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Estimation of a Ship's Nominal Wake Fraction Through Full-Scale Speed Trials

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Abstract

A ship's nominal wake fraction is a key parameter in the design of the marine propulsion system, i.e. the the marine propulsor and main engine. Determination of the wake fraction is commonly done through empirical formulas and / or based on model-scale experiments. However, a discrepancy exists between the model- and full-scale estimation results because of the way scaling is applied. Speed trials are conducted to estimate the full-scale nominal wake fraction. Results show the ability of the developed speed-trial methodology to provide an initial estimation of the full-scale nominal wake. However, comparison between the empirical, model-scale, and full-scale results fails to provide conclusive results. No real insight into the validity of the estimated full-scale nominal wake fraction could be established. However, the applied methodology is deemed to have value but additional research is required before further conclusions can be drawn.

Introduction

Modern day ships and marine vehicles are, for the large majority, equipped with propulsion systems operating behind a ship or vehicle's hull [2]. The performance of the propulsion system will be directly affected by the ship in front of it, and vice versa the behaviour of the ship is affected by the propeller running behind it's hull [4]. The ship's hull and propulsion system will thus affect each other, referred to as 'hull-propeller interaction', a phenomenon which has three distinct effects on the overall combined performance of the propeller and ship. The three effects are described by Ghose [4] as follows:

1. The ship's hull disturbs the flow in which the propeller operates, resulting in the propeller experiencing a non-uniform flow field. The average flow velocity of the non-uniform flow field will be different from the ship's velocity and the term 'wake fraction' is used to characterise the observed velocity difference.
2. The propeller alters the pressure and velocity distribution around the hull, thereby increasing the total ship resistance. The resistance increase is for practical reasons substituted by a decrease in the thrust generated by the propeller and labelled as 'thrust deductions'.
3. The propeller efficiency operating behind the hull will be different when compared to a propeller operating in open water, i.e. operating in a flow not-affected by a hull shape. The 'relative rotative efficiency' is used to describe the ratio between both efficiencies.

Currently, the first effect is studied and mainly the (scaling) difference in estimation results between different methodologies is of interest. As mentioned before, the nominal wake fraction of a ship w characterises the mean velocity in which a ship's propeller operates. The nominal wake fraction, $w = \frac{v - v_a}{v}$, relates the actual ship speed v to the mean velocity experienced by the propeller v_a as operating behind the ship.

The origins of the nominal wake fraction, i.e. the difference between both velocities, can be found in three aspects or causes [4, 1], breaking down the wake into three components: the potential / streamline wake, the viscous / frictional / boundary layer wake, and the wave wake.

- Potential / streamline wake: the ship's shape and flow around it converges into the propeller plane, resulting in a lower velocity at the place of the propeller compared to the ship's velocity.
- Viscous / frictional / boundary layer wake: the formation of a boundary layer along the hull of the ship as the ship moves through the water will influence the velocity of the flow entering the propeller.
- Wave wake: the stern wave system, and the occurrence of a wave crest or through is present at the ship's stern, will have a significant effect on the flow velocity experienced by the propeller.

Appropriate estimation and understanding the effect of a ship's wake is considered of key importance for the accurate design of the entire marine propulsion system, i.e. the marine propulsor and main engine selected to power a ship [3]. The nominal wake fraction is responsible for a shift of the force coefficients between open-water and behind hull conditions. The observed shift has to be accounted for in the design of the propulsion system, i.e. the propeller and main engine, as it will effect the overall efficiency. Determination of the nominal wake fraction however cannot be achieved through direct measurements of the flow velocity at the propeller location.

The nominal wake fraction can be determined through comparison between model-scale open water and behind hull test results (both experimental and numerical work) or using empirical formulas. Yet model-scale experiments are conducted at equal Froude numbers resulting in a discrepancy in Reynolds numbers between model and full-scale [3]. The Reynolds number difference presents itself in the form of a relative difference between boundary layer thickness of the model and full-scale ship, and thus a different effective wake because the viscous / frictional / boundary layer wake component will be different. Scaling of the model results is thus necessary to allow for full-scale propeller design. However, little is known about the relation between the model and full-scale nominal wake fraction (denoted as w_m and w_f, respectively), as well as about the effectiveness of different wake scaling methods, full-scale wake measurements, and empirical formulas.

The ITTC special committee report on wake scaling [3] reviewed scaling methods, the potential of performing full-scale nominal wake simulations, and the use of geosim models. Scaling methods are classified in four categories: scaling using simple methods, scaling through CFD methods, corrections of the measured wake field with CFD results, and boundary layer derived wake scaling methods. None of the common scaling methods, however, have been widely accepted and the recent developments in CFD have opened new methods to gain insight into the full-scale wake. In theory, full-scale simulations should be straightforward but the lack of full-scale validation data restricts the confidence in the results of such simulations. Geosim models, finally, require a series of models to be both geometrically and hydrodynamically similar, which is not easily achieved.

In the current research, a methodology to estimate the full-scale nominal wake fraction of a ship is developed and investigated. The estimation method is based on full speed trials on MV *Bluefin* (shown in figure 1) and results are compared to experimental model-scale estimation results of the same ship. Additionally, a brief comparison of empirical wake estimations is used to further investigate the observed results. MV *Bluefin* is a training and research ship, owned and operated by the Australian Maritime College, University of Tasmania. A series of speed trials was undertaken, providing measurements of the fuel consumption and main engine loading in order to determine the most efficient propeller and engine conditions. In the first section of the paper, the general idea and methodology behind the model-scale experiments and empirical calculations is discussed briefly. A extended discussion of the full-scale methodology, including outline of the speed-trials and analysis of the test procedure, is presented next. Finally, the full-scale nominal wake fraction is estimated and results are analysed, compared, and discussed before summarising the most important findings in the concluding remarks.

Figure 1: MV *Bluefin*

Empirical and Model-Scale Methodology

Empirical Formulas

Empirical formulas to estimate the nominal wake fraction, either developed based on regression analysis or the plotting of historical model and / or full-scale data, can provide a useful and powerful tool in early design stages. Carlton [2] lists four formulae (by Schoenherr [6], Taylor [7], and Harvald [5]) for the estimation of the full-scale nominal wake fraction. The empirical formulas, which vary in complexity, make use of various ship parameters and derived hydrostatic coefficients. More information and discussion on the estimation formulas can be found in the references and in the results section.

Model-Scale Experiments

Model-scale experiments provide a lot of opportunities for the testing of marine vehicles that are not available in full-scale. One such, is the possibility to conduct open-water propeller and self-propulsion experiments, which together can be used to estimate the wake fraction of a ship design.

The model-scale experiments (1/20th scale) were conducted by undergraduate students of the Australian Maritime College as part of a unit on resistance and propulsion. For the experiments the 100m long AMC towing tank is used, equipped with a manned variable speed carriage. The tests were conducted with the model fixed in all degrees of freedom under the carriage (no relative motion allowed) and without the presence of waves present. The open-water data (1/10th scale) was provided by another series of experiments conducted as part of the same unit. Based on the 'thrust-identity', the nominal wake fraction can be estimated. Using the 'thrust identity', the velocity at which the self-propulsion thrust is generated is compared to the velocity needed to reach that same thrust value in the open-water condition [4]. A similar procedure can be applied using torque measurements, i.e. a 'torque-identity', but is not considered here.

The outlined procedure was applied to self-propulsion tests at three different pitch settings, with the open-water curves available for the same three pitch settings. Results of the model-scale wake estimation are presented, discussed, analysed, and compared in the results section of the paper.

Full-Scale Experiments / Speed-Trials

Speed-Trials Outline and Procedure

The speed-trials are conducted on board of MV *Bluefin*, using only readily available equipment and systems. MV *Bluefin* has, over the past decades, been used by hundreds of students and staff members of the Australian Maritime College, University of Tasmania to investigate on-board marine systems, deploying offshore marine mooring systems, conducting speed-trials, and much more. MV *Bluefin* has an overall length of 34.5 $[m]$, a beam of 10.0 $[m]$, and a draft of 4.4 $[m]$ (displacing 550 $[tonnes]$). Equipped with a Caterpillar 3512B (820 Brake $[kW]$) and a 4-bladed controllable pitch propeller (diameter of 2.2 $[m]$ and a gear ratio of 4.94 $[-]$), MV *Bluefin* has a range of approx. 2500 nautical miles at a cruise speed of 10.5 $[kn]$.

The test procedure is based on previously conducted speed-trials and developed in consultation with the ship's master, the helmsmen and the chief-engineer of MV *Bluefin*. Important to note is the fact that the test program depended heavily on the real-life capabilities of the ship, as mentioned before, as well as conditional limitations. Additionally, the test program was related back to available experimental data as much as possible to allow for the later comparison study.

The test program of the speed trials included twelve runs, conducted at four different engine rotational speeds (n_{eng} = 900, 1000, 1100, and 1200 $[rpm]$) and three different propeller pitch settings (P/D = 60, 80, and 100 $[\%]$). The original test program was extended with three 'double' runs, to allow for the determination of the trial uncertainty (conducted at 1200 $[rpm]$ for all pitch settings), additional / intermediate runs were proposed but could not be conducted due to time and fuel-usage restrictions.

Each run was conducted in a straight-line, over a period of five minutes, in front of Cape Barren Island, Tasmania, Australia. After every run, the new settings were applied, the ship was given the time to settle into the new state and once deemed settled, a new measurement was started. The runs were conducted in two different directions, with two double runs conducted in the same direction and one in opposite direction to allow for necessary (tide) corrections to be applied. Additional discussion and comments on the test schedule, procedure, and data collection methods are found in the following sub-sections.

Data Variables and Data Logging

The data variables were logged and recorded manually during the trials as no direct, continuous logging equipment was available on-board. Four categories of data variables were recorded: space-time variables (date, start-stop time, start-stop GPS location, and heading angle), velocity variables (velocity through water and velocity over ground), performance variables (fuel consumption, engine load and boost pressure), and environmental variables (minimum water depth and true wind speed / direction. Except for the space and time variables, all variables were logged every minute during the five minute (including start, resulting in six data points per test condition).

The performance variables need some additional discussion. First, the fuel consumption (fc) specifies the average consumption of fuel during the trials expressed in litres per hour. Second, the engine load is measured as a percentage of the maximum continuous rating (MCR) and defines the maximum power able to be generate by the engine continuously under normal conditions over the course of a year. Finally, the engine boost pressure (p_{boost}) describes the pressure forcing air into the engine (essential to burn fuel in an internal combustion engine).

Test Condition Analysis and Data Processing / Corrections

Speed trials will be affected by a wide range of environmental aspects (logged for exactly those reasons). Proper consideration needs to be given to those aspects before any validity can be given to the results of the trials, as they can drastically affect the ship's performance (as discussed by various ITTC regulations). The sea state, water depth, wind, tidal forces, and hull smoothness and roughness are all considered and discussed.

The sea state could not be measured directly and was visually determined and confirmed based on crew experience. During the trial, the sea state was estimated to be between 4 and 5 (moderate to rough), which is less than ideal for the current purposes. Measurements of the water depth recorded water depths consistently larger than 20 [m] and were monitored to avoid shallow water effects, i.e. the water depth influencing the ship performance. The measured water depths meant shallow water effects could be disregarded as a minimum water depth of 19 [m] was calculated based on the maximum ship velocity (ITTC guidelines). A maximum wind speed of 5 Beaufort, or 17-21 [kn], is allowed before corrections are recommended (for ships smaller than 100 [m]). The conditions during the trial were not ideal, as seen in sea state, and wind speeds recorded were consistently between 20 and 30 [kn]. Corrections however were deemed unnecessary as conditions were consistent over the trials and the performance is only examined on a relative basis for the current trials. The tide and tidal forces needed to be included in the results analysis as they will affect the observed measured flow velocities. Using the double runs (and the omni-directional trials) the effect of the tide is established, with the tide to be approximated at 0.75 [m/s]. Finally, the effect of the hull smoothness and roughness was considered minimal, as the last anti-fouling treatment was applied as recently as February 2017.

From the discussion above, it can be concluded that the full-scale trials were conducted in less than ideal, but constant conditions for all trials. Again, the fact needs to be stressed that the trials were conducted during 'regular' operation of the ship, without causing major disruptions to its planned voyage. The main crux behind the current work is investigating if there is merit in the current procedure to provide insight into the full-scale wake. When proven valid, the same methodology can easily be implemented on a larger series of ships, for which model-scale data is available, and as such contribute to a wider investigation into the scale effect of the wake estimation.

Full-Scale Data Analysis

As mentioned before, data on the velocity and performance of the ship is collected during the speed-trials. The collected data has to be converted and manipulated in order to be able to estimate the full-scale nominal wake fraction, and then compare this to the model-scale and empirical estimation results.

The full-scale data analysis is done in three parts. First, the raw data is analysed and corrected with regard to the trial repeatability, the environmental conditions, and the difference between performance parameters. Second, the data is converted to determine the achieved efficiency under the applied conditions, which includes a correction for the difference in achieved final ship velocity. The efficiency η is determined by relating the fuel consumption fc, measured in [l/h], to the achieved and corrected velocity over ground v_{sog}, is expressed in [km/l], and calculated as follows $\eta = \frac{v_{sog} \cdot 3.6}{fc}$. Finally, the actual full-scale nominal wake fraction is estimated. The estimation of the full-scale nominal wake fraction takes advantage of the capability of the propeller to change the blade pitch. Based on the results the optimal, most efficient blade pitch angle can be determined, and more importantly the advance ratio $J = \frac{v_{stw}}{n \cdot D}$ at which this optimum is achieved can be derived (using the velocity through water v_{stw}, the propeller rotational speed n, and propeller diameter D). A similar procedure can then be applied to the available open-water curves to determine the corresponding optimal open-water advance ratio at the chosen pitch point (avoiding the discrepancy in Reynolds vs Froude scaling discussed in the introduction). The full-scale nominal wake fraction is now calculated using the two advance ratios, $w_f = 1 - \frac{J_O}{J_f}$ (analogous to the wake definition) with the full-scale advance ratio J_f and the open-water advance ratio J_O. The applied method could be referred to as the 'pitch-identity' in analogy to the model-scale methods (discussed earlier) as it applies a similar principle.

Results

Raw Data and Corrections

The first analysis of the data consisted of plotting of the performance parameters against the input variables, i.e. as a function of the applied propeller pitch for the different engine rotational speeds. Figure 2 shows the initial results for the fuel consumption results and very consistent behaviour was observed for all three measured performance variables. Only the fuel consumption is plotted here as it is the performance parameter used to define the efficiency. The results show significant but expected increases in the fuel consumption as both the engine speed and propeller pitch is increased.

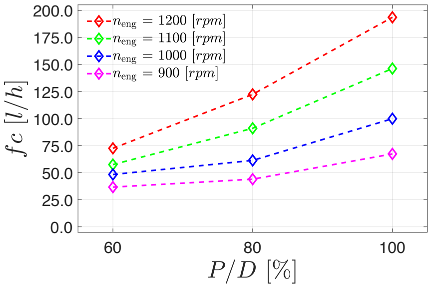

Figure 2: Raw data performance results (fuel consumption).

Additionally, analysis of the raw data showed very little variation during each measurement, with a maximum spread of less than 5% of the mean values to be used in further calculations. The overall repeatability, based on analysis of the double runs, was shown to be consistent and, as discussed before, a tidal correction of 0.75 [m/s] was measured and applied to the measured over the ground ship velocities (and thus the efficiency calculations). In figure 3, the measured fuel consumption is corrected against the corrected speed over ground, as will be used to calculate the resulting efficiencies. For future calculations the achieved velocity at a certain engine and propeller setting is of major importance. Figure 3 shows a wide range of achieved velocities (majority around the 4.5 [m/s]), and thus corrections need to be applied to be able to compare efficiencies.

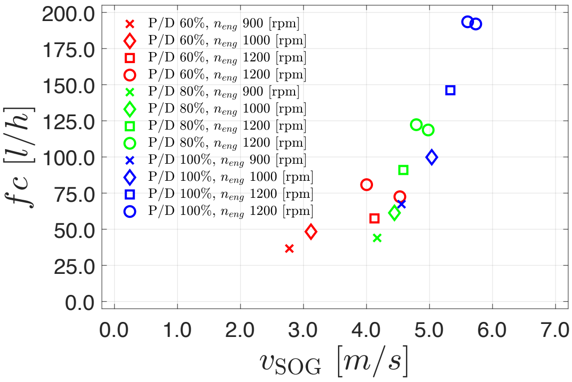

Figure 3: Fuel consumption vs uncorrected velocity.

Efficiency Calculations

In figure 4, the achieved and corrected efficiencies are plotted for the different engine rotational speeds as a function of the propeller pitch. The corrections applied are based on the assumption that a ship's resistance and thus fuel consumption has a cubed relationship to the ship's velocity (and that the fuel consumption at zero forward speed is equal to zero). The impact of the applied corrections is reduced as much as possible through the use of 4.5 $[m/s]$ as reference value, seen discussed before.

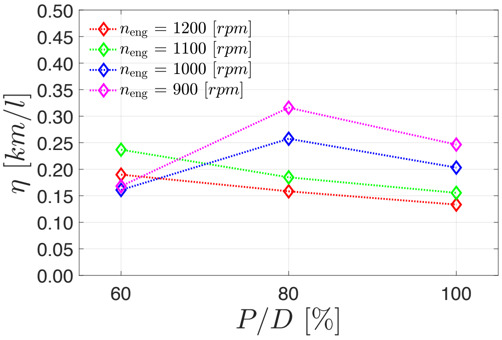

Figure 4: Efficiency vs pitch ratio (corrected).

From figure 4, two conclusions can be drawn. First of all, the two highest engine speeds do not achieve an optimum pitch ratio withing the current tested pitch range and will not be considered further. Second and most importantly, the lower engine speeds show very similar behaviour, present the ability to calculate an optimal pitch ratio, and will both be used for further estimation of the full-scale nominal wake fraction.

Full-Scale Nominal Wake Fraction Estimation

Using the cubic regression of the efficiency results presented in the previous sub-section, the full-scale optimal pitch ratio is estimated to be 83.2 $[\%]$ at an advance ratio of 0.624 $[-]$. In combination with the available open-water data, the corresponding open-water advance ratio is determined through a regression of the peak values of the known pitch ratios and established to be equal to 0.588 $[-]$. The full-scale nominal wake fraction is then estimated using both advance ratios and estimated at 0.06 $[-]$.

Comparison of Nominal Wake Fraction Estimations

The final estimation results are presented for comparison in table 1. First, it needs to be noted that the model-scale results fail to predict a consistent value for the nominal wake fraction over the applied test conditions, as can be observed from the large range of predicted values. Second, one can observe that the applied empirical formulas provide a fairly consistent estimation of the nominal wake fraction for all three formulas. Most importantly however, the full-scale estimation is approx. three times lower than the empirical values. Based on the current results, it is close to impossible to draw a meaningful conclusions on the predicted full-scale estimation result because of the aforementioned reasons. A more thorough analysis of both the model-scale results and the full-scale methodology is needed before any further work can be undertaken.

Method	Nominal Wake Fraction, $w\ [-]$
Model-Scale	-0.10 – 0.20
Schoenherr [6]	0.16
Taylor [7]	0.18
Harvald [5]	0.18
Full-Scale	0.06

Table 1: Comparison of nominal wake fraction estimations.

Concluding Remarks

A methodology to estimate the full-scale nominal wake fraction of a ship, based on full-scale speed trials and a 'pitch-identity', was developed and investigated. The speed trials were conducted during regular ship operation and using on-board available equipment only. The methodology proved its potential to estimate the full-scale wake fraction, however comparison with both empirical and model-scale results warranted further investigation before further conclusions can be drawn.

Future work should include different aspects, looking at all aspects of the current work. First of all the estimated range of the model-scale results should be investigated and potentially reduced. Second, the speed trials should be repeated and ideally extended to determine the accuracy of the predicted optimum used as basis for the full-scale wake estimation. Third, the assumptions and limits of the empirical formulas should be investigated to determine where the discrepancy between the estimation results originates from. Finally, a more general recommendation can be made concerning the potential of the outlined novel methodology. When applied on a wide range of ships, a database of prediction results could be developed providing a practical method to investigate the nominal wake fraction and the associated scaling effect.

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