Numerical modelling of the effects of trim on a ship's form factor and viscous resistance

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Abstract

Predicting ship resistance with high accuracy is essential to reduce fuel consumption. An understanding of the factors affecting the resistance of a ship is needed to enable the development of strategies to that end. A well-known way to reduce the resistance is to optimise the trim angle of the ship. However, uncertainty is an obstacle to optimisation as the total resistance can reduce by about the same order of magnitude as the overall modelling uncertainty at full-scale while model-scale approaches suffer scale effects. Understanding the scale effects and devising strategies to account of them is therefore essential. The dependence of form factor on the trim angle is investigated using Reynolds Averaged Navier-Stokes modelling. While trim is known to impact predominantly the wave resistance, its effects on the form factor are less known, which is particularly important for slow ships where the viscous resistance accounts for the vast majority of the total. The present paper demonstrates a drop of 3% in viscous resistance when the ship is trimmed of 2° by bow with a fixed sinkage. The optimal trim angle of 2° is independent of scale effects as we found the same results for $Re = 10^6$ and $Re = 10^8$. The CFD form factor shows a high stability with differences of less than 1% between trim angle of 0° to 3°. The minimum form factor is also found for a trim angle of 2°. Scales effects are, however, observable on the form factor and on the trim moment and vertical force. These scale effects will have an impact on the ship resistance when sinkage and trim will be degrees of freedom.

Keywords: CFD; scale effects; ship hydrodynamics; RANS; double body model; trim optimisation

1. Introduction

In the context of global warming causing an environmental disaster, the IMO (International Maritime Organization) has set a program to reach net-zero greenhouse gases from maritime industry by 2050. To reach this goal, the promising methods are to decarbonize the fuel and to employ energy saving devices and strategies, such as wind-assisted propulsion. Other methods to reduce fuel consumption, central in current research, include the optimisation of the propeller and hull shape or the development of hull anti-fooling coatings. These methods are promising but can be computationally and commercially expensive, particularly if they involve retrofitting. However, other solutions which are operational could help us limit GHG emissions quickly, such as slow steaming and route optimisation. Another widely used, quickly applicable method is trim optimisation. While the main target of trim optimisation is the wave resistance, the trim angle also modifies underwater shape of the hull, and hence, the form factor, leading to changes in fuel consumption. Trim optimisation at model scale has already been studied extensively through computational and potential methods (Coraddu et al., 2017), but Le Strat & Terziev, (2024) demonstrated the existence of scale effects on trimming moment with a double-body model. Assuming trim angle depends linearly on trimming moment, there is a scale effect on trim angle. Then, we must optimize the ship trim angle at full-scale or estimate the scale effects to extrapolate results. Consequently, focus on the optimisation at different scales is crucial to observe these scale effects and understand their proportions.

To extrapolate the resistance of a ship, the ITTC-endorsed approach follows Hughes' form factor, (1+k), dependant solely on the shape of the hull. The total resistance coefficient is then decomposed as $C_T = (1 + k)C_F + C_W$ where C_T, C_F and C_W are the total, frictional and wave resistance coefficients, respectively. The form factor is estimated using a Prohaska test, which involves the towing of a ship at very low speeds where C_w may be neglected (Korkmaz, et al., 2021). Alternatively, Computational Fluid Dynamics modelling may be used in double body mode, that is, where the water surface is replaced by a symmetry plane to eliminate C_w. The present study uses that approach to eliminate the wave resistance.

Knowing the existence of scale effects on trim and sinkage when using Reynolds Averaged Navier-Stokes (RANS) Computational Fluid Dynamics, numerical modelling is carried out with a particular attention to limit scale effects. This paper aims to test the effect of trim angle on the viscous resistance and form factor at different scales. A fixed trim and sinkage of the boat and the use of a double body simulation eliminate the possibility of the observed results being contaminated by secondary effects. Moreover, the use of the CFD form factor reduces the impact of its scale effects on the predictive accuracy of full-scale ship resistance.

2. Background

The dependence of the form factor on the Reynolds number ($Re = VL\rho/\mu$ where V is the ship speed, L is the ship length, ρ=998.561 kg/m^3 is the water density, and μ=8.8875×10^{-4} Pa-s is the dynamic viscosity of water) is well-known from experimental and numerical studies such as García-Gómez (2000), and evidence to suggest a dependence on the Froude number also exists. However, some definitions of form factor are less dependent of scale effects.

It is instructive to examine the approaches to calculate the form factor to explain our choice. In the literature, two definitions of the form factor can be found:

1. $(1 + k) = C_T/C_{F,ITTC}$, that is, the ratio between the total resistance and the frictional resistance obtained through the ITTC correlation line. This is the standard definition adopted by the ITTC.
2. $(1 + k) = C_V/C_{F,CFD}$, that is, the ratio of the viscous and frictional resistances, both of which can be obtained through CFD. This is not an accepted definition despite its similarity to (1).

Regardless their apparent disagreements, both definitions suffer from the same problem. They are in direct contravention to the formal definition of the form factor. That is, neither definition uses a flat plate friction line: (1+k) is defined as the ratio of the ship's total resistance in the absence of waves, and the frictional resistance of a flat plate of equivalent surface area. As all relevant ITTC documents point out, the ITTC57 line is a correlation line and not a flat plate line (Toki, 2008). Even if the original definition of the form factor with reference to a flat plate friction line were to be strictly adhered to, there is no agreement on which equation represents the friction of a flat plate, particularly at high Reynolds number in the region 10^8 – 10^9 where most commercial ships operate.

Scale effects must have some contribution to a ship's dynamic attitude in calm water due to the nature of boundary layers. As discussed in detail by Gourlay & Tuck (2001), the varying thickness of the boundary layer and velocity distribution therein will cause some changes in the pressure at the stern at full-scale relative to model-scale. The magnitude of such changes, however, is not known and likely depends on the shape of the hull. Transom sterns where separation-induced changes are important are more likely to have a stronger scale effect relative to non-transom sterns. A change in trim should then impact the pressure around the hull and the total resistance.

Korkmaz et al., (2023) demonstrated that trim angle does not influence the total resistance the same way depending on the speed of the ship. They used a combined double-body RANS and potential flow method to take wave resistance into account. However, they could not obtain accurate results with the potential flow method. This paper explores how viscous resistance, form factor and sinkage depend on trim angle. Wave resistance is not measured, considering that viscous resistance represents most of the resistance at low speed.

3. Case studies

The KRISO container ship (KCS) is used throughout the present study at the operational Froude number of $F_n = 0.26$, equivalent to 24 knots. The principal characteristics of the KCS are given in Table 1. The Froude number is fixed in all instances to ensure that subsequently obtained results are not subject to variation from dimensionless groups other than the Reynolds number, which is systematically varied. Making use of the KCS also allows the present study to compare form factor estimates across multiple Reynolds numbers derived experimentally and numerically.

Table 1. Principal characteristics of the KCS ship.

Quantity	Symbol	Model-scale	Full-scale	Unit
Scale factor	λ	31.599	1	-
Length	L	7.279	230	m
Beam	B	1.019	32.2	m
Depth	D	0.601	19	m
Draught	T	0.342	10.8	m
Displacement	∇	1.649	52028	m^3
Block coefficient	C_B	0.651	0.651	-
Wetted area with rudder	S_w	9.553	9538	m^2

Reynolds numbers of 10^6 and 10^8 for trim angle between -1° and 3° (a positive trim angle corresponds to a trim by bow) are modelled while maintaining the ship length but altering the viscosity of the water. This is a useful approach to model ship resistance at varying Reynolds number (Haase et al., 2016). To ensure the validity of results obtained by varying the viscosity of water, an additional set of numerical simulations are carried out where the ship is physically scaled to match the same Reynolds numbers (10^6 and 10^8) for a fixed Froude number (F_n =0.26). The resulting test matrix is given in Figure 1.

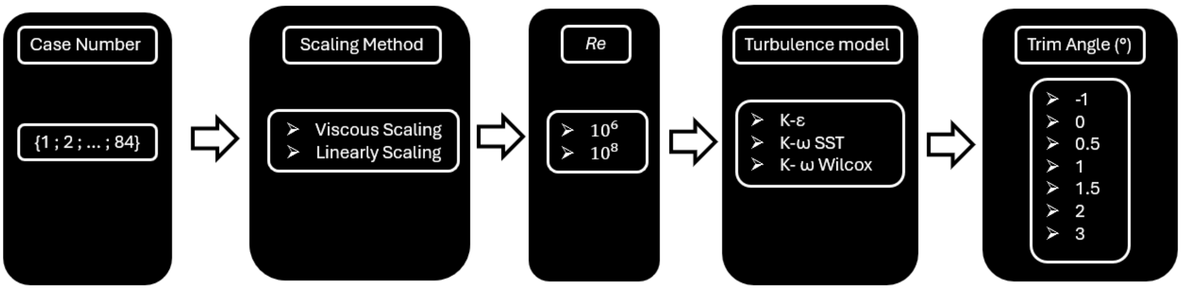


Figure 1: Case studies modelled using viscous scaling to optimise the trim angle

4. Numerical Modelling

The commercially available finite volume solver, Star-CCM+, version 17.04.008 with double precision, was used throughout. The automatic meshing facilities within the solver were employed to create unstructured hexahedral grids on which to solve the Reynolds Averaged Navier-Stokes equations. As discussed previously, employing the double body allows all simulations to be ran in steady state. In addition, ship vertical motions, that is, sinkage and trim, are not modelled. As shown in section 2, sinkage and trim modelling and measurement suffer from considerable uncertainties. The present paper therefore measures the force and moment causing the sinkage and trim which can be predicted with less uncertainty. For simplicity, it is assumed that the ship sinks and trims around its centre of gravity. All discretisation orders are set to 2nd order accuracy.

4.1. Computational domain

The computational domain consists of a rectangular box with dimensions set in multiples of the ship length. In the x direction, the domain inlet is set around 2.5 ship length upstream of the forward perpendicular where the fluid velocity is introduced, while the outlet is placed around 1.5 ship lengths downstream of the aft perpendicular where a pressure outlet maintains 0 pressure. A 0-pressure condition is admissible since in double body mode, gravity is not relevant and therefore not modelled, making the pressure equivalent to the dynamic pressure. The domain side and bottom are placed 2.5 ship lengths from the ship centreline where symmetry plane and velocity inlet conditions are implemented, respectively. Finally, the domain top is placed to match the design draft of the ship. This boundary, along with a plane bisecting the ship are symmetries. These boundary conditions are summarised in Figure 2.

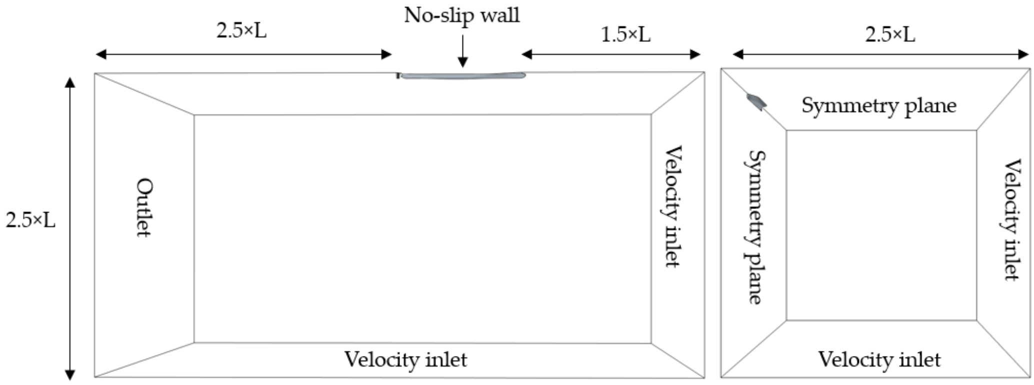


Figure 2. Computational domain dimensions and boundary conditions.

An accurate representation of the resistance of the ship is highly sensitive to near-wall meshing, particularly in double body mode where friction accounts for a vast majority of the total. To ensure consistent results, the methodology given in Terziev et al. (2021a) to construct the mesh is employed. A 3D view of the generated mesh is presented in Figure 3.

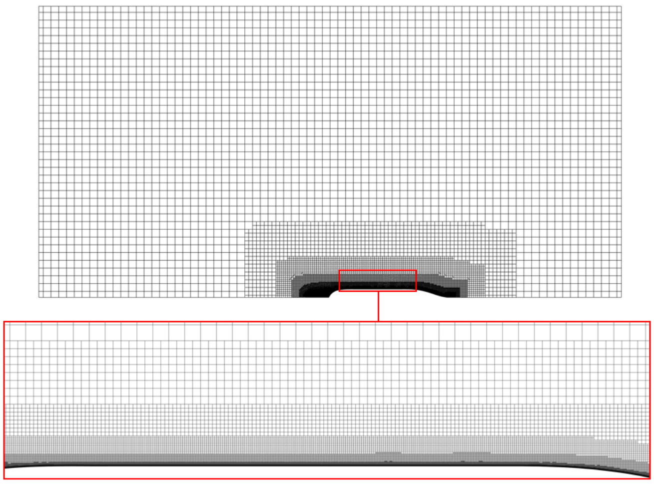


Figure 3. Top view of the generated mesh. Case depicted: mesh around the hull for λ = 10 and $Re = 10^8$.

4.2. Turbulence modelling

Modelling errors, introduced by the choice of turbulence model are handled by employing three widely used turbulence models. Specifically, the realizable k-ε model, the standard k-ω model, and the Shear Stress Transport (SST) model. These turbulence models represent the most widely used turbulence models in ship hydrodynamics and are known to provide robust results.

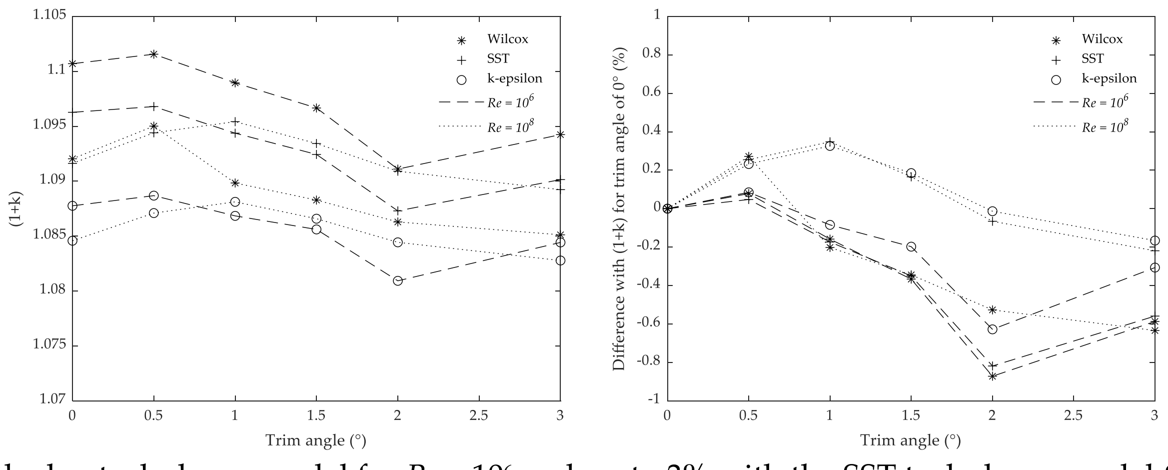
5. Results and discussions

To ensure data from different scale factors can be compared directly, results must be made dimensionless. In the case of resistance, it is known that the viscous resistance, modelled in the present paper through double body simulations, decreases monotonically. That is a phenomenon primarily driven by the reduction in the value of the frictional resistance coefficient with increasing *Re*. In addition, it is known that the viscous pressure resistance coefficient shows a similar monotonic decrease with scale factor. Thus, the three resistance coefficients are all expected to decrease in value. Their definition follows the standard form: $C_{T,F,VP} = R_{T,F,VP}/(0.5\rho SV^2)$, where the subscripts T, F, VP indicate the total, frictional and viscous pressure component respectively. It should be noted that the viscous resistance is treated as the total for the purposes of the present paper. For simplicity, the vertical force (C_S, subscript S to demote sinkage) is made dimensionless using the same procedure which is positive upwards while the trimming moment (C_M) is further divided by the length of the ship ($0.5\rho SV^2L$). The figures come from the viscous scaling simulations but the linearly scaling model showed the similar results.

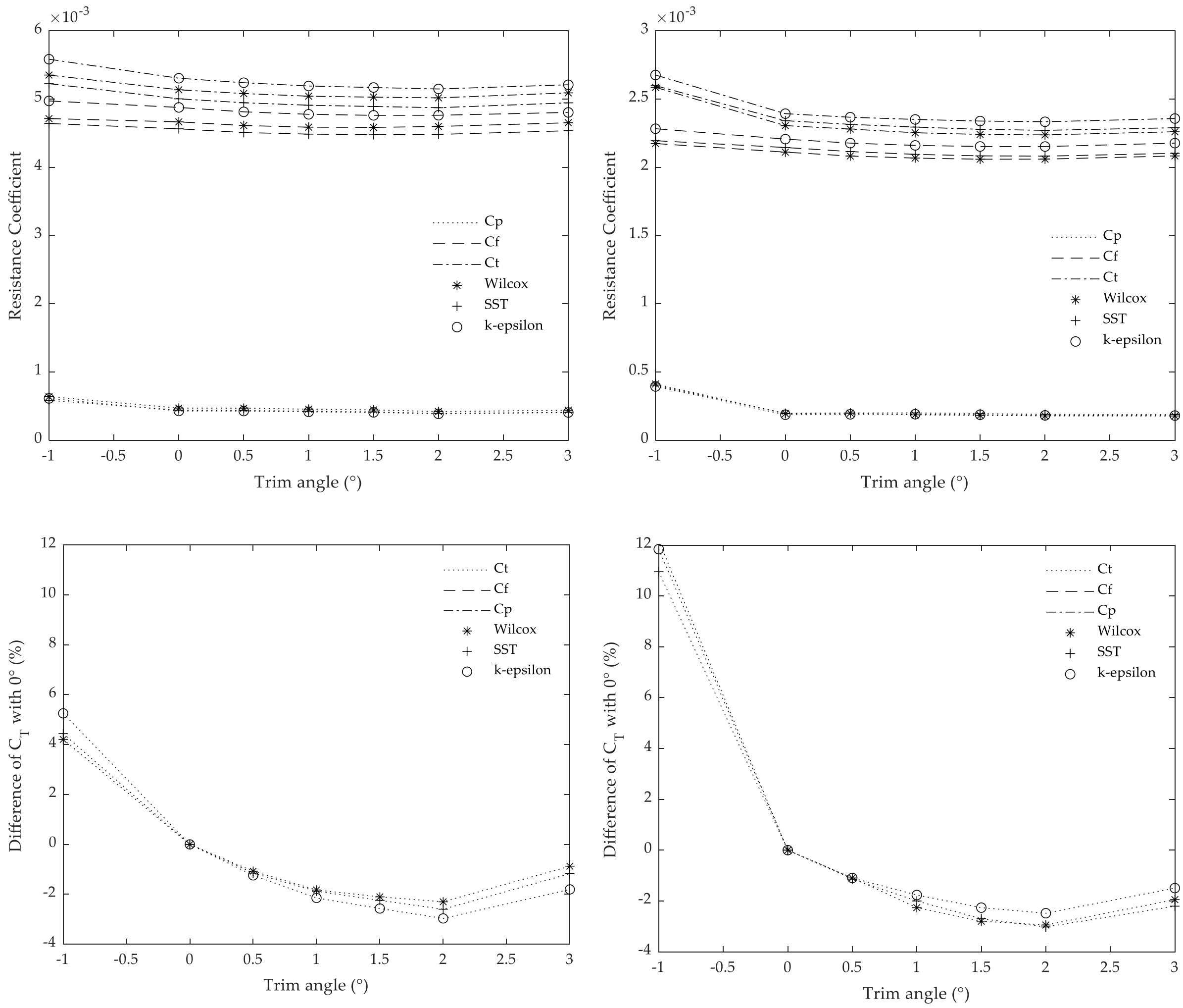
5.1. Trim angle dependence of ship resistance and form factor

To observe the impact of trim angle on the boat consumption, the present study analyses the influence on the different resistance coefficients ($C_t, C_f\ and\ C_p$) and the form factor $(1+k)$. On the

Figure 4, we can observe a spike of the pressure coefficient for a trim angle of -1°. This spike could be due to an inclined boat pushing the water and augmenting the pressure at the bottom of the hull. We will not consider the result for a trim angle of -1° as the total resistance is too high. The difference in total resistance reduces up to 2.97% with



the k-ε turbulence model for *Re* = 10^6 and up to 3% with the SST turbulence model for *Re* = 10^8 when the trim angle is 2°. As trim can be limited on a boat due to loading



restrictions, the output of this study is to trim the ship as much as possible toward 2° for the KCS.

Figure 4 : Influence of trim angle on total, shear and pressure resistances for *Re* = 10^6 on the left and *Re* = 10^8 on the right. The graphs in the bottom highlight the differences with the trim at 0°.

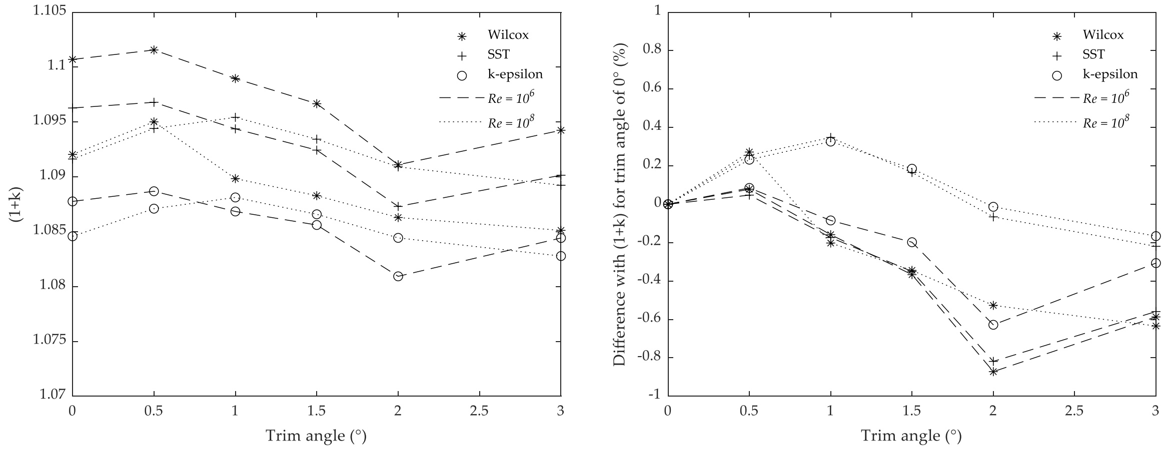


Figure 5 : Trim angle dependence of form factor for *Re* = 10^6 (dashed-lines) and *Re* = 10^8 (dotted-lines)

Unexpectedly, the CFD form factor is near constant when the trim angle varies with the highest variation of 0.87% for a trim angle of 2°. The only difference exists for a trim angle of -1° because of the high value of Cp, which was removed from the results. The form factor is also stable when the scale changes, as demonstrated by Le Strat & Terziev, (2024). CFD-based form factors are therefore not only near-invariant with Reynolds number, but also with trim. This represents a key advantage of using CFD-based form factors as opposed to ITTC-based ones.

5.2. Trim angle dependence of Sinkage variation

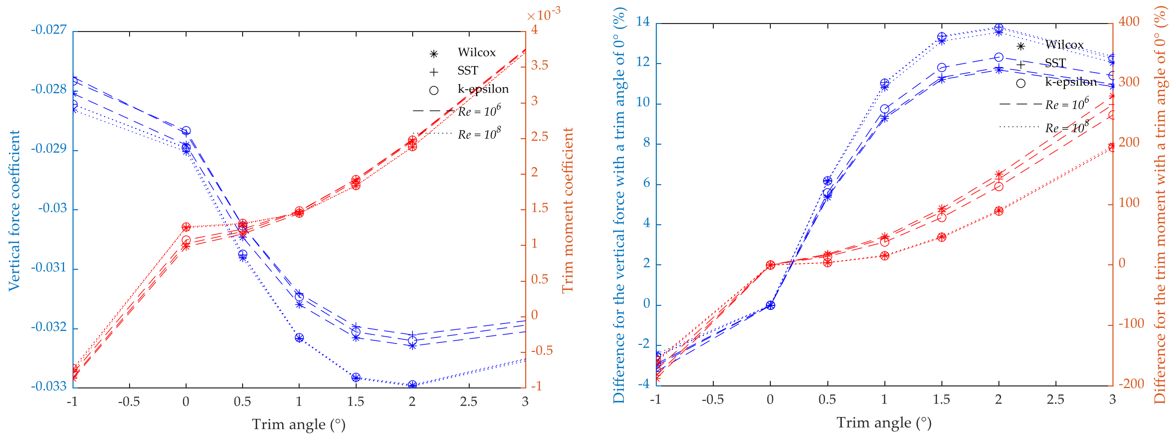


Figure 6 : Vertical force coefficient variation with trim angle for three turbulence models. Dashed-lines represent Re = 10^6 and dotted-lines Re = 10^8.

In this article the sinkage and the trim of the ship were fixed to simplify the simulation. However, by trimming the ship, the vertical force changes and, hence, the sinkage. It is well-known that sinkage will influence the total resistance of the ship. A predictable result can be observed when the ship trims: when the ship trim by the bow, the vertical force coefficient drops and the ship sinkage increases. The direct consequence on the total resistance, however, is difficult to quantify. A future study could focus on quantifying the rise of total resistance when changing the vertical force and the sinkage of the ship. The trim moment coefficient is also changing a lot when the trim angle changes which is normal as trimming the ship require a change in trim moment created by a specific loading. However, a difference between Re = 10^6 and Re = 10^8 can be observed. Therefore, when the trim is not fixed, the boat will not trim the same way at model-scale and at full-scale.

6. Conclusion

In this paper, the impact of the trim angle on a ship viscous resistance was studied. Trim angles between -1° and 3° and *Re* of 10^6 and 10^8 were modelled using three turbulence models to measure the total resistance in double body mode for each case. The results demonstrated that a drop of around 3% in viscous resistance is possible with a trim angle of 2°. Considering the loading conditions, the viscous resistance can reduce if the KCS is trimmed by bow. However, the wave resistance and the sinkage of the boat probably modify these results, reducing the benefits of trimming the ship in terms of viscous resistance. Scale effects on the form factor and total resistance do not give the best trim angle in this study as the same results for the two *Re* modelled were found. Thus, scale effects do not significantly affect the viscous resistance in this sense. Especially, we can note that the CFD form factor is almost constant when changing the trim angle with variations of less than 1%. This confirms the stability and reinforces the utility of the CFD-based form factor.

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References

Coraddu, A., Oneto, L., Baldi, F., & Anguita, D. (2017). Vessels fuel consumption forecast and trim optimisation: A data analytics perspective. In *Ocean Engineering* (Vol. 130, pp. 351–370). Elsevier Ltd. https://doi.org/10.1016/j.oceaneng.2016.11.058

García-Gómez, A. (2000). On the form factor scale effect. In *Ocean Engineering* (Vol. 26). www.elsevier.com/locate/oceaneng

Gourlay, T. P., & Tuck, E. O. (2001). The Maximum Sinkage of a Ship. In *Journal of Ship Research* (Vol. 45, Issue 1). http://onepetro.org/JSR/article-pdf/45/01/50/2231667/sname-jsr-2001-45-1-50.pdf/1

Haase, M., Zurcher, K., Davidson, G., Binns, J. R., Thomas, G., & Bose, N. (2016). Novel CFD-based full-scale resistance prediction for large medium-speed catamarans. *Ocean Engineering*, *111*, 198–208. https://doi.org/10.1016/j.oceaneng.2015.10.018

Korkmaz, K. B., Werner, S., & Bensow, R. (2023). Investigations on experimental and computational trim optimisation methods. *Ocean Engineering*, *288*. https://doi.org/10.1016/j.oceaneng.2023.116098

Korkmaz, K. B., Werner, S., Sakamoto, N., Queutey, P., Deng, G., Yuling, G., Guoxiang, D., Maki, K., Ye, H., Akinturk, A., Sayeed, T., Hino, T., Zhao, F., Tezdogan, T., Demirel, Y. K., & Bensow, R. (2021). CFD based form factor determination method. *Ocean Engineering*, *220*(September 2020), 108451. https://doi.org/10.1016/j.oceaneng.2020.108451

Le Strat, M., & Terziev, M. (2024). A method to observe scale effects on ship sinkage and trim. *Ocean Engineering*, *under review*.

Terziev, M., Tezdogan, T., Demirel, Y. K., Villa, D., Mizzi, S., & Incecik, A. (2021a). Exploring the effects of speed and scale on a ship's form factor using CFD. *International Journal of Naval Architecture and Ocean Engineering*, *13*, 147–162. https://doi.org/10.1016/j.ijnaoe.2020.12.002

Terziev, M., Tezdogan, T., Demirel, Y. K., Villa, D., Mizzi, S., & Incecik, A. (2021b). Exploring the effects of speed and scale on a ship's form factor using CFD. *International Journal of Naval Architecture and Ocean Engineering*, *13*, 147–162. https://doi.org/10.1016/j.ijnaoe.2020.12.002

Terziev, M., Tezdogan, T., & Incecik, A. (2019). A geosim analysis of ship resistance decomposition and scale effects with the aid of CFD. *Applied Ocean Research*, *92*(March). https://doi.org/10.1016/j.apor.2019.101930

Toki, N. (2008). *Investigation on Correlation Lines through the Analyses of Geosim Model Test Results*.