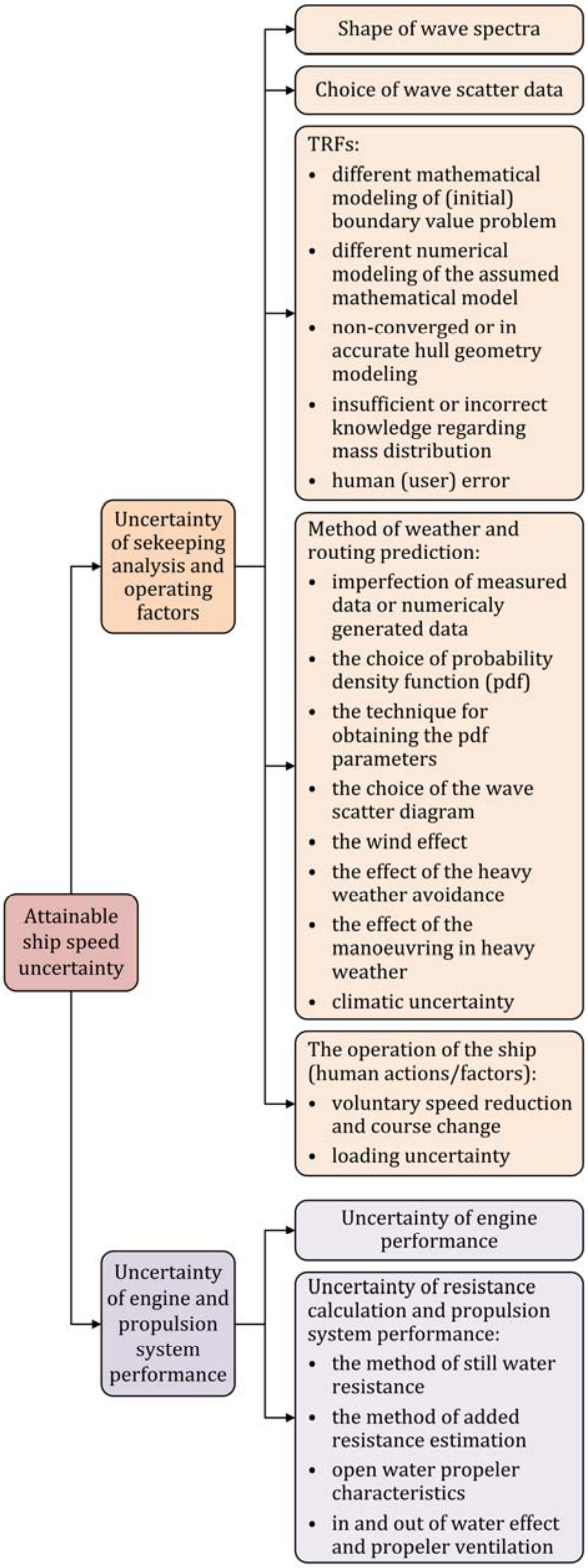

FIGURE 1. SCHEMATIC REPRESENTATION OF UNCERTAINTIES

Uncertainties may be classified into two groups: aleatory and epistemic. Related to metocean description, aleatory uncertainty (natural and physic) considers natural randomness of random variable, such as variability of wave intensity in time [7]. This uncertainty is also known as intrinsic or inherent and cannot be reduced or eliminated. Epistemic (knowledge based) uncertainty can be reduced by collecting more information as well as by improving the applied models. This uncertainty can be: data related, statistic related, model related or due to climatic variability.

Uncertainty of seakeeping analysis and operating factors

Uncertainty of seakeeping analysis is strongly related to applied weather condition and its representation as well as to the methodology of transfer function estimation. Wave loads uncertainty may be classified in two main groups: uncertainty of linear theory based model and uncertainty of non-linear effects [8]. The main source of uncertainty in both linear theory and calculation of non-linear effects is uncertainty related to metocean description. It is expected that this uncertainty will represent the largest challenge for the shipping, offshore and renewable energy industry in the future [9]. Bitner-Gregersen et al. [7] use different wave data and models for specifying design and operational criteria for two types of marine structures and discuss different associated uncertainties.

It is important to assign an uncertainty measure to the waves and responses that are being estimated as a base for ship motion and evaluation of loads. Real time estimation of waves and ship responses using on-board measurements has been under investigation in recent years [10, 11, 12]. In general, two main concepts have been applied to estimate the on-site directional wave spectrum based on ship response measurements: a parametric method which assumes the wave spectrum to be composed by parameterized wave spectra, or a non-parametric method where the directional wave spectrum is found directly as the values in a completely discretized frequency-directional domain without a priori assumptions on the spectrum.

The very important factor of attainable ship speed estimation as well as fuel consumption and greenhouse gas emissions are the methodology of transfer function calculation. Recent studies [13] show that values of transfer functions depend on many factors: different mathematical modeling of (initial) boundary value problem; different numerical modeling of the assumed mathematical model; non-convergence in accurate hull geometry modeling; insufficient or incorrect knowledge regarding mass distribution and human, i.e. user error.

The difference in estimated ship motion reflects on both involuntary and voluntary speed reduction. Lu et al. [14] and Sasa et al. [15] have analyzed three extreme cases of bulk-carrier sailing during storms at Southern Hemisphere. They reproduced the environment by three different wind inputs with various spatial and temporal resolutions. The simulated waves (wave hindcasts) and ship responses were validated and compared using measured on-board ship motion data. The compared data show significant uncertainty related to weather database, as well as seakeeping theory and speed prediction technique.

Uncertainty of factors that affects the modeling of ship operations are mainly in the weather and routing prediction and human factors governing the ship operation.

The local storm conditions can be described by the probability density function associated with an environmental condition. Having selected one distribution as a likely model, it remains to estimate the parameter values that will provide the best empirical fit between the distribution and the data. The method of parameter fitting can greatly influence on results. In many cases measured data or numerically generated data is used as empirical data. Those data related uncertainties refer to imperfection of measured data or numerically generated data (or combined – the gap between measured data is filled by numerically generated data). Uncertainties due to insufficient number of data and applied technique for obtaining the probability density function parameters are statistic uncertainties, while imperfection, simplification and idealization made in physical model for an event, choice of probability density function as well as climate variability are model related uncertainties. The avoidance of heavy weather during ship design process may be modeled by modifying the original wave scatter diagrams obtained from Global Wave Statistics (GWS). The modifications can be done by truncating the probability density function of the significant wave heights at limiting value H_{Slim}. The probability of the truncated area should then be added to the sea states bellow the limiting significant wave heights. Moan et al. [16] propose 3 methods to modify the original scatter diagram:

- to add the probability of the truncated area just below limiting significant wave height H_{Slim},
- to add the probability of the truncated area uniformly bellow H_{Slim} ,
- to allow a small probability of encountering sea states above H_{Slim} by reducing the tail of the probability density function. The truncated probability is then distributed uniformly below H_{Slim}.

First method approximates situation where the ship master avoids the heavy weather by maneuvering the vessel just into calmer sea states. The second method is represented by the assumption that the sea state forecasts are available to the master and that rerouting is made. The last option accounts the fact that the significant wave heights higher than H_{Slim} cannot be absolutely avoided in the reality [16].

Besides the selection of the modification method of the wave scatter diagram, the crucial question is the choice of an appropriate limiting significant wave height H_{Slim} [17].

The operation of the ship is governed and organized by humans. The fact that human (master and crew) decisions are very subjective, they import high uncertainties in prediction of their behavior. One of the general indicators of ship quality is the ability to maintain speed in severe head seas. The excessive motions, slamming, deck wetness, propeller emergence, excessive accelerations are the main causes of the master's decision to reduce ship speed and avoid ship or cargo damage or people injuries. This decision is very subjective and greatly depends on the master's expertise and experience but for the ship design purpose it is possible to consider some average behavior. This average behavior must be expressed by numerical values to be applicable for numerical analysis. Prpić-Oršić et al. [18] have presented the real-life operation of ultra large container ships from the point of view of shipmasters. Authors provide some insight in uncertainty related to decisions of masters during voyage.

The speed at which ship would sale is important parameter in seakeeping analysis [18]. The choice of design speed or speed profile during life time of the ship is important decision which has consequences in long term predictions and it is a key factor for ship route planning [19] and ship route optimization [20].

When the ship is caught in heavy seas, there are two maneuvers that shipmaster can undertake to avoid excessive ship rolling and hull damage [21]. These are:

- course changing,
- voluntary speed reduction.

The course changes in heavy weather are mainly to avoid the ship capsizing or excessive ship rolling amplitudes that may interfere with normal working activities onboard [21]. Consequently, the probability of head seas is much higher in heavy weather than in normal sea conditions. However, this is valid only for smaller ships, less than about 200 m in length. For larger ships, the course changes in heavy weather are not so frequent [18]. The explanation for this finding could be that the masters of large ships feel safe even in rather rough seas.

Another important maneuver in rough seas is the speed reduction. This action is not dependent on the ship size [21]. The reasons for speed reduction may generally be divided into two categories:

- natural reasons, such as the added resistance due to wind, waves and current, steering, change of wake field and loss of thrust [22].
- technical or "design" reasons that are controlled by the shipmaster, such as very large motion amplitudes, velocities and accelerations, slamming, green seas, overload of the main engine.

The natural reasons influence the ship speed at relatively low significant wave heights H_s, while in heavy seas the shipmaster decides whether to reduce speed. There is no strict rule that determines under which conditions the shipmaster would reduce the speed, so various authors have proposed different criteria.

One of the important segments of the ship speed drop in real weather conditions is voluntary ship speed reduction. This situation occurs in higher sea states when the captain judges that maintaining the current speed may compromise the ship, cargo or people on board, and decides to reduce deliberately the speed of the ship. The reasons and criteria due to which the captain decides to reduce speed are extremely subjective and dependent on the experience and the personality of the captain. Prpić-Oršić et al. [23] have analyzed the impact of variations of the limiting values of certain criteria due to which the captain intentionally reduces the ship speed. The influence of the limit values of slamming, deck wetness, excessive acceleration, propeller emergence and roll criteria at different significant wave heights of head and following sea are analyzed for the S175 container ship with length between perpendiculars of 175 m. The curves in Figures 2 and 3 refer to involuntary speed reduction and to different cases of limiting values of voluntary speed reduction criteria.

For both head and following sea cases, the master would reduce main engine power at the weather condition of approximately 3 m significant wave height and the wave length that is approximately half ship length. At head waves, the variations of limit acceleration values have evident impact on estimated ship speed. Due to stricter limiting rms value of 0.1 g, estimated speed varies up to 4 kn. This is not the case for the effect of propeller emergence limiting value on attainable ship speed. The effect of considering this criterion is visible, but attainable ship speed value is not sensitive to the variation of the limiting values.

At following sea, voluntary speed reduction would happen mainly due to propeller emergence. In the range of significant wave height values of 3 to 8 m (which corresponds to wave length – ship length ratio approximately 0.5 to 1.0), the attainable speed is, due to propeller racing, reduced up to 11.3 kn.

The master would voluntary reduce ship speed at the weather condition of approximately 2 m significant wave height at beam sea. This would happen due to excessive rolling. At waves of significant wave height values of 7 m and more, the speed will be reduced due to excessive accelerations.

The analysis shows quite low sensitivity of result (attainable ship speed) on criteria limit variations. When taking into account deck wetness, propeller emergence and roll, the values of involuntary reduced speed starts diverging from voluntary reduced speed at H_s = 6 m, H_s = 3 m, and H_s = 2 m, respectively. However, the effect of different limiting values on speed is almost negligible. The main reason is that the small change in probability (for example for slamming and deck wetness, but also for propeller emergence) slightly affect the threshold values that lead to each phenomenon. The excessive accelerations and roll criteria limits are expressed as rms values and the difference of threshold values in that case is more pronounced.

Another uncertainty regarding the ship operation is loading uncertainty. The prediction of ship speed considering the effect of various loading circumstances should give a relatively more realistic evaluation of the fuel consumption as well as GHG emissions. However, these circumstances are not easy to foresee. Acero et al. [24] developed the methodology for assessment of the operational limits and the operability of marine operations during the planning phase.

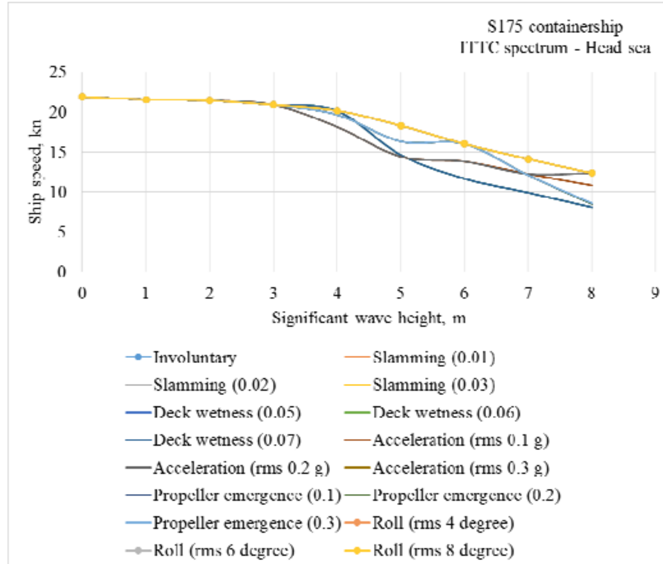

FIGURE 2. SHIP SPEED LOSS FOR HEAD SEA

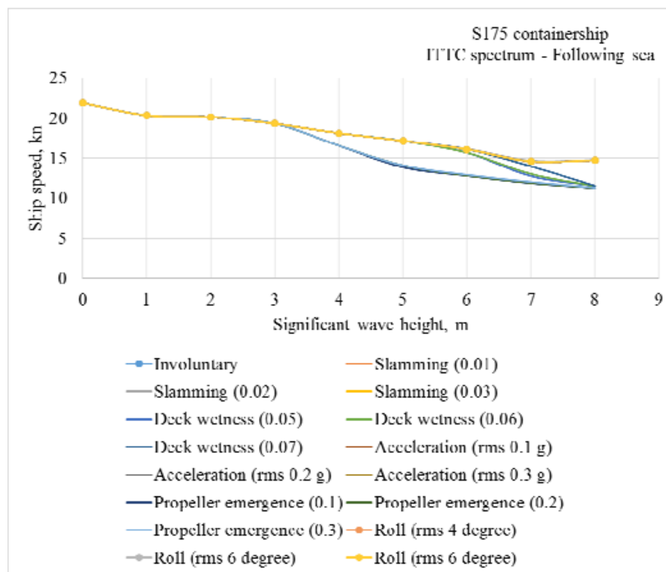

FIGURE 3. SHIP SPEED LOSS FOR FOLLOWING SEA

The influence of loading condition and initial ship speed on attainable ship speed is analyzed in [25]. The change of loading conditions means the change of wetted hull surface (and above water area) and affects all aspects of the attainable ship speed calculation: estimation of still water and added resistance, wind loads, seakeeping performance (absolute and relative motions), propulsive performance, etc. It is shown that the small change of draft could significantly affect the speed loss under real weather conditions. The analysis of the speed loss percentage for different initial ship speed (full ahead and lower engine loads) shows that lowering the ship speed doesn't always mean economic voyage, especially considering various loading conditions.

Uncertainty of engine and propulsion system performance

Predictions of the fuel consumption and CO_2 emissions under transient load, imposed by the ship dynamics in heavy sea to the propulsion plant, must be done only by using adequate numerical modelling of the complete propulsion power plant, consisting of the diesel engine system with auxiliary systems and propeller. In that way the ship speed model and engine dynamic model could be coupled and the information about speed loss and fuel consumption (CO_2 emissions) could be obtained in short time. It would be possible to better account for voluntary speed reduction and related CO_2 emission since in that case the main engine conditions would change [26].

The estimation of CO_2 emission from the ship can be based on the ship speed variation and engine behaviour. The specific emissions rate for GHG may be calculated simply by the general equation adopted from the study by Marintek and Det Norske Veritas [27], [28]. This method is simple and fast but neglects the variability of engine characteristics as well as engine behaviour under higher loads.

During voyage in wind and waves, the increase of the resistance requires an adequate power increase to maintain a certain cruising speed. The added resistance may also have significant influence on ship's performance in moderate seas, especially for ships with blunt bow-forms in head and bow seas. Therefore, a preliminary estimation of added resistance considering a given sea condition needs to be performed. Different methods of still water resistance and added resistance estimation can be chosen, starting from the simplest empirical ones to the most recent computational methods and this choice can significantly affect the estimated values of attainable ship speed [29].

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 the 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. This phenomenon is very difficult to solve numerically, but the effect can be captured by implementing a thrust loss model using available experimental data [30]. The estimation of attainable ship speed at higher sea states is strongly affected by the fact whether we include this effect in numerical model or not [31].

CONCLUSION

A correct assessment of the ship speed loss in conditions of exploitation is becoming increasingly important for ship owners as well as ship designers. We are witnessing the increasing concern for the environment and awareness of the necessity to preserve it as much as we could. The ship speed drop in the real environmental conditions causes the increased fuel consumption as well as increased emissions of CO_2 and other GHG from ships. Decrease of the ship speed in real conditions is a consequence of the added resistance due to the impact of weather conditions (waves and wind) and due to aggravated working conditions of propeller – engine system. Moreover, the estimation of this problem solution is very affected by human factor. Ship master, concerning for safety, can make a judgment that, under certain adverse weather loads, it is necessary to slow down or change ship's course in order to moderate or bypass the worst condition. In addition, the loading condition of the ship is constantly changing which govern the basic parameters of the ship: the mass and mass moment of inertia, draft and trim and, consequently, the ship behavior on sea.

All these parameters affect the assessment of ship speed and it is necessary to be conscious of the intensity of their impact on the final value. At the same time, they can not be predicted with absolute certainty so it is necessary to estimate the impact of each weather and operational uncertainties on the actual speed of the ship in real terms.

ACKNOWLEDGMENTS

This work was supported by the Research Council of Norway through the Centers of Excellence funding scheme AMOS. This work was also supported by the Croatian Science Foundation - project 8722 and the University of Rijeka (contract no. 13.09.1.1.05).

REFERENCES

[1] IMO, 2006. MARPOL, Consolidated Edition, MARPOL Annex VI: "Regulations for the prevention of air pollution from ships". London.

[2] IMO, 2011. "Prevention of Air Pollution from Ships". IMO GHG study, MEPC 62 London.

[3] IMO, 2009. "Prevention of Air Pollution from Ships". IMO GHG study, MEPC 59, London.

[4] IMO, 2015. "Amendments to the 2014 Guidelines on Survey and Certification of the Energy Efficiency Design Index (EEDI)". MEPC 254(67), London.

[5] CE Delft, Germanischer Lloyd, MARINTEK, Det Norske Veritas, 2006. "Greenhouse Gas Emissions for Shipping and Implementation Guidance for the Marine Fuel Sulphur Directive". Delft.

[6] Papanikolaou, A., Mohammed, E.A., Hirdaris, S.E., 2014. "Stochastic uncertainty modelling for ship design loads and operational guidance". *Ocean Engineering* 86, pp. 47-57.

[7] Bitner-Gregersen, E.M., Dong, S., Fu, T., Ma, N., Maisondieu, C., Miyake, R., Rychlik, I., 2016. "Sea state conditions for marine structures' analysis and model tests". *Ocean Engineering* 119, pp. 309-322.
[8] Guedes Soares, C., 1996. "On the definition of rule requirements for wave induced vertical bending moments". *Marine Structures* 9, pp. 409-425.
[9] Bitner-Gregersen, E.M., Ewans, K.C., Johnson, M.C., 2014. "Some uncertainties associated with wind and wave description and their importance for engineering applications". *Ocean Engineering* 86, pp. 11-25.
[10] Nielsen, U.D., 2006. "Estimations of on-site directional wave spectra from measured ship responses". *Marine Structures* 19, pp. 33-69.
[11] Montazeri, N., Jensen, J.J., Nielsen, U.D., 2015. "Uncertainties in ship-based estimation of waves and responses". In *Proceedings of OCEANS '15,* Washington, DC, USA.
[12] Pascoal, R., Perera, L.P., Guedes Soares, C., 2017. "Estimation of directional sea spectra from ship motions in sea trials". *Ocean Engineering* 132, pp. 126-137.
[13] Parunov, J., Guedes Soares, C., Hirdaris, S., Lee, Y., Liu, S., Papanikolau, A., Prpić-Oršić, J., Rodrigues, M., Ruponen, P., 2017. "Benchmark study on uncertainty assessment in numerical predictions of global wave loads in damaged ships". ISSC-ITTC Workshop on load uncertainties, 16.9. 2017, Wuxi, China, 2017.
[14] Lu, L., *Sasa*, K., *Sasa*ki, W., Terada, D., Mizojiri, T., 2017. "Rough wave simulation and validation using onboard ship motion data in the Southern Hemisphere to enhance ship weather routing". *Ocean Engineering* 144, pp. 61-77.
[15] Sasa, K., Faltinsen, O.M., Lu, L., Sasaki, W., Prpić-Oršić, J., Kashiwagi, M., Ikebuchi, T., 2017. "Development and validation of speed loss for a blunt-shaped ship in two rough sea voyages in the Southern Hemisphere". *Ocean Engineering* 142, pp. 577-596.
[16] Moan, T., Shu, Z., Drummen, I. and Almashi, H., 2006. "Comparative Reliability Analysis of Ships – considering different Ship Types and the Effect of Ship Operations on Loads". *Transactions SNAME* 114, pp.16-54.
[17] Moan, T. et al., 2006. "Reliability based structural design and code development". Special task committee VI.1, *16th International ship and offshore structures congress*, 20-25, Southampton, UK, pp. 321-395.
[18] Prpić-Oršić, J., Parunov, J., Šikić, I., 2014. "Operation of ULCS - real life". *International Journal of Naval Architecture and Ocean Engineering* 6, pp. 1014-1023.
[19] Mao, W., Rychlik, I., Wallin, J., Storhaug, G., 2016. "Statistical models for the speed prediction of a container ship". *Ocean Engineering* 126, pp. 152-162.
[20] Vettor, R., Guedes Soares, C. 2016. "Development of a ship weather routing system". *Ocean Engineering* 123, 1-14
[21] Guedes Soares, C. 1990. "Effect of Heavy Weather Maneuvering on the Wave Induced Vertical Bending Moments in Ship Structures". *Journal of Ship Research.* 34(1), pp. 60-68.
[22] Faltinsen, O.M. 2005. "Hydrodynamics of High-Speed Marine Vehicles". Cambridge University Press
[23] Prpić-Oršić, J., Faltinsen, O. M., Parunov, J., 2015. "The effect of voluntary speed reduction criteria on attainable ship speed", 16th Congress IMAM 2015, Pula, pp. 143-149.
[24] Acero, W.G., Li, L., Gao, Z., Moan, T., 2016. "Methodology for assessment of the operational limits and operability of marine operations". *Ocean Engineering* 125, pp. 308-327.
[25] Prpić-Oršić, J., Vettor, R., Faltinsen, O. M., Guedes Soares, C., 2016. "Route choice and operating conditions influence on fuel consumption and CO_2 emission". *Journal of Marine Science and Technology*, Vol. 21, No. 3, pp. 434-457.
[26] Prpić-Oršić, J., Faltinsen, O. M., Mrakovčić, T., 2013. "Influence of ship behaviour in a seaway on CO2 emissions," in Proc. of the 32nd Int. Conf. on Ocean, Offshore and Arctic Eng. OMAE 2013, Nantes, France
[27] Marintek, 1996. "Environmental indexing of ships - Exhaust gas emissions". Report nr. 222514.00.01, Trondheim
[28] Det Norske Veritas, 1998. "Data and Algorithms for Ship Pollution". Internal report 98-2058, Oslo
[29] Vitali, N., Prpić-Oršić, J., Guedes Soares C., 2016. "Uncertainties related to the added resistance estimation". Proceedings of Maritime Technology and Engineering - MARTECH 2016, ISBN 978-1-138-03000-8, 391-399, Lisabon
[30] Smogeli, Ø.N., 2006. "Control of Marine Propellers - From Normal to Extreme Conditions," Ph.D. dissertation, Dept. of Marine Technol., NTNU, Trondheim, Norway
[31] Prpić-Oršić, J., , Faltinsen, O.M., 2012. "Estimation of Ship Speed Loss and Associated CO_2 Emissions in a Seaway". Ocean Eng., vol. 44, no 1, pp. 1-10