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Scale Effects on a 4-Bladed Propeller Operating in Ducts of Different Design in Open Water

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ABSTRACT

This paper presents a comparative analysis of scale effects on the open water characteristics of a moderately skewed 4-bladed controllable pitch propeller operating inside three ducts of different design. Two standard ducts- Duct 19A and Duct 37 were chosen, along with an innovative duct concept Innoduct10, which is proposed by Rolls-Royce and which belongs to the group of so-called high-lift ducts. Model scale open water tests at different propeller speeds were performed to study the effect of Reynolds number on the propeller and duct thrust, propeller torque, and open water efficiency. CFD calculations were performed using the RANS solver of STAR-CCM+ at both model and full scale conditions for a range of advance ratios and blade tip loading conditions. It has been observed that scale effects on the open water characteristics are essentially in the same range for all duct designs in spite of certain differences in the local flow patterns at the leading and trailing edges of the ducts.

Keywords

Propeller, duct, scale effect, open water characteristics

1 INTRODUCTION

The estimation of propeller open water characteristics in full scale is frequently based on model scale experiments, where some scaling procedures are applied to the measured thrust and torque values. For a ducted propeller, one of the most important factors influencing scale effect is the propeller-duct interaction at different Reynolds numbers, in addition to the influences due to flow separation and vortex shedding. Hence, the simple methods devised for scaling of open water characteristics of open propellers are not directly applicable for ducted propellers. Further, due to complexities of interactions and dependency on specific geometries of propeller and duct, it has been difficult to arrive at a universal scaling approach for ducted propellers. In most of the model basins today, the scaling of model scale open water thrust and torque values for a ducted propeller are based on previous database, and correlation with the results of full scale trials, or not scaled at all. The aim of this work is a systematic study of scale effects on ducted propellers using ducts of different design, and variable blade tip loading which can form a basis for the development of a practical scaling approach.

The study is based on both model scale open water tests, as well as CFD calculations in both model and full scales. All the CFD simulations presented here have been performed using the commercial software STAR-CCM+ provided by CD Adapco. From the operational point of view for ducted propellers, four advance ratios are chosen for the scale effect study: the bollard condition (J=0), the trawling condition (J=0.2), a medium advance ratio (J=0.4), and the free sailing condition (J=0.6). The effect of blade tip loading has also been studied using a higher (0.91) and a lower (0.65) value of pitch factor (P_f) = P(1.0R)/P(0.7R), in addition to the design value of 0.82. Duct design influences the flow pattern around duct and inflow on propeller, and hence plays an important role in the interaction mechanism. A comparison of three ducts regarding scale effects is made based on CFD calculations. Open water tests at different propeller speeds have been conducted to understand the effect of Reynolds number in the range where model tests are conducted, and to provide data for CFD validation.

For the powering prediction for ships fitted with ducted propellers, three extrapolation methods proposed in Stierman, 1984, which have been discussed in the proceedings of the Specialist Committee on Unconventional Propulsors of the 22nd ITTC (ITTC, 1999) are presently used. The second method, which considers the nozzle as a part of the propulsion unit has been followed in our work, where open water tests are performed with the propeller operating inside the duct.

CFD investigations of ducted propeller characteristics have widely been carried out using the RANS method along with isotropic turbulence models, one of the most common being the SST k-ω model *(Menter, 1994)*. Scale effects on open water characteristics of a ducted propeller had been investigated by *Abdel-Maksoud and Heinke (2002)*, using a Wageningen Ka 5-75 propeller fitted with a Duct 19A. The

nozzle thrust increased at high Reynolds numbers, and its change was found dependent on the flow pattern around the nozzle, which in turn, depends on thrust loading coefficient. The Reynolds number effect on propeller characteristics was found manifested in a reduction of the propeller torque coefficient, higher than that commonly seen on open propellers, and also a reduction of propeller thrust coefficient. *Krasilnikov et al. (2007)* presented a similar study, using a hybrid mesh generation technique for the steady RANS analysis of the series Ka propellers operating in different duct designs, including Duct 19A, Duct 24 and a generic duct with lifted trailing edge. For all cases, the duct thrust was found to increase in full scale, the scale effects being more pronounced at lighter propeller loadings. It was concluded that different ducts may result in different flow pattern changes with varying Reynolds number, and ultimately to different magnitude of scale effect on propulsor characteristics, even with the same propeller.

Consequently, a scaling approach for ducted propellers should take into consideration the flow physics at different propeller loadings and different Reynolds numbers in order to result in adequate changes in thrust and torque coefficients with scale.

2 EXPERIMENTS AND CFD ANALYSES

A 4-bladed controllable pitch propeller has been investigated within three different duct designs. The open water tests and CFD calculations were performed at the design pitch ratio of 1.236.

2.1 Propeller and Duct Designs

The details of the target propeller are presented in Table 1. The propeller with the Duct 19A is shown in Fig. 1. The length/ diameter ratio for ducts is 0.5. The three duct profiles are shown in Fig. 2.

Table 1: Details of the propeller

Number of Blades	4
Blade Area Ratio	0.64
Hub Ratio	0.269
Pitch ratio at r/R = 0.7	1.236
Tip pitch factor	0.65, 0.82 (design), 0.91

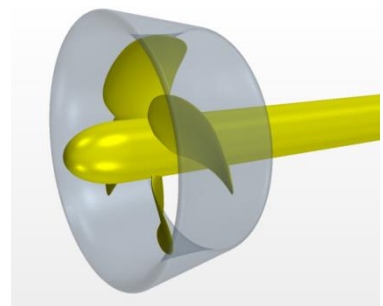

Fig. 1: Propeller with Duct 19A

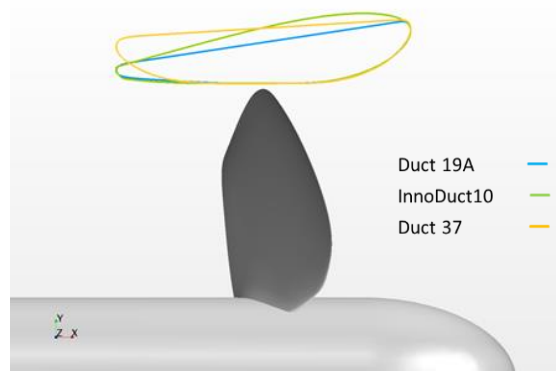

Fig. 2: Profiles of the three ducts

2.2 Open Water Tests

The open water tests have been performed at the large towing tank at MARINTEK. The test program included force measurement for propeller in Duct 19A and Innoduct10 and paint tests at variable propeller RPS. Earlier the same propeller was tested in Duct 19A and Duct 37 at China Ship Scientific Research Center (CSSRC). Only the results of force measurements at the highest RPS of 15 [Hz] are used in the present work for comparisons with CFD calculations in model scale.

2.3 CFD Simulations

CFD calculations have been done in both model and full scales using the RANSE solver of Star-CCM+. The full scale propeller has a diameter of 20 times the model propeller, while propeller RPS was scaled according to the Froude number identity. In order to ensure a consistent comparison, both the model and full scale simulations were performed on topologically similar meshes using the low Reynolds near wall modelling (wall y+ <5) for all scales. The boundary layer on propeller blades and duct was resolved using 20 prism cell layers, while polyhedral cells were used in the rest of the computation domain. Based on a preliminary study (Bhattacharyya and Krasilnikov, 2014), it was observed that the turbulence model (k-ω-SST, k-ε-Realizable and RSM linear pressure strain models were used) had minor effect on the calculated thrust and torque values in open water. The k-ω-SST turbulence model was chosen for the present scale effect study. Both the steady

(Moving Reference Frame) and unsteady (Sliding Mesh) approaches are investigated for the CFD study. In most of the operation range (J=0.2 to 0.6), the steady approach has been found to provide satisfactory results, in comparison to values obtained from model tests. At the bollard condition, where the speed of advance is close to zero, the unsteady approach becomes necessary as the steady flow assumption does not hold true due to flow re-circulation phenomena in the outer domain. In the present study, scale effects are calculated in the typical operation range using the steady approach. Here, a rotating coordinate system fixed with the propeller is used to solve the incompressible 3D RANS equations. The setup uses only one fluid region corresponding to one blade passage with periodicity boundaries, whose rotational motion is considered in the rotating reference frame. Appropriate wall boundary conditions take into account relative motion of propeller with respect to stationary duct. The setup is shown in Fig. 3.

Fig. 3: CFD simulation setup (MRF, steady)

3 RESULTS AND DISCUSSIONS

In Figs. 4-7, relative differences- Δ=(FS-MS)/MS*100%, between the full scale and model scale values of open water thrust and torque coefficients obtained from CFD computations are presented in bar diagrams. These results correspond to the case of design tip pitch factor P_f=0.82. The duct thrust coefficient- K_{TD} (Fig. 4) shows increase in full scale for about 4% at bollard to about 14% at free sailing conditions. The magnitude of scale effects for the three studied ducts is quite similar. Propeller thrust coefficient- K_{TP} (Fig. 5) decreases in full scale at all advance coefficients. This decrease is rather small, and it does not exceed 1.5%. This tendency is different from what one can observe for open propellers, where propeller thrust increases in full scale due to the increase of lift and reduction of drag of blade section at higher Reynolds numbers. However, when propeller operates inside the duct, the duct produces higher flow acceleration in full scale, and the effective J value for propeller increases, resulting in lighter loading. Another important influence comes from the pattern of the trailing edge flow that affects the expansion rate of propulsor slipstream.

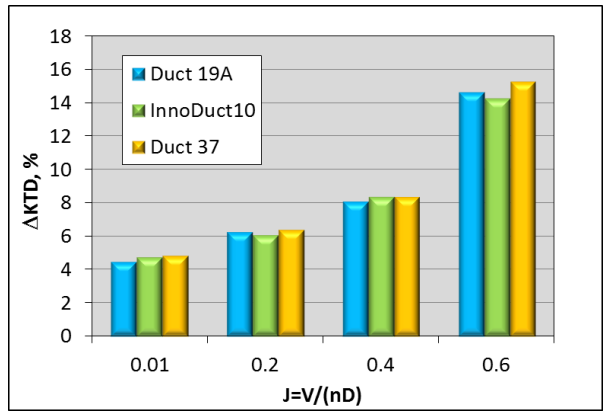

Fig. 4: Scale effects on duct thrust

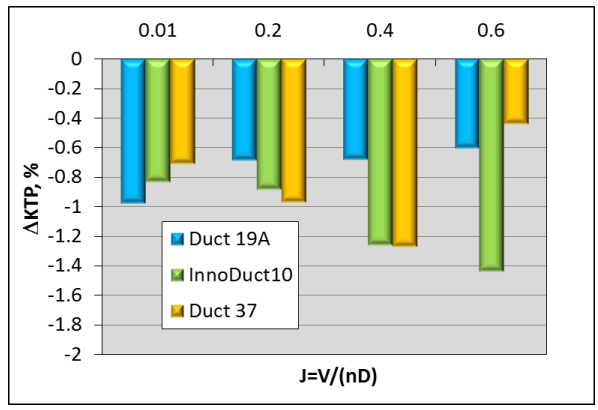

Fig. 5: Scale effects on propeller thrust

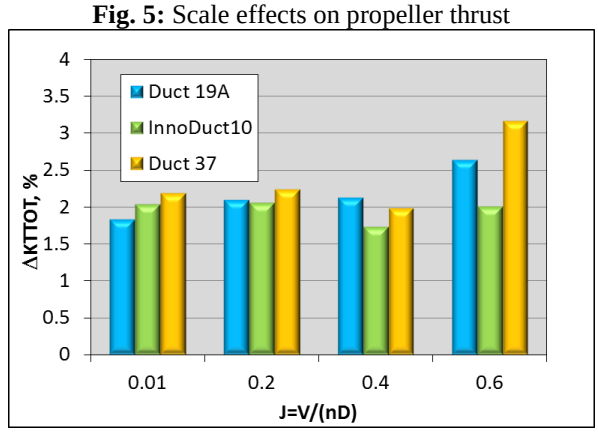

Fig. 6: Scale effects on total thrust

In terms of total thrust coefficient- $K_{T,TOT}$ (Fig. 6), the aforementioned changes result in increase of about 2-3% in full scale conditions. The increase of total thrust in full scale shows little dependence on loading, since at higher J values, where the duct thrust increases the most, its contribution in total thrust is smaller.

For propeller torque coefficient- K_Q (Fig. 7), one observes decrease in full scale, which is larger than it is usually observed for open propellers under equivalent loading

conditions. The reason is again found in higher flow acceleration produced by the duct in full scale. The change in propeller torque with Reynolds number shows weak dependence on loading, increasing only slightly at higher advance coefficients. The above findings regarding thrust and torque variation with scale are in agreement with the results presented in earlier referred works by *Abdel-Maksoud and Heinke (2002)* and *Krasilnikov et al (2007).*

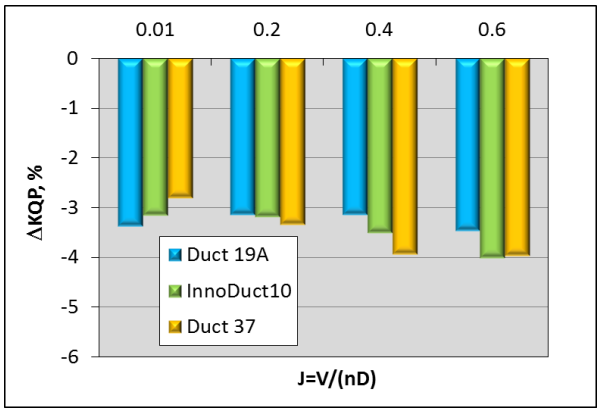

Fig. 7: Scale effects on propeller torque

The analysis of pressure and friction components shows that scale effect on duct thrust is mainly caused due to the change in the pressure component which makes it dependent on propeller loading. For propeller torque, the friction component has been found to have a greater relative contribution in scale effect, and it is less loading dependent.

In relative terms, this change is larger at higher J values, where duct thrust increase is greatest, but at those operation conditions of lighter loading the absolute contribution from duct to the total inflow velocity on propeller is smaller.

Comparing the numerical results with model test data, one can see that, duct thrust values for the three ducts are very well predicted by CFD calculations. This comparison is illustrated in Fig. 8.

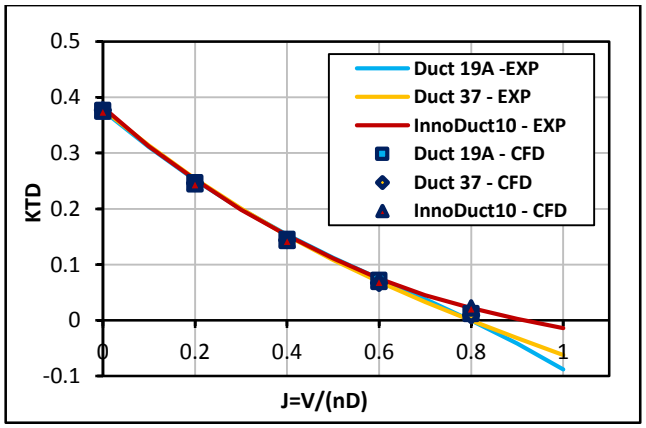

Fig. 8: Duct thrust comparison: Model test and CFD

One can notice that the main differences in duct thrust between the three ducts take place in the range of light loading operation, around and behind the point of maximum efficiency. These differences are primarily related to flow separation on the exterior side of the duct, downstream of the leading edge.

In order to estimate the sensitivity of the numerical analyses to duct design, differences in thrust and torque produced by the same propeller operating in Innoduct10 and Duct 37 compared to Duct 19A have been examined. Figs. 9 and 10 show consistent trends observed between the experimental and numerical predictions. This gives sufficient confidence that the interaction mechanisms between duct and propeller are well reproduced by the CFD simulations.

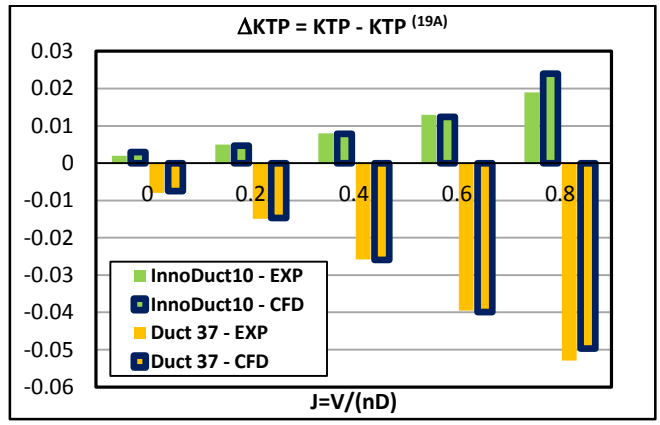

Fig. 9: Comparison of thrust difference with Duct 19A

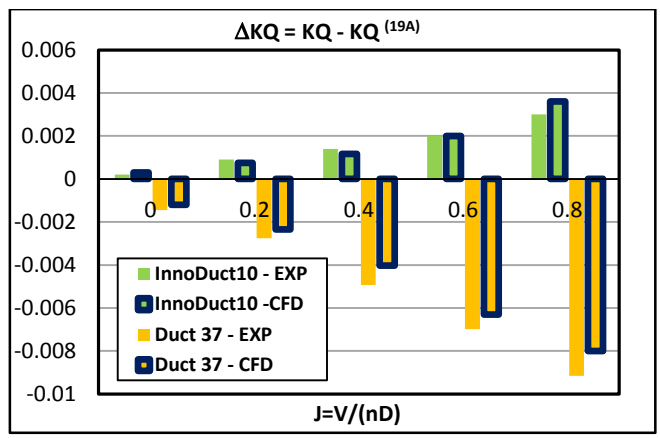

Fig. 10: Comparison of torque difference with Duct 19A

The blade tip loading, defined by the tip pitch factor P_f is an important design parameter for a ducted propeller. The magnitudes of scale effect found at the higher (0.91) and lower (0.65) values of P_f have been compared to those found at the design value (0.82) for propeller with the Duct 19A and Innoduct10. The comparisons are presented in Figs. 11-16.

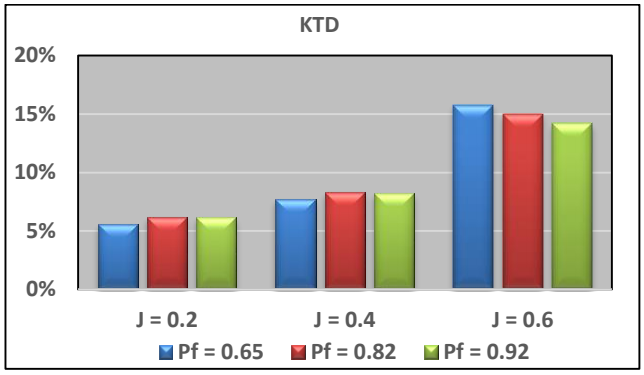

Fig 11: Duct thrust scale effects with P_f (Duct 19A)

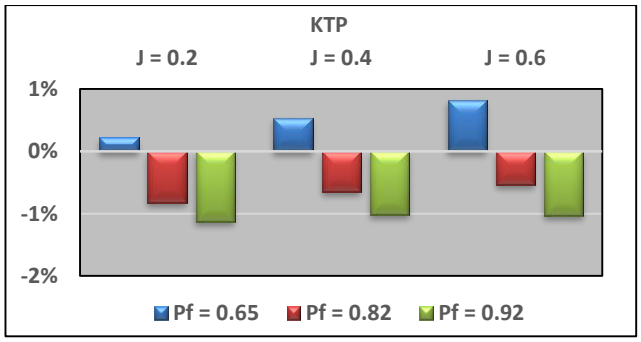

Fig 12: Propeller thrust scale effects with P_f (Duct 19A)

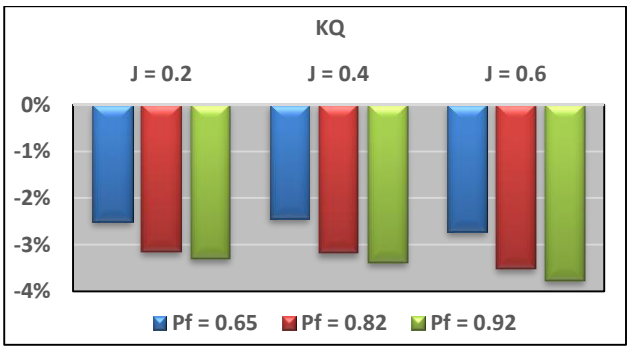

Fig 13: Propeller torque scale effects with P_f (Duct 19A)

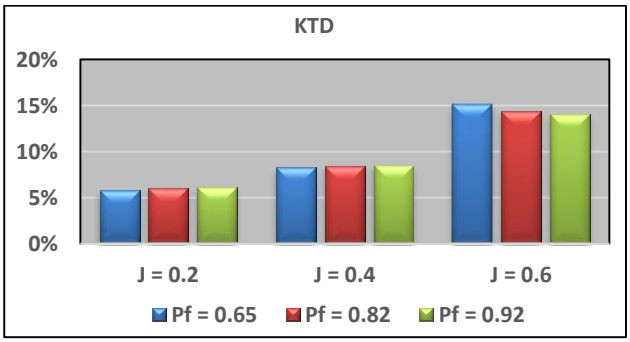

Fig 14: Duct thrust scale effects with P_f (Innoduct10)

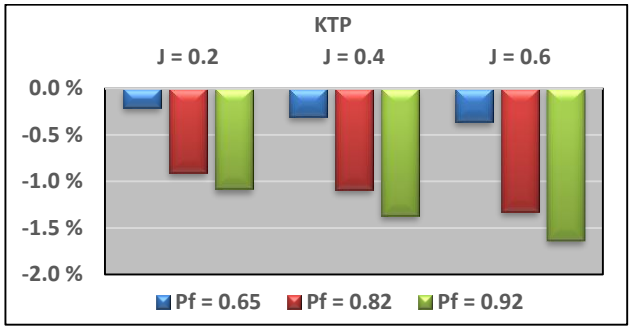

Fig 15: Propeller thrust scale effects with P_f (Innoduct10)

Scale effects on duct thrust for both the Duct 19A and Innoduct10 appear comparable at all values of tip pitch factor. For propeller thrust, scale effects are less pronounced at the lower pitch factor, and their changes in full scale are smaller for the Duct 19A.

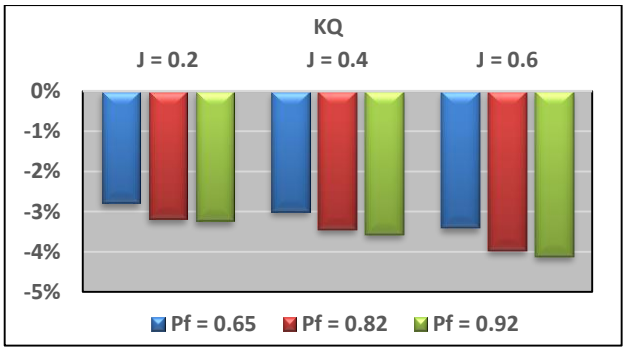

Fig 16: Propeller torque scale effects with P_f (Innoduct10)

Considering equal advance coefficients, in the case of reduced P_f (0.65), the propeller operates at the condition of lighter loading compared to the original P_f (0.82) due to both the lower pitch and lower duct induction on propeller. At a lighter loading, the Reynolds number effect on blade forces is normally more pronounced due to a greater relative contribution of frictional forces in both lift and drag. This effect results in a relatively higher increase of blade thrust in full scale at lower P_f. Thus, scale effect on propeller thrust, which is negative at the design P_f, is reduced for the propeller with Innoduct10 (Fig. 15), and even becomes positive for the Duct 19A (Fig. 12) at the lower P_f (0.65). This latter result agrees very well the results presented in (Krasilnikov et al, 2007) where scale effects were discussed for a propeller operating in Duct 19A at the pitch ratio 1.0, which is lower than design pitch of the presently studied propeller. Due to a larger increase of blade thrust in full scale we have a larger increase in total thrust of ducted propeller for the lower tip loading factor (0.65). The reverse case occurs for higher tip loading (0.92). Unlike the situation with propeller thrust, the aforementioned changes in lift and drag have counteracting influences on propeller torque with increasing Reynolds number. Besides that, the interaction between blade tip and duct boundary layer

affects torque to a greater degree, and this interaction is stronger at the higher tip loading condition. As the relative thickness of the boundary layer is reduced in the full scale, the impact of its reduction on the interaction with blade tip can be stronger for propeller with a higher tip loading factor. Therefore, one observes greater torque reduction in full scale for propellers with higher P_f.

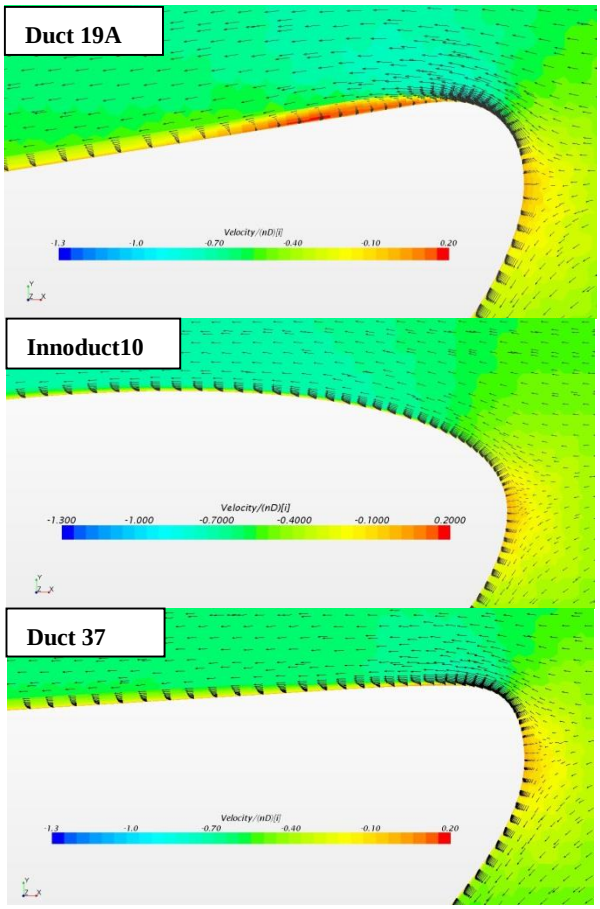

Fig. 17: Velocity profile near duct leading edge at J=0.6 (model scale)

The flow pattern around the duct depends on the duct design, as well as Reynolds number and loading conditions. In model scale, the boundary layer over duct reveals typical low-Reynolds velocity profiles, in some areas close to those of laminar flow regime. In the full scale, the relative thickness of the boundary layer is reduced, and velocity profiles are much fuller, which is typical for high-Reynolds, fully developed turbulent regime. Figs. 17-18 show the velocity profiles near the leading edge of the ducts at the free-sailing condition (J= 0.6). The Duct 19A reveals a separation zone of considerable extent on the outer surface downstream of the leading edge in model scale. The extent of separation grows with increasing advance coefficient. It is this separation phenomenon that is responsible for lower duct thrust shown by the Duct 19A in model scale in comparison with other ducts (Fig. 8). For the Duct 37, the separation on the outer side is delayed to higher advance coefficients, while for the Innoduct10 it is not evident for all studied J values.

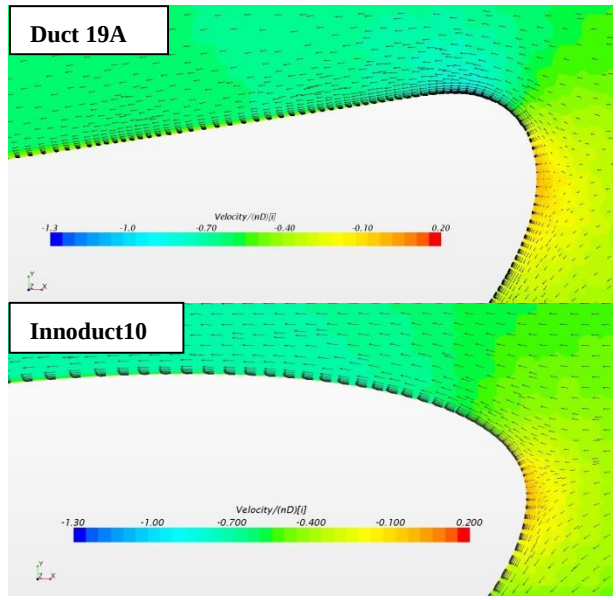

Fig. 18: Velocity profile near duct leading edge at J=0.6 (full scale)

In full scale, the ducts are free from separation in the considered operation range.

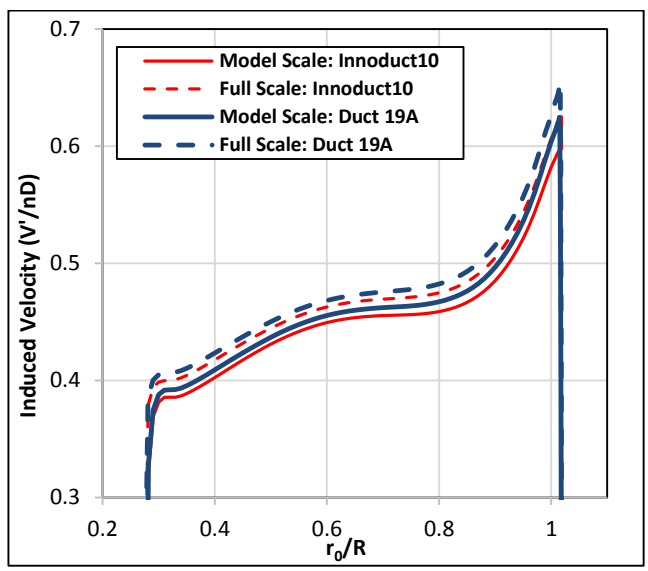

Fig. 19: Non-dimensional induced velocity in front of the propeller in model and full scales at J=0.6

Fig. 19 shows the non-dimensional axial induced velocity plotted along the radial direction, at the distance of 0.25R in front of the propeller for the Duct 19A and Innoduct10. The induced velocity is higher in full scale condition for the ducts compared to model scale due to the aforementioned increase in duct thrust. The average percentage of velocity increase in full scale compared to model scale calculated in

the range of radii 0.29< r/R< 1 is in the range of 3%-4%. For the considered case, propeller thrust in full scale is lower than in model scale thrust. Hence, it can be said that the increase in total induced velocity through the duct is largely due to higher flow acceleration produced by the duct in full scale.

As it can be seen from Fig. 19, different duct designs provide different accelerations to the flow coming onto propeller. The results presented in Fig. 19 explain findings about propeller thrust in torque in different ducts presented above in Figs. 9 and 10. For example, Innoduct10 induces lower axial velocity on propeller than Duct 19A, so that propeller operates at lower effective J value in Innoduct10, producing a higher thrust. The opposite can be concluded about the Duct 37. The increase of duct induced velocity with increasing Reynolds number causes a ducted propeller to operate at a higher effective advance coefficient in full scale compared to model scale conditions. Hence, comparison of open water efficiency in model and full scale based on the same advance coefficient is not a fair way to judge about propulsor efficiency. In order to compare the effectiveness of the ducted propulsors, the thrust-power ratio was compared at different scales, at the condition of equal power consumed by propeller. For this comparison, two coefficients were defined- the Merit coefficient (C) as the target function, and inverse Taylor's coefficient (B_P^{-1}) as the argument of the target function.

$$C = \frac{{K_{T,TOT}}^{3/2}}{\pi^{3/2} \cdot K_Q}$$

$$B_P = \frac{{P_D}^{1/2} \cdot RPM}{V^{2.5}}$$

Here, $K_{T,TOT}$ is the total thrust coefficient, K_Q is the torque coefficient, P_D is the shaft delivered power (in HP), RPM is the propeller rate of revolution per minute, and V is the speed of advance (knots).

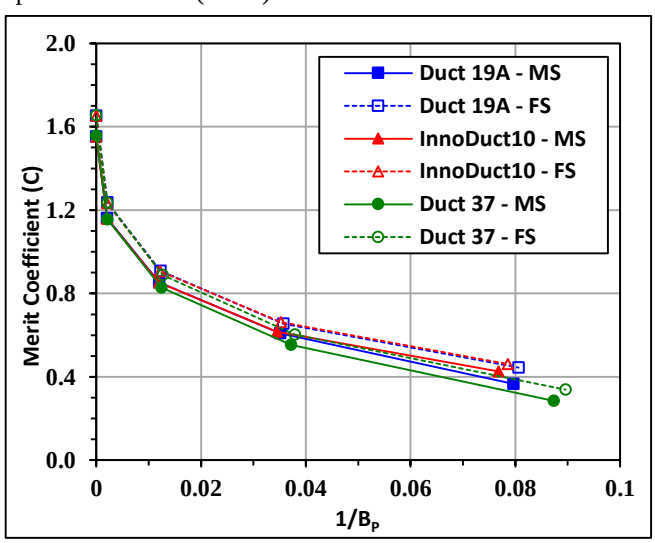

Fig. 20: Merit Coefficient with different duct designs at model and full scales

From the results summarized in Fig. 20, it can be concluded that the Merit coefficient for all ducts are higher in full scale than in model scale at all loading conditions. While at bollard and trawling operation conditions, the Merit coefficients are at very close level for all ducts, the largest differences are seen in free sailing, where Innoduct10 offers considerable gain compared to the other two ducts in model scale. The Innoduct10 shows the highest Merit coefficient in this range also full scale, but the differences compared to Duct 19A are much smaller, since flow separation does not develop on the exterior side of Duct 19A in full scale.

4 CONCLUSIONS

Scale effects on the open water characteristics of a propeller working within three ducts of different designs have been investigated in this study. The conclusions may be summarized as follows:

Scale effects on the open water thrust and torque characteristics have been found to be in a comparable range for the three investigated ducts – Duct 19A, Innoduct10 and Duct 37. The Reynolds number effect is most pronounced for the duct thrust which is found to increase in full scale, while its change shows clear dependence on propeller loading, increasing at lighter loading conditions. Propeller torque decreases in full scale for about 3%-4% from model scale values, but it shows weaker dependence on loading. Propeller thrust shows little scale effects (around 1%). Total propulsor thrust increases in full scale for about 2-3% from model scale values, and it shows little dependence on loading due to smaller absolute contribution from duct at lighter loading condition, where scale effect on duct thrust is greatest.

The blade tip pitch factor, which determines tip loading, influences the magnitude of scale effects on both propeller thrust and torque. Propellers with lighter loaded tips show larger increase in total thrust and smaller decrease in torque compared to propellers with heavier loaded tips, at all loading conditions. The mechanism of interaction between the blade tip and duct boundary layer plays an important role in this picture, especially as regards propeller torque. If assessed separately, the effect of blade tip loading on duct thrust is fairly small, but one should remember that propeller and duct operate as an entire system.

The flow patterns around the ducts depend on duct geometry. The significant differences between flow patterns are observed at higher advance coefficients, corresponding to free-sailing operation. For example, the Duct 37 and Innoduct10 are found free from separation at the near-design point (J=0.6), while the Duct 19A has a distinct zone of separated flow on its exterior side downstream of the leading edge.

All three ducts produce higher flow acceleration in full scale, causing an increase of total induced velocity in front of the propeller. This makes the ducted propeller to operate

at a higher effective advance coefficient at sea compared to model scale conditions, especially so considering the fact that hull axial wake fraction may also decrease in full scale, for certain hull forms.

The comparison of Merit coefficients gives an idea of the effectiveness of different ducts, in both model and full scales, which can help propeller designers to make a balanced choice of the duct design. The effectiveness of all the three ducts is found higher in full scale whereas the differences in Merit coefficient between different duct designs are considerably more pronounced in model scale, in particular at free-sailing conditions.

ACKNOWLEDGEMENT

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DISCUSSIONS

Question from Chen Yang Li

Why are there three different sections on the same duct?

Authors' reply

Thank you for your question. The three sections of the duct (Fig. I) shown in the presentation were chosen with respect to different positions of the blade, as the analysis is performed using Steady MRF method. The aim is to plot the pressure and friction coefficients over the sections. But, they are not shown in the present paper.

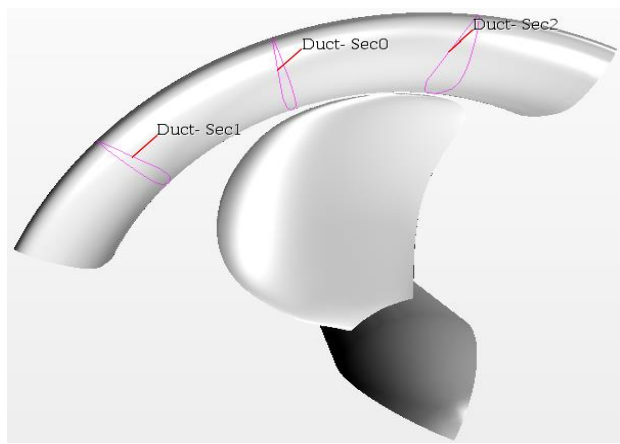

Fig. I: Duct sections

Question from Douwe Rijpkema

What are the differences in model scale between simulations with and without transition model?

Authors' reply

Thank you for your question. In our work, special attention has been paid to the influence of flow transition on propeller characteristics. We kindly request to go through the paper entitled 'Influence of Flow Transition on Open and Ducted Propeller Characteristics' in Volume I of SMP'15 proceedings.