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# A CFD-based scaling approach for ducted propellers

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ABSTRACT

This paper addresses the problem of scale effect on the open water characteristics of ducted propellers. Based on systematic CFD calculations performed at different Reynolds numbers, a scaling approach is proposed for practical use. A controllable-pitch propeller working within two ducts of different design-the standard Duct 19A, and an innovative duct concept Innoduct10 proposed by Rolls-Royce, have been considered as the main target cases. Scale effects predicted on the pressure and friction components of propeller thrust and torque coefficients and duct thrust coefficients are compounded into a component-based scaling procedure using individual scaling functions. While the principal focus has been on the range of operation conditions from trawling to free-sailing, other critical conditions such as bollard and high advance coefficients are also discussed. The same propeller is also studied in open conditions (without duct) in order to understand the difference in the mechanisms underlying scale effects between ducted and open propellers. The applicability of the developed scaling approach is discussed using two different propulsor cases. The scaling procedure can be used to obtain the full scale open water diagram for ducted propellers from the results of open water tests conducted in model scale, without the need for new CFD computations in each case. Although the use of the developed scaling method on the test propeller shows good results, more test cases should be added before the scaling method can be recommended for general use.



## 1. Introduction

The most popular device for marine propulsion is the screw propeller. Depending on the operational advantages, different types of propellers have been developed including conventional open propeller, ducted propeller, podded propeller etc. Once a particular propulsion system is chosen in the ship design process, the propeller design is performed based on systematic series data, or using a propeller design tool for given operation conditions behind the ship hull. While the propeller design procedure takes into account corrections for full scale Reynolds number, it is still essentially based on model scale data as regards ship hull wake, propulsion factors and open water characteristics. The open water tests and self-propulsion tests are then performed to verify propeller design and give ship performance prediction. At the same time, the flow characteristics over the ship hull and propulsion system in full scale are different from those in model scale, due to the differences in the boundary layer which occur with the increase in Reynolds number. The force and moment coefficients of a full scale propeller are in general different from the coefficients measured in the model test. In order to calculate the full scale characteristics an appropriate scaling method has to be applied to the model scale values. Such a method should ideally take into consideration the effects of changes in flow characteristics on the propulsor performance.

Considering ducted propellers, there is a knowledge gap regarding the understanding of mechanisms underpinning scale effects, which need to be addressed in order to devise an effective scaling approach. The present work aims to expand the knowledge base regarding the nature and magnitude of scale effects on ducted propellers by investigating the changes in the pressure and friction components of the blade and duct forces. This is very important for a ducted propeller system where the changes in these individual components, influenced by the scale effect on the induced velocity, add to or counteract each other in the observed total scale effect. The dependencies of each pressure and friction component are discussed in details, and the respective scaling functions are developed. Further, for the same propeller, but operating in open condition, i.e. without duct, the scale effects are investigated, and a comparison study is presented between open and ducted operation conditions. Finally, a stepwise scaling procedure is proposed, which uses the scaling functions to extrapolate the propeller and duct force coefficients. The applicability of the

Abbreviations: CFD, Computational Fluid Dynamics; RANSE, Reynolds-averaged Navier-Stokes equations; MRF, Moving Reference Frame; SM, Sliding Mesh

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**Nomenclature**

| | |
|---|---|
| $n$ | Propeller rotational speed [Hz] |
| $D$ | Propeller diameter [m] |
| $R$ | Propeller radius [m] |
| $L_D$ | Duct length [m] |
| $V$ | Advance speed in open water [m/s] |
| $J$ | Advance coefficient ($V/nD$) dimensionless] |
| $\upsilon$ | Kinematic viscosity of water [$m^2/s$] |
| $\rho$ | Density of water [$kg/m^3$] |
| $T_D$ | Duct thrust [N] |
| $T_P$ | Propeller thrust [N] |
| $T$ | Total thrust [N] |
| $Q$ | Propeller torque [N m] |
| $K_{TP}$ | Propeller thrust coefficient ($T_P/\rho n^2 D^4$) [dimensionless] |
| $K_{TD}$ | Duct thrust coefficient ($T_D/\rho n^2 D^4$) [dimensionless] |
| $K_{T\_Tot}$ | Total thrust coefficient ($K_{TP}+K_{TD}$) [dimensionless] |
| $K_Q$ | Torque coefficient ($Q/\rho n^2 D^5$) [dimensionless] |
| $C_{TH}$ | Thrust loading coefficient ($8T/\rho\pi D^2 V^2$) or ($8K_{T\_Tot}/\pi J^2$) [dimensionless] |
| $\eta_O$ | Open water efficiency ($JK_T/2\pi K_Q$) [dimensionless] |
| $C_{0.7}$ | Chord length of propeller blade at 0.7$R$ [m] |
| $Re_{0.7}$ | Reynolds number based on blade chord length at 0.7$R$ $\left(\sqrt{(0.7\pi nD)^2+V^2}\times C_{0.7}/\upsilon\right)$ [dimensionless] |
| $C_p$ | Pressure coefficient $[(P-P_0/0.5\rho(nD)^2, \quad P_0=0]$ [dimensionless] |
| $C_f$ | Skin-friction coefficient $[\left[\tau_w/0.5\rho(nD)^2, \tau_w\text{-wall shear}\right]$ [dimensionless] |
| $V_D$ | Duct velocity $\left(\sqrt{1+8K_{TP}/\pi J^2}\times V\right)$ [m/s] |
| $Re_D$ | Reynolds number based on duct length ($V_D\times L_D/\upsilon$) [dimensionless] |

procedure is tested with two different propulsor configurations. For a propeller designer, this method can provide the open water characteristics for a ducted propeller at higher Reynolds numbers given the open water diagram obtained from model tests.

In the following section, reviews of previous studies on ducted propellers, and the development of propeller performance scaling methods in general are presented. Next, the specific cases investigated in this study and the methodology used are discussed, followed by the main results. A detailed investigation of the integral and component scale effects are presented, culminating into the development of a scaling approach. Finally, the applicability of the developed method is discussed with suitable comparisons, and some concluding remarks are made on the present study including some future possibilities.

## 2. Background

### 2.1. Ducted propellers

Ducted propellers, first conceptualized by Stipa (1931) and Kort (1934), are often installed on the vessels for which the requirements of high thrust are critical in the low speed operation range. The flow characteristics over the entire ducted propulsion system are governed by strong duct-propeller interaction.

Earlier investigations by Dyne (1977) regarding scale effects on propulsion factors of ducted propellers are based on model tests, and full scale measurements, and point to the separation over the duct as an important factor. The paint tests performed by Kuiper (1981) and Falcão de Campos (1983) show that the flow patterns over a particular propeller blade and the duct depend on both the Reynolds number and loading conditions. The domain of boundary layer transition over a propeller blade varies with the propeller loading, and this feature is more prominent at lower Reynolds number, where a greater extent of laminar zone is observed in model scale (Bhattacharyya et al., 2016). The complexity of the interaction mechanisms, affected also by vortex shedding and separation effects, demands for a high fidelity method to be used for the assessment of the magnitudes of scale effect on ducted propellers. Based on extensive RANSE computations it was concluded in the works of Abdel-Maksoud and Heinke (2002) and Krasilnikov et al. (2007) that the scale effects on the characteristics of ducted propellers depend on propulsor geometry (duct type and blade design) and loading conditions. The effective advance coefficients of a propeller working inside a particular duct depends on the flow acceleration provided by that duct, which would depend on the duct profile. The duct thrust was found to always increase in full scale. A reduction in the propeller thrust and torque coefficients was registered in full scale. The reduction in propeller torque was found to be larger compared to what is usually predicted for an open propeller under equivalent conditions. Bhattacharyya et al. (2016) presented very similar observations based on the same cases as investigated in the present work. The performance and scaling of ducted propellers can also be addressed by calculating the nozzle flow rate and using pump efficiency and loss coefficients, as presented by Bulten and Nijland (2011).

In the present study, the open water tests are performed with the propeller operating inside the duct. This conforms to the second extrapolation method proposed by Stierman (1984) that considers the nozzle as a part of the propulsion unit.

### 2.2. Propeller performance scaling methods

A variety of scaling methods has been proposed to address the problem of scale effect on marine propellers at different levels. Lerbs (1951) developed a scaling method for the blade force coefficients based on the concept of 'equivalent profile'. This profile is a representative section of the propeller blade, for which the model scale frictional drag coefficient $C_D$ found from the results of open water tests is corrected to obtain the full scale value based on the commonly used proportional dependency of $C_D$ on the friction coefficient of flat plate. The section pressure drag and lift are assumed unaffected by Reynolds number, while they are considered dependent on angle of attack and profile shape. The full scale values of propeller thrust and torque coefficients are computed from the model scale values multiplied by respective factors which include inverse fineness of the equivalent profile (Re dependent) and inductive advance ratio (Re independent). The Lerbs method was implemented in the work by Meyne (1968) to extrapolate to full scale conditions the open water characteristics of the B-series propellers, and subsequently has become a popular scaling approach in many institutions. The method of equivalent profile conceptually similar to the Lerbs method is employed in some of the potential propeller codes to account for viscosity, and hence Reynolds number effect on propeller characteristics, for example as described in Krasilnikov et al. (2006). The methods of this group are based on the extrapolations derived from systematic viscous flow calculations over 2D profiles. They consider the effect of Reynolds number on both the drag and lift, but necessitate the use of propeller code. One of the most widely used scaling approaches