The impact of variation in added resistance computations on voyage performance prediction

Taskar, Bhushan; Regener, Pelle Bo; Andersen, Poul

Published in:

Practical Design of Ships and Other Floating Structures. PRADS 2019. Lecture Notes in Civil Engineering

Link to article, DOI:

[10.1007/978-981-15-4624-2_8](https://doi.org/10.1007/978-981-15-4624-2_8)

Publication date:

2021

Document Version

Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):

Taskar, B., Regener, P. B., & Andersen, P. (2021). The impact of variation in added resistance computations on voyage performance prediction. In *Practical Design of Ships and Other Floating Structures. PRADS 2019. Lecture Notes in Civil Engineering* (pp. 133-149). Springer. Lecture Notes in Civil Engineering Vol. 63 https://doi.org/10.1007/978-981-15-4624-2_8

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

The impact of variation in added resistance computations on voyage performance prediction

Bhushan Taskar^[0000-0001-9509-6962], Pelle Bo Regener^[0000-0002-6195-8170], and
Poul Andersen^[0000-0001-5115-2491]

Technical University of Denmark, Department of Mechanical Engineering,
Kgs. Lyngby, Denmark
`bhta@mek.dtu.dk`

Abstract. Prediction of added resistance of a ship in waves is essential to evaluate vessel performance in a seaway. Also, added resistance in waves increases the fuel consumption. Today different methods are used to predict the added resistance of a ship in waves. Model tests play an important role, and researchers employ a range of computational methods, from two-dimensional potential flow in frequency domain to viscous time-domain CFD computations. These methods agree to a varying degree for different wavelengths and wave headings. How much do these differences in added resistance prediction affect the overall voyage performance prediction in a realistic weather condition and a practical route is an interesting question which has been addressed by this paper. The results give an idea about the importance of added resistance formulation on economic operations of ships.

Keywords: Vessel performance, added resistance, accuracy and uncertainty, route simulations

1 Introduction

Added resistance, which is an increased resistance in the presence of waves, can be a significant part of resistance leading to increased fuel consumption and emissions. Prediction of added resistance is essential to evaluate the vessel performance in a seaway. Due to EEDI and EEOI regulations by IMO to curb emissions due to shipping, it is essential to optimize ships for realistic operating conditions. Also for existing vessels, precise estimation of added resistance helps to reduce fuel consumption and emissions by changing the operating profile of the ship or by advanced weather routing. Therefore, added resistance has an impact on the economic performance of a vessel.

Many researchers have developed approaches to predict the added resistance using experimental fluid dynamics (EFD, model tests), potential flow-based calculations, and lately computational fluid dynamics (CFD). However, the spread in predicted added resistance in different wave conditions using various methods is notable. Therefore, this paper aims to quantify the variation in predicted

energy consumption for a ship's voyage in realistic operating conditions due to uncertainty in added resistance.

Added resistance computed by many different organizations using experimental, potential flow, as well as CFD methods can be seen in [1] and [2] for two standard benchmark vessels, KVLCC2 (a very large crude oil carrier) and KCS (a feeder-sized container ship).

Uncertainty analysis for added resistance calculated using model tests has been performed in [3] where added resistance has been computed in head waves for KVLCC2 using different methods. Uncertainty in the estimation of added resistance using different methods has been studied in [4] where a considerable variation in added resistance estimation is seen for many different ships. [5] and [6] have presented added resistance for KVLCC2 using model tests, CFD and potential flow codes. [7] have compared added resistance using different methods at three different ship speeds. Added resistance for many different ships has been computed in [8].

Similar computations for KCS have been performed by [9] where added resistance has been calculated using CFD, model tests and potential flow methods. Added resistance and motion responses (RAOs) have been obtained experimentally at six wavelengths with the non-dimensional wavelength λ/L varying from 0.5 to 2 for five wave headings. The comparison of experimental results with potential flow calculations shows a good agreement except for beam sea and stern quartering sea. Detailed investigation of the effect of different wave headings on added resistance can be found in [10] where experimental added resistance has been calculated at seven different wave headings each at wavelengths with λ/L ranging from around 0.15 to 2.5. Moreover, peaks in added resistance which correspond to resonance in a particular degree of freedom have been identified. That gives an idea of the cause of an especially large increase in added resistance in certain wave conditions.

This paper investigates the effect of variation in added resistance RAOs computed using different methods on overall vessel performance using voyage simulations. Voyage simulations have been performed for realistic weather and routes considering resistance as well as propulsion of ships.

2 Methods

The details of simulation methodology, selected routes and weather conditions used for voyage simulations will be discussed in this section.

2.1 Simulation Methodology

Voyage simulations were performed on multiple routes to calculate the total energy consumption of a vessel on a given voyage. Simulations were performed at multiple points along the route spaced 50 nautical miles apart. The propulsion points were calculated at each location assuming the ship in steady state condition. The ship speed was assumed constant, equal to the design speed of

Fig. 1. Routes used for the simulations along with average wave conditions in October.

the respective ship. The propeller speed was calculated to balance total thrust (including thrust deduction) with total resistance at the design speed. The propeller rpm and torque were used to calculate delivered power. In the absence of any engine details for both the ships, different simulations were compared based on the energy consumption obtained by integrating power over the time taken for voyage.

2.2 Weather and Routes

The weather data averaged for each month have been obtained from ECMWF [11]. The data consist of significant waveheight, peak period and wave direction at different latitudes and longitudes.

Four different routes were selected for the simulation (Los Angeles to Osaka, Panama to Auckland, Seattle to Yokohama and Halifax to Bremerhaven). The routes between these points were obtained from [12] which generates a route between the given locations based on historical AIS data. The routes can be seen in Fig. 1. These routes are typical, especially for container ships. The distribution of wave headings faced by the ships at different points on these routes in different months can be seen in Fig. 2. Wave headings between 0° to 180° have been used for convenience as the ships and their responses are symmetrical.

3 Case Vessels

The aforementioned benchmark vessels KCS and KVLCC2 were selected for the current analysis, as a large amount of validation data are available for these ships. The main dimensions and other relevant data for these ships can be seen in Table 1, more details about these ships can be found in [13].

Fig. 2. Box plots for wave headings faced by ships on the routes used for simulations. 180° corresponds to head waves. The green line corresponds to the median (50^{th} percentile) of all wave headings and the box represents the range of 25^{th} to 75^{th} percentile.

Table 1. Ship details

	KVLCC2	KCS
Length	320 m	230 m
Breadth	58 m	32.2 m
Depth	30 m	19 m
Draft	20.8 m	10.8 m
Block coefficient	0.8098	0.651
LCB (forward of LPP/2)	3.48 %	-1.48 %
Wetted surface area	27194 m ²	9530 m ²
Design speed	7.97 m/s	12.35 m/s
Froude number	0.142	0.26
Propeller diameter	9.86 m	7.9 m
No. of blades	4	5
Blade area ratio	0.431	0.80
P/D (0.7R)	0.721	0.997
Thrust deduction fraction	0.190	0.154
Effective wake fraction	0.305	0.208
Relative rotative efficiency	1.005	1.011
$C_T \cdot 10^3$	2.055	2.103

3.1 Resistance and Propulsion

Calm water resistance has been calculated using the experimental measurements of residual resistance coefficients presented by [14] and using the ITTC 1957 friction line to calculate the friction coefficient. Total calm water resistance coefficients (C_T) and propulsion factors at the design speed of the vessels have been presented in Table 1. Thrust deduction, effective wave fraction and relative rotative efficiency have been taken from [14] for KVLCC2 and from [15] for KCS. Even though propulsion factors varying due to waves can affect vessel performance [16], they have been considered constant to study the effect of added resistance alone.

Propeller openwater diagrams that are needed for the calculation of propeller rpm and torque were computed using B-series polynomials and the principal particulars of the respective propellers.

Added resistance has been calculated in irregular waves using added resistance RAOs in regular waves and a Bretschneider wave spectrum. The wave spectrum is obtained using the significant waveheight and peak period of waves at a particular location provided by the weather data (see following section). Wind resistance has been neglected in these computations.

3.2 Added Resistance Methods

Added resistance has been calculated in different wave conditions using the method proposed by ITTC [17] and a method developed at the Technical University of Denmark (DTU) [18, 19].

The ITTC method considers the waves coming from 225° to 135° as head waves (180° corresponds to head waves) when computing the added resistance. The added resistance is assumed zero for other wave directions. The DTU method is based on strip theory [20], Faltinsen's method [21] for short waves and WAMIT [22] calculations for zero forward speed cases. The DTU method can compute the added resistance for wave headings from head sea (180°) to beam sea (90°). In addition to these methods, multiple added resistance RAOs for the ships from Sec. 3 have been obtained from the literature.

3.3 Added Resistance Data: KVLCC2

Experimental added resistance data in head waves have been obtained from the experiments performed at Osaka University reported in [1]. The experiments were performed at a range of λ/L from 0.6 to 2. Added resistance data at wavelengths shorter than $\lambda/L = 0.6$ have been taken from the experiments performed at NTNU as mentioned in [5, 6]. These RAOs together will be referred as experimental measurements of added resistance in this paper.

Multiple added resistance computations by various institutes have been reported in [1]; however, most of the computations have been performed at a limited number of wavelengths. Therefore, it is difficult to construct added resistance RAO at a complete operating range of the vessel. Added resistance of

Fig. 3. Added resistance RAOs for KVLCC2 in head waves.

KVLCC2 has been computed using CFD by [5, 6] at 14 different wavelengths in the range of λ/L from 0.18 to 2.0. Simulations for wavelengths below $\lambda/L = 0.6$ have been performed by fixing the ship in surge motion whereas the ship was free to surge in the longer waves. At $\lambda/L = 0.6$ computations were performed both using free and fixed surge which give a slightly different value of added resistance. As a result, there are two values of added resistance at that point. These RAOs will be referred to as CFD computations.

Added resistance calculated using potential flow (PF) methods (Gerritsma, Beukelman [23], and enhanced unified theory [24]) reported by [5] are also considered for the simulations. These will be referred to as PF1 and PF2 respectively in this paper. RAOs obtained from the literature along with the ones calculated using DTU and ITTC methods for KVLCC2 have been presented in Fig. 3.

3.4 Added Resistance Data: KCS

From the many results presented in [2], two RAOs have been chosen to represent the spread in added resistance data. Neither of the two shows particularly good agreement with the experimental values, but here they serve as examples to illustrate the impact of different CFD results on vessel performance prediction. These RAOs will be referred to as CFD1 and CFD2 in this paper. Besides simulation results, [2] also reports added resistance at multiple wavelengths obtained using experiments performed at FORCE Technology. CFD1, CFD2, and experimental RAOs are available at five wavelengths in the range of λ/L from 0.65 to 1.95. RAOs have been interpolated using linear interpolation within the range of available data as evident in Fig. 4.

Considering the chosen routes and the weather conditions, peak periods encountered along the routes are in the range of 5 to 14 seconds. For KCS, a regular wave of period of 5 to 14 second corresponds to λ/L equal to 0.17 and 1.33, respectively. Therefore, the values of RAO even below $\lambda/L = 0.17$ are required to

Fig. 4. Added resistance RAOs for KCS in head waves. Extrapolated part of RAOs has been denoted using dotted lines.

calculate added resistance in irregular waves of peak period 5 seconds. Added resistance RAOs calculated using the DTU and ITTC methods are reasonably flat in the region below $\lambda/L = 0.6$. Moreover, the values of added resistance predicted by CFD1, CFD2, experimental data, and ITTC method are very similar at $\lambda/L = 0.65$. Therefore, it was decided to extrapolate these RAOs below $\lambda/L = 0.65$ by assuming the same non-dimensional value of added resistance at all wavelengths below $\lambda/L = 0.65$. The extrapolated part of the RAOs has been depicted using dotted lines in Fig. 4.

4 Simulations and Results

The effect of different added resistance formulations, approximations and RAOs has been studied in this section. As noted earlier, added resistance is often available only in head waves, and an approximation is required in other wave conditions. It is argued that the added resistance in head waves affects vessel performance the most. The aim here is to quantify the effect of such approximations.

4.1 Effect of variation in RAOs in head sea

One set of simulations were performed in predominantly head sea conditions as most of the RAOs for both ships are available only for head waves. To perform realistic simulations to evaluate the impact of RAO differences alone, weather and route should be chosen such that ships face predominantly head waves. As observed in Fig. 2, this condition is met on a voyage from Los Angeles to Osaka in April. The detailed wave conditions on this route in April are presented in Fig. 5.

Fig. 5. Wave conditions along the route from Los Angeles to Osaka in average weather of April.

KVLCC2 and KCS were simulated using added resistance RAOs seen in Fig. 3 and Fig. 4. Waves coming from 135° to 225° (180° corresponds to head sea) were considered head waves for this set of simulations and the added resistance was calculated using the RAOs in head waves. Even though the DTU method can take into account the effect of any wave headings in the range of 180° to 90° , added resistance corresponding to 180° wave heading was used when wave direction was between 135° to 225° for a fair comparison between different RAOs.

The total energy consumption was computed over the entire route to study the influence of different added resistance RAOs on overall fuel consumption. The total energy consumption using different RAOs has been compared with the energy consumption using experimental RAO. Percentage change in energy consumption can be seen in Table 2.

In the case of KVLCC2, the prediction in energy consumption varies from 5.3% higher using the ITTC method to 10.2% lower using PF2 RAO as compared to the energy consumption obtained using experimental RAO. It is important to notice that the waves on this route are in the range of 8 to 12 seconds peak period which corresponds to 100 m to 224 m wavelengths. KVLCC2 being a 320 m vessel, these wavelengths correspond to λ/L in the range of 0.3 to 0.7. Therefore, RAOs in the range of wavelengths below ship length are playing an important role. The trends in energy consumption are also seen in RAOs in short waves where the ITTC method predicts the highest added resistance and PF2 RAO shows lowest added resistance. This observation also underlines the fact that in

Table 2. Percentage change in energy consumption of a voyage using different RAOs compared to experimental RAO

KVLCC2 Results						
RAO	DTU	ITTC	Exp.	CFD	PF1	PF2
% change	-6.0	5.3	0	-1.3	-1.7	-10.2
KCS Results						
RAO	DTU	ITTC	Exp.	CFD1	CFD2	
% change	-2.2	-0.2	0	2.1	0.3	

typical weather conditions, added resistance in shorter waves plays a critical role for large vessels like KVLCC2.

In the literature, ship motion analysis or added resistance computations for KVLCC2 are performed in the range of λ/L from 0.6 to 1.6 [1]. From the ship hydrodynamics point of view, the focus is generally on wavelengths close to the ship length as ship motions and added resistance have a peak in this condition. However, from the operational perspective and considering typical weather conditions, the ships are much more likely to encounter much shorter waves. Therefore, accurate estimation of added resistance in shorter waves will improve the overall vessel performance prediction.

In the case of KCS, the percentage change in energy consumption varies from 2.1% higher using CFD1 RAO to 2.2% lower using DTU code as seen in Table 2. The variation in energy consumption is lower in this case as compared to that in KVLCC2, even though the spread in added resistance RAOs is not lower for KCS. The smaller change in case of KCS is due to lower contribution of added resistance in total resistance as the design Froude number is much higher, which leads to larger calm water resistance. In the case of KVLCC2 the maximum percentage of added resistance in total resistance is 15.6%, whereas in case of KCS it is 7.3% for the weather conditions in Fig. 5. In this case, the range of peak periods on the chosen route corresponds to λ/L from 0.43 to 0.98 for KCS. Therefore, again, in this case, waves shorter than the ship are crucial. For a validation exercise like [2] it would have been better to cover a broader range of wave lengths, particularly towards shorter waves, from the operational perspective.

4.2 RAO: Head waves only vs. 90° to 180° wave headings

Moving on from comparing simple RAO differences and their impact on voyage performance, the aim of this section is to investigate the importance of taking wave heading into consideration when wave conditions vary from head sea to beam sea. This is particularly relevant, as added resistance RAOs are often only available for head sea conditions, and an approximation is required in other wave conditions.

In this case, simulations were performed for both KVLCC2 and KCS using the DTU method, which can provide RAOs for any wave heading ranging from head to beam seas. The following two sets of simulations were run:

- Case 1: Added resistance is calculated using the DTU method for head waves. Wave headings between 135° and 225° are considered pure head wave conditions (180°). Added resistance is neglected (assumed zero) in other wave directions.
- Case 2: Added resistance is calculated using the DTU method considering the actual wave heading. Added resistance is neglected for wave headings below 90° (stern-quartering and following waves), which are outside the range of capability of the method.

Fig. 6. Added resistance in different wave headings used in Cases 1 and 2.

Fig. 7. Percentage increase in energy consumption in Case 2 (actual wave heading) compared to Case 1 (only head waves) for different routes in various weather conditions.

Added resistance in different wave conditions in both cases are presented in Fig. 6. Polar plots for added resistance have been plotted from 0° to 180° in each case as added resistance is symmetrical about 180° . Note that the RAOs for a wave heading of exactly 180° are identical for Case 1 and Case 2. In the case

of KCS, the DTU method (for Case 2) predicts the maximum added resistance in a condition other than head waves. Also, it is seen that the peak of added resistance shifts to lower λ/L in both the cases in a bow quartering sea.

Simulations were performed on all the four routes shown in Fig. 1 using the average weather conditions of all 12 months. The difference in total propulsion energy consumption between the Case 1 and Case 2 formulations of added resistance is presented in Fig. 7.

Fig. 7 shows that the assumptions from Case 2 lead to higher resistance in all the simulations as compared to the simplified added resistance formulation used in Case 1. The difference varies significantly on all routes and weather conditions except in case of Halifax to Bremerhaven where the difference is always less than 3% for KVLCC2 and less than 1% for KCS. The trend of difference between the two cases is similar for KCS and KVLCC2; only the range of variation is different. The trends are similar because the difference between Case 1 and Case 2 simulations depends on the dominant wave directions encountered along the route. Wave directions from 0° to 90° will not make any difference as the added resistance is zero for this condition in both cases. This is happening in the case of the Halifax to Bremerhaven route where stern quartering and following waves are predominant (see Fig. 2). On the other hand, wave directions in the range 90° to 135° will lead to significant differences as added resistance is non-zero in one case and zero in other. This is the case for the route from Panama to Auckland (see Fig. 2).

4.3 RAO: Head waves only vs. all wave headings

Experimental values of added resistance for all wave headings for KCS were obtained from [9]. Computations considering all wave headings were compared with the simplified approach where only the added resistance RAO in head waves is known. The two added resistance approaches used for the comparison were:

Case 3: Experimental added resistance RAO in head waves. Wave headings in the bow sector ($\pm 45^\circ$ off bow) are considered head waves. Added resistance for other wave headings is neglected.

Case 4: Experimental added resistance RAOs in all wave headings.

Added resistance values for both cases can be seen in Fig. 8. It should be noted that the RAOs for Case 3 and Case 4 are identical for a wave heading of 180° . The highest values for added resistance appear for head wave conditions in the range of λ/L from 1 to 1.5. Moreover, high values are also observed in beam sea for wavelengths smaller than $\lambda/L = 0.5$ which are probably due to the resonance in roll motion. As is apparent from Fig. 8, one can expect that the approximation of added resistance using the head waves-only RAO will overestimate the added resistance when the wave heading is within the bow sector ($\pm 45^\circ$ off bow), but not exactly 180° . However, it will be underestimated in other wave conditions especially in beam sea for short waves.

Simulations were performed considering all four routes in average weather conditions of each month. The relative difference in the energy consumption

Fig. 8. Added resistance in different wave headings used in Cases 3 and 4.

Fig. 9. Percentage increase in energy consumption in Case 4 (considering all wave heading) compared to Case 3 (only head waves) for different routes in various weather conditions.

between Case 3 and Case 4 computations can be seen in Fig. 9. A difference in energy consumption up to 8% can be observed if simplified added resistance RAOs are used as compared to RAOs in all wave directions. Fig. 9 therefore provides the range of “uncertainty” in performance, due to considering added resistance only in head waves for a ship similar to KCS. Given that the contribution of added resistance to total resistance is lower for KCS than for KVLCC2, the difference would have been higher for a ship like KVLCC2.

4.4 RAO: 90° to 180° wave headings vs. all wave headings

This set of simulations was carried out to assess the influence of added resistance in following seas on voyage performance. Simulations considering added wave resistance in all wave directions (Case 4 from the previous section) were compared with the approach that assumes zero added resistance for beam, stern quartering and following sea conditions (Case 5). The difference in RAOs is visualized in Fig. 10. Note that values for added resistance for wave headings between 90° and 180° are entirely identical.

Fig. 10. Added resistance in different wave headings used in Cases 4 and 5.

As in previous sections, simulations were run for all four routes in different weather conditions. The results were compared in terms of total energy consumption over the route. Percentage difference between the energy consumption in the two cases can be seen in Fig. 11. In most of the cases, the difference is small. However, the route Halifax to Bremerhaven shows a significant change in total energy consumption with maximum 7% in October. As observed earlier, this route showed minimum changes in Fig. 7 but maximum changes in Fig. 11. This is because beam to following waves are predominant on this route as is obvious from Fig. 2.

Fig. 11. Percentage increase in energy consumption in Case 4 (considering all wave headings) compared to Case 5 (considering added resistance for 90° to 180°) for different routes in various weather conditions.

5 Discussion

Voyage simulations were performed using added resistance RAOs from different sources. The results quantify the effect of variations in added resistance approximations on voyage performance in terms of energy consumption. The results have been obtained for realistic operating conditions (weather and routes) as the chosen routes are some of the important shipping lanes. Also, the scatter in voyage energy consumption purely caused by different approaches to added resistance was found to be sizable.

Results in Sec. 4.1 show significant difference (-10.2 to 5.3% for KVLCC2, and -2.2 to 2.1% for KCS) in total energy consumption for a voyage when different methods are used to calculate added resistance. These differences, especially in case of KVLCC2, are high from the vessel performance estimation point of view given that the variations are only due to uncertainty in added resistance with all other factors kept constant. Therefore, a method or software used for the calculation of added resistance can significantly affect vessel performance prediction.

Yet, very accurate added resistance RAOs for head waves are not sufficient for consistently accurate performance predictions. Sections 4.2–4.4 assessed the influence of the range of wave headings for which RAOs are available. As this aspect is quite different from the comparison of RAOs from different methods, the magnitude of discrepancies between approaches described in those sections cannot be directly compared to the differences described in Sec. 4.1. In fact, one might argue that the effects from Sec. 4.1 and Sec. 4.2–4.4 are largely independent from each other and might therefore be additive.

The differences in RAOs seen in Sec. 4.2 appear small at first sight. However, these limited differences lead to a notable influence on total voyage energy consumption depending on weather conditions. The difference in energy consumption varies up to 10% for KVLCC2 and up to 3% for KCS. Wave heading can have substantial influence even when wave headings are limited within beam sea and head sea especially in the case of vessels where the contribution of added resistance in total resistance is high.

For the ships and voyages considered, using a simplified approach only using a RAO for added resistance in head waves was seen to affect total energy consumption by up to 8% (Sec. 4.3), whereas only neglecting the added resistance in stern quartering and following seas still led to up to 7% lower energy consumption (Sec. 4.4). These numbers are relative to using the “correct” added resistance RAOs in all wave headings. However, in most of the cases, the differences are largely lower than these maximum values, as the results are highly dependent on the dominant wave direction encountered along the route- which again underlines the critical role of wave heading in added resistance formulation.

6 Conclusion

When taking into account operational considerations when looking at added resistance in waves and its impact on energy consumption the following conclusions can be drawn:

- Added resistance should be computed at a range of wavelengths considering operational as well as hydrodynamic perspective. From the operational point of view, frequently encountered waves are critical whereas from the hydrodynamic perspective, waves causing considerable added resistance are relevant.
- Wave headings play a vital role in the estimation of total energy consumption. Therefore, one must be aware of the uncertainty or error introduced by simplified methods when the ship is sailing not only in head waves.
- Simplified added resistance methods will lead to larger errors in the case of slow speed ships since the proportion of added resistance in total resistance is higher for these ships.

7 Limitations and Future Work

Simulations in this work have been performed at the design speed of the ships whereas, in reality, the ship speed can vary over the course of a voyage. However, to simulate voyages with varying ship speed, added resistance RAOs are required at multiple ship speeds as ship speed can significantly affect added resistance. As noted earlier, added resistance RAOs are rarely available at speeds other than the design speed. This is probably because it is sufficient to have RAOs at design speed for the assessment of ship in extreme weather conditions. In such cases,

RAOs at design speed can provide a conservative estimate of added resistance even at lower ship speed. However, to move towards efficient operations, accurate added resistance at multiple speeds will be required for the correct estimation of vessel performance considering realistic operating profile. Moreover, along with multiple ship speeds and a broad range of wave lengths, added resistance data will be required for multiple wave headings as well.

The further step in this analysis would be to incorporate an engine model in the simulations so that engine limits can be taken into consideration in different weather conditions. This is because the ship speed is likely to decrease in bad weather due to limited engine power depending on the sea margin. Moreover, considering engine fuel consumption at different loadings will allow us to consider the effect of variation in specific fuel consumption in different weather conditions. Therefore, the effect of different added resistance formulations and differences in RAOs can be measured on fuel consumption instead of energy consumption.

References

1. Lars Larsson, Frederick Stern, and Michel Visonneau, editors. *Numerical Ship Hydrodynamics - An assessment of the Gothenburg 2010 Workshop*. Springer, 2014.
2. Lars Larsson, Frederick Stern, Michel Visonneau, Nobuyuki Hirata, Takanori Hino, and Jin Kim, editors. *Tokyo 2015: A workshop on CFD in ship hydrodynamics*. <http://www.t2015.nmri.go.jp/>.
3. Dong-Min Park, Jaehoon Lee, and Yonghwan Kim. Uncertainty analysis for added resistance experiment of KVLCC2 ship. *Ocean Engineering*, 95:143–156, 2015.
4. Natalija Vitali, Jasna Prpić-Oršić, and Carlos Guedes Soares. Uncertainties related to the estimation of added resistance of a ship in waves. In *3rd International Conference on Maritime Technology and Engineering*, pages 391–400, Lisbon, 2016.
5. Hamid Sadat-Hosseini, Ping-Chen Wu, Pablo M Carrica, Ho Kim, Yasuyuki Toda, and Frederick Stern. CFD verification and validation of added resistance and motions of KVLCC2 with fixed and free surge in short and long head waves. *Ocean Engineering*, 59(0):240–273, 2013. doi: 10.1016/j.oceaneng.2012.12.016
6. Ping-Chen Wu. *A CFD Study on Added Resistance, Motions and Phase Averaged Wake Fields of Full Form Ship Model in Head Waves*. PhD thesis, Osaka University, 2013. doi: 10.18910/26191
7. Mingyu Kim, Olgun Hizir, Osman Turan, and Atilla Incecik. Numerical studies on added resistance and motions of KVLCC2 in head seas for various ship speeds. *Ocean Engineering*, 140:466–476, 2017. doi: 10.1016/j.oceaneng.2017.06.019
8. Min-Guk Seo, Dong-Min Park, Kyung-Kyu Yang, and Yonghwan Kim. Comparative study on computation of ship added resistance in waves. *Ocean Engineering*, 73:1–15, 2013. doi: 10.1016/j.oceaneng.2013.07.008
9. Hamid Sadat-Hosseini, Serge Toxopeus, Dong Hwan Kim, Teresa Castiglione, Yugo Sanada, Mark Stocker, Claus Simonsen, Janne Flensburg Otzen, Yasuyuki Toda, and Frederick Stern. Experiments and computations for KCS added resistance for variable heading. In *Proceeding of the 5th World Maritime Technology Conference*, 2015.
10. Petri Valanto and Yongpyo Hong. Experimental investigation on ship wave added resistance in regular head, oblique, beam, and following waves. In *International*

- Society of Offshore and Polar Engineers*, pages 19–26. International Society of Offshore and Polar Engineers (ISOPE), 2015. doi: 10.1016/j.nucmedbio.2005.08.007
11. Copernicus Climate Change Service (C3S). *ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate*. Copernicus Climate Change Service Climate Data Store (CDS), 2017. <https://www.ecmwf.int/>.
 12. SEAROUTES.COM. <https://www.searoutes.com/>.
 13. SIMMAN 2008. <http://www.simman2008.dk/>.
 14. W J Kim, S H Van, and D H Kim. Measurement of flows around modern commercial ship models. *Experiments in Fluids*, 31(5):567–578, 2001. doi: 10.1007/s003480100332
 15. Vladimir I Krasilnikov. Self-propulsion RANS computations with a single-screw container ship. In *Third International Symposium on Marine Propulsors (SMP'13)*, Launceston, Tasmania, Australia, 2013.
 16. Bhushan Taskar, Pelle Bo Regener, and Poul Andersen. The impact of propulsion factors on vessel performance in waves. In *Proceedings of the Sixth International Symposium on Marine Propulsors (SMP'19)*, Rome, Italy, 2019.
 17. ITTC. Speed and Power Trials, Part 2 Analysis of Speed/Power Trial Data, 2014.
 18. Christian Simon Nielsen. A ship design support tool for estimating added resistance in waves. Master's thesis, Technical University of Denmark, 2015.
 19. Mads Asbjørn Martinsen. An design tool for estimating the added wave resistance of container ships. Master's thesis, Technical University of Denmark, 2016.
 20. Nils Salvesen. Added resistance of ships in waves. *Journal of Hydronautics*, 12(1):24–34, 1978.
 21. Odd Magnus Faltinsen, Knut J Minsaas, Nicolas Liapis, and Svein O Skjördal. Prediction of resistance and propulsion of a ship in a seaway. In *13th Symposium on Naval Hydrodynamics*, pages 505–529, Tokyo, 1980.
 22. Chang-Ho Lee and J Nicholas Newman. WAMIT user manual, version 7.0, 2013. <http://www.wamit.com/manual.htm>.
 23. J Gerritsma and W Beukelman. Analysis of the resistance increase in waves of a fast cargo ship. *International Shipbuilding Progress*, 19(217):285–293, 1972. doi: 10.3233/ISP-1972-1921701
 24. Masashi Kashiwagi. Prediction of surge and its effect on added resistance by means of the enhanced unified theory. *Transactions of West-Japan Society of Naval Architects*, (89):77–89, 1995.