CONFEDERATION OF EUROPEAN MARITIME TECHNOLOGY SOCIETIES

International Conference on Postgraduate Research in Field of Maritime Technology

2021

A SHORT REVIEW OF SCALE EFFECTS IN SHIP HYDRODYNAMICS WITH EMPHASIS ON CFD APPLICATIONS

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SUMMARY

The increased availability of computational resources has transformed the prediction of engineering quantities of interest at the design stage. For ship hydrodynamics, this means analysts are now able to predict the power requirements of a vessel at model-scale with good accuracy, routinely. As ever more intricate analysis methods and tools are developed, it has become apparent that modelling all physical phenomena at full-scale remains unattainable both presently, and in the near future. The difficulty in accounting for the full-scale performance frequently limits analysis to model-scale, causing scale effects. Scale effects arise due to the discrepancy in force ratios a model and the prototype will experience. One main consequence of the presence of scale effects is the difficulty in demonstrating the efficacy of new technologies, such as novel energy saving devices. The naval architecture community is therefore not ready to shed many of the historic assumptions made in the design of vessels. A prime example of this is the hydrodynamic modelling of a ship's full-scale power requirements. Performing solely numerical simulations to obtain such data is considered risky, and is typically accompanied by model-scale experimentation and/or simulations. This work will focus on scale effects encountered when modelling the towed resistance of a ship at model and full-scale. The reasons scale effects are in many cases tolerated, and the problems they may cause are also reviewed. The only remedy to circumventing the presence of scale effects is to work in full-scale at the design stage, but there are a number of problems in doing so. These issues are also explored in this work, with special emphasis on the bottlenecks in adopting full-scale Computational Fluid Dynamics (CFD) numerical simulations as the only prediction tool used in the design process.

1. INTRODUCTION

Historically, the field of naval architecture has relied on a combination of model testing and scaling laws, known as extrapolation procedures, to predict full-scale power requirements. These model-scale experiments aim to represent real-world prototypes and can be used to hone in on a final design while bypassing possible modelling assumptions and simplifications such as the neglect of non-linear phenomena or viscous effects in calculations.

Economic pressures, or the availability of facilities, space, and time frequently result in intentionally small models, which may attract non-negligible differences with respect to the full-scale prototype. These differences can be split into three categories [1]:

1. **Model effects**: a result of incorrect reproduction of geometrical features, flow properties such as turbulence, or wave characteristics.
2. **Measurement effects**: a consequence of dissimilar techniques of data collection between model and prototype. For example, De Rouck et al. [2] report on the influence of measurement location and related uncertainties on wave overtopping predictions.
3. **Scale effects**: a result of disparities in force ratios acting on model and full-scale structures.

In ship hydrodynamics, model and measurement effects are typically considered negligible. Large scale factors cause large scale effects, meaning that a model may not represent a prototype well. Scale effects are therefore a source of considerable uncertainty, negatively impacting the development of technology and innovations that may improve operational performance, such as energy saving devices.

2. RESISTANCE EXTRAPOLATION AND SCALE EFFECTS IN SHIP HYDRODYNAMICS

Scale effects arise due to dissimilarities in force ratios between model and full-scale ships. Assuming one is able to reproduce geometrical and dynamical features correctly, similarity between only two dimensionless groups is necessary: the Foude number and the Reynolds number, shown in Eq. (1) and Eq. (2), respectively:

$$F_n = V/\sqrt{gL} \tag{1}$$

$$Re = VL/\nu \tag{2}$$

where V is the ship speed, g is the acceleration due to gravity, L is the ship length, and ν is the kinematic viscosity. The Froude number represents the ratio of inertial and gravitational forces and is associated with wave making. On the other hand, the Reynolds number indicates the ratio of inertial and viscous forces. Moreover, it serves as an indicator to whether flow is laminar, transitional or turbulent. If a hull is scaled for the purpose of an experiment, the dissimilarity between either F_n or Re is unavoidable for a model and prototype, leading to scale effects.

2.1 EXTRAPOLATION PROCEDURES

There are two widely used approaches to extrapolate resistance from model to full-scale. These are Froude's approach, which splits the resistance into a frictional and residual component, and Hughes' [3] method which splits the total into a form resistance, frictional resistance, and wave resistance. Both approaches rely on knowledge of the total resistance of a model and a friction line, expressing the frictional resistance coefficient as a function of the Reynolds number. When this component is subtracted from the total, according to Froude's approach, the residual component remains constant across all scales for a given F_n, while Hughes retains a constant wave resistance coefficient for a given F_n and form factor (which is F_n and Re independent). The two approaches are shown in Eq. (1) in dimensionless (coefficient) form. In other words, changes in the total resistance coefficient of a ship and its model sailing at the same F_n can be attributed solely to changes in the frictional resistance component.

$$\text{Extrapolation methods} \begin{cases} Froude's\ method\colon C_T = C_F + C_R \\ Hughes\ method\colon \quad C_T = (1+k)C_F + C_W \end{cases} \tag{1}$$

2.1.1 SCALE EFFECTS ON SHIP RESISTANCE COMPONENTS

Until recently, extrapolation procedures are the only tool a naval architect can use to obtain an estimate the full-scale resistance and therefore power requirements of a vessel. It is therefore difficult to overstate their utility in the absence of alternative methods. However, as soon as extrapolation procedures were devised, conceptual and practical problems emerged. For example, it is known that no component of ship resistance remains constant for varying Reynolds numbers. In deep waters, the form factor increases with Re at a monotonically decreasing rate [4]. Thus, a 'terminal form factor' exists, which ceases changing with increasing Reynolds numbers. Each submerged shape has a unique form factor, which is estimated by via a Prohaska test, where the hull is towed slowly to eliminate C_W from Eq. (1). When combined with a friction line and the measured total resistance, one can obtain the form factor $(1+k)$.

However, the Prohaska test is plagued by uncertainties [5], making the derivation of this parameter non-trivial. There are also other problems, such as the procedure's inapplicability for hulls with submerged transom. Another difficulty lies in predicting the form factor's rate of change with Reynolds number (the scale effect) and the Reynolds number at which the so-called terminal form factor has been reached since. Both of these are thought to also be unique for each hull. Finally, there are outstanding questions with regards to turbulence stimulation in experiments, and Froude number effects on the form factor [6], [7].

The wave resistance coefficient suffers from similarly many problems. Waves are known to interact and modify the boundary layer of a ship meaning that wave resistance depends on the Froude and Reynolds number [8], [9]. This is in direct contravention to Froude's hypothesis and affects both extrapolation procedures, since C_R contains C_W in Eq. (1). Moreover, C_R contains the viscous pressure resistance component, which has not only eluded analytical description [10], but also suffers from scale effects itself [6]. Further problems arise when one considers that the International Towing Tank (ITTC) correlation line already contains a form factor in its derivation. Both extrapolation procedure require a 'flat plate' friction line to be used in the prediction of C_F, but correlation allowances are not calibrated for a flat plate line – they are calibrated for the ITTC line, which is by definition, not a flat plate line.

In summary, extrapolation methods are highly useful because they are the only engineering laws one can use to estimate the performance of a hull at full-scale. However, there are a plethora of problems associated with their application, meaning that correlation allowances are necessary to absorb the indeterminate magnitude of scale effects introducing considerable uncertainty in the final prediction. This has profound consequences for the meeting of IMO criteria to reduce greenhouse gas emissions from shipping because uncertainty constrains innovation and may lead to sub-optimal choices at the design stage.

3. COMPUTATIONAL FLUID DYNAMICS

The past few decades have seen explosive growth in the use of CFD methods based on Navier-Stokes equations. This has allowed the honing of techniques and procedures to predict ship resistance at model-scale [11]–[13]. In large part, these efforts were helped by the existence of benchmark geometries and high-quality validation data. A prime example is the KCS hull, which has been subject to numerous experiments [14]–[17]. This has allowed the research community to determine the best practice approaches for modelling ship hydrodynamics at model scale, although it could be argued that further improvements in robustness are necessary.

While model-scale predictions are largely routine, the identification of full-scale procedures and practices has not yet advanced sufficiently. If and when naval architects are able to provide robust and reliable results from full-scale numerical simulations, innovative designs and devices will emerge, improving overall performance. There are two main bottlenecks in the routine application of full-scale ship CFD, but as will become apparent subsequently, these can be reduced to a single problem – the availability of computational power.

3.1 TURBULENCE MODELLING AND GRID NUMBERS

Ships typically operate at high Reynolds numbers where turbulence plays an important role in determining local and global properties of the flow. At present, eddy-viscosity models (also referred to as closures) are widely used in estimating ship resistance at model and full-scale. However, to enable design that makes use of the flow properties, one must understand how structures (the hull, or energy saving devices) interact with the turbulent wake. Since energy saving devices operate in the viscously-dominated area of the flow, they suffer from considerable scale effects. Thus, full-scale numerical simulations where at least part of the turbulent kinetic energy spectrum is resolved are necessary. One popular approach is Detached Eddy Simulation (DES), which enforces a Reynolds Averaged solution provided by an eddy-viscosity model near walls, and switches to Large Eddy Simulation (LES) in the free-stream. Such simulations are highly useful, because they can resolve energetic eddies without resorting to the cell numbers required for LES, estimated at 10^9~10^{12} for full-scale applications [18]. The proportion of the turbulent kinetic energy spectrum resolved by DES increases with grid refinement, but taken to its limit at a cell size of $\Delta x \to 0$, DES will not converge to Direct Numerical Simulation (DNS) where all eddies are resolved. This is because DES requires an eddy-viscosity boundary layer.

On the other hand, approaches such as Partially Averaged Navier-Stokes (PANS), or Scale Resolved Hybrid (SRH) simulations can be truly adaptive and converge to DNS, but these have not yet been widely used in the field. This introduces some uncertainty, because the optimum set-up and choice among the available options is yet unknown. Increased automatic adaptability, be it for turbulence modelling, time stepping, or grid refinement, is likely to rapidly improve confidence and robustness of predictions. This will also enable a greater number of users to obtain accurate numerical predictions, improving access, tapping into a greater pool of talent, and accelerating innovation.

Provided one has decided on a suitable turbulence modelling strategy, the near wall grid is one of the key outstanding choices. There are two approaches in this respect: resolving the viscous sublayer (corresponding to $y^+ < 5$) and using wall functions (corresponding to $y^+ > 30$). It is usually desirable to resolve the viscous sublayer, since the use of wall functions carries additional assumptions. Grid resolution below $y^+ = 5$ is usually recommended for scale resolved simulations [19]. However, examples of full-scale ship hydrodynamics with corresponding y^+ values are rare. This is because of the scaling of grid requirements with Reynolds number. If the same number of near-wall layers were used for a model and full-scale simulation, the resulting y^+ would vary by a factor $\lambda^{1.35}$, with λ being the scale factor [20]. Assuming a λ of 50 and y^+ of 1 at model-scale gives $y^+ \approx 200$ if one simply scales the grid with λ. Reducing the wall-normal direction only is not always advisable, since high cell aspect ratios may cause divergence.

In full-scale, current evidence suggests that allowing y^+ to exceed 1,000 is not as problematic as it is in model scale. In fact, such grids have been shown to provide essentially identical results as grid with much lower y^+ [21]. To some extent, this alleviates the problem of computational power availability, but it does not remove it altogether.

3.2 PRESENT STATE AND ACHIEVEMENTS OF FULL-SCALE SHIP CFD

Full-scale ship CFD has been practiced for more than two decades. Yet the accuracy of such predictions are not considered robust. Since all energy saving devices either operate within the boundary layer or wake of a vessel, scale effects can have a profound impact on performance. Moreover, potential savings from such devices are typically in the same order of magnitude as scale effects. The work of the ITTC (International Towing Tank) Specialist Committee on CFD and EFD Combined Methods [22] in popularising scale effects and the underlying problems has stimulated research in this area resulting in a substantial body of literature on the topic [5], [8], [23], [24]. Similarly, workshops on full-scale ship hydrodynamics are key to determining the best practices in modelling to improve predictions.

3.2.1 THE 2016 LLOYD'S REGISTER FULL-SCALE SHIP HYDRODYNAMICS WORKSHOP

Representatives 15 countries came together in November 2016 with the aim of building confidence in full-scale ship CFD during a workshop organised by Lloyd's Register [25]. This international effort was the first numerical modelling workshop to focus exclusively on full-scale ship hydrodynamics. More importantly, it provided data for validation, which is extremely rare and usually proprietary. This has historically meant that full-scale research is not able to provide validation. For example, recent studies in full-scale ship hydrodynamics use geometries or data that are not accessible to other researchers [26], [27]. In this sense, the Lloyd's Register data is a potential game changer and the plan of further full-scale trials are particularly welcome.

The Lloyd's Register report reveals a large spread of results and adopted approaches. For example, some participants did not model the free surface and opted for a double body method, while others modelled the superstructure and its corresponding wind resistance. Similarly, some modelled sinkage and trim, while others did not. This likely contributes to the relatively large spread in predictions. The results of this report are in a sense similar to the early ship hydrodynamics workshops where model-scale results were examined. However, the achievements of some participants, who attained comparison errors within 3% should not be minimised.

One of the participants who achieved high accuracy summarised their work in a white paper on full-scale ship hydrodynamics [20], where it was highlighted that experienced users can provide robust results. Reliance on experience and presently available numerical modelling techniques may be adequate for highly experienced users, but it will not enable a sufficiently rapid transition to routine high-quality full-scale ship CFD. For this reason, increasingly adaptive solvers are necessary. For example, adaptive meshing, time marching and turbulence modelling.

4. CONCLUSIONS

It is difficult to overstate the value of robust full-scale ship resistance predictions. Achieving routine, high-quality numerical simulation at large Reynolds numbers will enable advances in energy efficiency and help ship owners or operators meet increasingly strict local and international standards. A prerequisite to this is the sufficient reduction of uncertainties to demonstrate the efficacy of energy saving devices in validated, full-scale operational conditions.

Additionally, once full-scale ship CFD becomes more established, the field of ship hydrodynamics will move on from tolerating and correcting for scale effects. Some of the key conditions necessary to enable this transition include the increased availability of computational power and the implementation of increasingly adaptive numerical set-ups to unlock CFD for a greater number of users. However, the most critical condition is the availability of openly available high-quality datasets for validation purposes. This is the main bottleneck at present, and if not resolved, it will continue to restrict confidence in full-scale simulation with knock-on effects on innovation and energy efficiency achievements.

REFERENCES

[1] V. Heller, “Scale effects in physical hydraulic engineering models,” *J. Hydraul. Res.*, vol. 49, no. 3, pp. 293–306, 2011, doi: 10.1080/00221686.2011.578914.

[2] J. De Rouck, J. Geeraerts, P. Troch, A. Kortenhaus, T. Pullen, and L. Franco, “New results on scale effects for wave overtopping at coastal structures,” in *Proceedings of the International Conference on Coastlines, Structures and Breakwaters*, 2005, pp. 29–43.

[3] G. Hughes, “Friction and form resistance in turbulent flow and a proposed formulation for use in model and ship correlation,” *Trans. Inst. Nav. Arch.*, vol. 96, no. April, 1954.

[4] K.-S. Min and S.-H. Kang, “Study on the form factor and full-scale ship resistance,” *J. Mar. Sci. Technol.*, vol. 15, pp. 108–118, 2010, doi: 10.1007/s00773-009-0077-y.

[5] K. B. Korkmaz *et al.*, “CFD based form factor determination method,” *Ocean Eng.*, vol. 220, no. September 2020, p. 108451, 2021, doi: 10.1016/j.oceaneng.2020.108451.

[6] M. Terziev, T. Tezdogan, Y. K. Demirel, D. Villa, S. Mizzi, and A. Incecik, “Exploring the effects of speed and scale on a ship’s form factor using CFD,” *Int. J. Nav. Archit. Ocean Eng.*, vol. 13, pp. 147–162, 2021, doi: 10.1016/j.ijnaoe.2020.12.002.

[7] A. M. Ferguson, “Factors affecting the components of ship resistance. PhD Thesis,” University of Glasgow, 1977.

[8] M. Terziev, T. Tezdogan, and A. Incecik, “A geosim analysis of ship resistance decomposition and scale effects with the aid of CFD,” *Appl. Ocean Res.*, vol. 92, no. March, 2019, doi: 10.1016/j.apor.2019.101930.

[9] A. Shahshahan and L. Landweber, “Interactions between wavemaking and the boundary layer and wake of a ship model,” no. May, 1986.

[10] A. Gotman, “Residual resistance of displacement vessels,” *J. Mar. Sci. Eng.*, vol. 8, no. 6, 2020, doi: 10.3390/JMSE8060400.

[11] T. Hino, F. Stern, L. Larsson, M. Visonneau, N. Hirakata, and J. Kim, *Numerical Ship Hydrodynamics: An Assessment of the Tokyo 2015 Workshop*, vol. 49, no. 0. 2020.

[12] L. Larsson, F. Stern, and M. Visonneau, *Numerical Ship Hydrodynamics: An assessment of the Gothenburg 2010 Workshop*. Springer, 2014.

[13] L. Larsson, F. Stern, V. Bertram, and V. Bertrami, “Benchmarking of Computational Fluid Dynamics for Ship flows: The Gothenburg 2000 Workshop,” *J. Sh. Res.*, vol. 47, no. 1, pp. 63–81, 2003.

[14] E. Shivachev, M. Khorasanchi, and A. H. Day, “Trim influence on KRISO container ship (KCS); an experimental and numerical study,” in *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*, 2017, pp. 1–7, doi: 10.1115/OMAE2017-61860.

[15] K. Elsherbiny, T. Tezdogan, M. Kotb, A. Incecik, and S. Day, “Experimental analysis of the squat of ships advancing through the New Suez Canal,” *Ocean Eng.*, vol. 178, no. November 2018, pp. 331–344, 2019, doi: 10.1016/j.oceaneng.2019.02.078.

[16] C. D. Simonsen, J. F. Otzen, S. Joncquez, and F. Stern, “EFD and CFD for KCS heaving and pitching in regular head waves,” *J. Mar. Sci. Technol.*, vol. 18, no. 4, pp. 435–459, 2013, doi: 10.1007/s00773-013-0219-0.

[17] S. J. Lee, H. R. Kim, W. J. Kim, and S. H. Van, “Wind tunnel tests on flow characteristics of the KRISO 3,600 TEU containership and 300K VLCC double-deck ship models,” *J. Sh. Res.*, vol. 47, no. 1, pp. 24–38, 2003.

[18] M. Liefvendahl and C. Fureby, “Grid requirements for LES of ship hydrodynamics in model and full scale,” *Ocean Eng.*, vol. 143, no. March, pp. 259–268, 2017, doi: 10.1016/j.oceaneng.2017.07.055.

[19] R. Spalart, “Young-Person’s Guide Simulation Grids Detached-Eddy,” no. July, 2001.

[20] M. Peric, “White paper: Full-scale simulation for marine design,” *Siemens White Pap.*, 2019.

[21] L. Eca and M. Hoekstra, “On the application of wall functions in ship viscous flows,” *Mar. 2011 - Comput. Methods Mar. Eng. IV*, pp. 585–604, 2011.

[22] ITTC Specialist Committee on CFD and EFD Combined Methods, “The Specialist Committee on CFD and EFD Combined Methods Final Report and Recommendations to the 29th ITTC.” 2021, [Online]. Available: https://ittc.info/media/9098/sc-combined-cfd-efd-methods.pdf.

[23] M. Terziev, T. Tezdogan, and A. Incecik, “A numerical assessment of the scale effects of a ship advancing through restricted waters,” *Ocean Eng.*, vol. 229, no. April, p. 108972, 2021, doi: 10.1016/j.oceaneng.2021.108972.

[24] A. Dogrul, Y. H. Ozdemir, S. Sezen, and B. Barlas, “Uncertainty Assessment and Self-Propulsion Estimation of Duisburg Test,” no. 2012, pp. 829–843.

[25] D. Ponkratov, “Lloyd’s Register workshop on ship scale hydrodynamics,” in *2016 Workshop on Ship Scale Hydrodynamic Computer Simulation*, 2016, no. April, p. 2016, doi: 10.1002/ejoc.201200111.

[26] H. Mikkelsen, M. L. Steffensen, C. Ciortan, and J. H. Walther, “Ship scale validation of CFD model of self-propelled ship,” *Mar. 2019 Comput. Methods Mar. Eng. VIII*, pp. 718–729, 2019.

[27] W. Sun, Q. Hu, S. Hu, J. Su, J. Xu, and J. Wei, “Numerical Analysis of Full-Scale Ship Self-Propulsion Performance with Direct Comparison to Statistical Sea Trail Results,” *J. Mar. Sci. Eng.*, vol. 8, no. 24, pp. 1–22, 2020.