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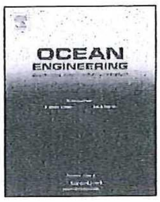

Hydrodynamic development of Inclined Keel Hull-propulsion

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ABSTRACT

The gain in propulsive efficiency using a large propeller diameter with lower shaft rotation is perhaps the simplest and most robust way of improving the fuel economy of a ship. Within this framework the concept of "*Inclined Keel Hull*" has attracted much interest in small vessels such as fishing boats and tug boats to improve their pulling power however there has been no application of this concept to large commercial ships. This is the second of two papers on a hydrodynamic development of an Inclined Keel Hull with a well-designed 3600 TEU container vessel based on the recently completed postgraduate study, (Seo, 2010). In the first paper (Seo et al., 2012) the validation for the bare hull resistance and wake distribution on the propeller plane was conducted by using advanced numerical tools and large scale model tests as part of an on-going collaborative FP7-EU research project, Streamline (2010). The present paper is the continuation of the validation study for the propulsion analysis of the same vessel by using numerical analysis and large scale self-propulsion tests as part of the same project. The validation study confirmed the worthiness of the Inclined Keel Hull concept by achieving a 4.3% maximum power saving in the delivered power around design speed.

1. Introduction

A successful ship design in terms of ship powering demands propulsion devices designed to give maximum efficiency and to absorb a low shaft power with low hull pressures, noise, cavitation erosion and vibration. In general it is a platitude for naval architects that a large propeller diameter in combination with a low rotational speed leads to an attractive gain in propulsive efficiency due to the reduction of axial losses. Additionally, a slow turning propeller can also have cavitation benefits. Many applications, especially for larger tankers (high thrust loading case) in which the axial energy loss dominates, therefore have taken place in adapting large and slow turning propellers as being one of the more robust and effective ways of achieving significant propulsive efficiencies (Beek, 2004; Ciping et al., 1989). For the same vessel a further increase of propeller diameter would require the development of the new propeller aperture. In order to secure a deeper aft draught for a large diameter propeller the Authors have introduced "*Inclined Keel Hull*" configuration where the draught of the vessel is greater at the aft perpendicular than that at the fore perpendicular with a linear variation in between.

Newcastle University have been exploring the design and operational benefits of the Inclined Keel Hull concept using a well-designed 3600 TEU container vessel, which is designated as 'Basis Hull (BH)', by increasing the diameter of its propeller about 13%. However, improving the operational benefits by the increase in propeller size and hence in propulsive efficiency is not a simple issue as the latter is the product of the hull, propeller and relative-rotative efficiencies. The bare hull resistance around the hull and inflow velocity into the propeller plane are important hydrodynamics aspects of the hull form development. If the increase of the bare hull resistance of Inclined Keel Hull (IKH) is considerable than that of BH (Basis Hull) the economics of the IKH will not work since the expected propulsive gain from the enlarged diameter of the IKH will be lost to the potential increase in the effective power of the IKH. Using numerical design and analysis methods supported by limited model test analysis, Seo (2010) demonstrated that the IKH concept may provide a 4–5% of power saving.

In the previous companion paper (Seo et al, 2012) a brief definition of the IKH concept and its development for the 3600 TEU container vessel were presented including the analyses for the resistance and hull wake by using the CFD codes. The numerical results were validated for the bare hull resistance and wake of the BH and IKH based on the model test measurements. Main particulars of the BH and IKH are given in Table 1.

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The resistance tests with two 7.15 m (L_{PP}) hull models confirmed the successful design of the IKH form which resulted in a 1% increase in the effective power as the authors had targeted in the IKH development. In order to demonstrate the effectiveness of the IKH concept over the BH, the propeller must be designed to operate effectively in a non-uniform and unsteady wake flow field behind the hull. In general, the main particulars of propellers are determined for the optimum condition by using standard (or chart) series model propeller data and the basic particulars of the propeller is further optimized with respect to the radially varying wake distribution. And final step of the design approach involves an analysis of the optimum propeller in circumferential varying three dimensional wake distributions by using advanced unsteady propeller analysis tools to further refine the propeller geometry for better cavitation and vibration performance.

In this paper, propeller designs and propulsion analyses for the IKH and BH hulls are presented for further validation of the relative propulsive performance for the Inclined Keel Hull based on the self-propulsion tests conducted in the SSPA towing tank (Allenstrom and Riisberg-Jensen, 2011a).

Table 1
Main particulars of Basis Hull (BH) and Inclined Keel Hull (IKH).

Main dimensions		BH	IKH
Lpp (m)		232.8	232.8
Beam (m)		32.2	32.2
Design Draft (m)	T_F	11.3	10.5
	T_A	11.3	12.1
WSA (m2)		9266	9220
Volume (m3)		50849	51136
C_{WA}		0.840	0.841

2. Numerical analysis of propulsion

Prior to the design of an efficient propeller for the IKH and comparison of its propulsive performance with that of the BH a set of preliminary self-propulsion tests were conducted with both hull models.

Based on the propeller hull-interaction data obtained from these early self-propulsion model tests, which were obtained with suitable stock propellers for the BH and IKH and reported in Allenstrom and Riisberg-Jensen (2011a, 2011b), the propeller designs were carried out for both BH and IKH. Both propellers (i.e. for BH and IKH) were designed using the same procedure in three stages that are "Basic Design", "Lifting Line design (or Wake Adaptation)" and "Balanced Design (or Design Analysis)". For each of these stages, the design strategy and criteria were different to achieve the ultimate design objective, i.e., higher propulsion efficiency with lower cavitation and vibration. Each design stage was iterative with its own objective that made the entire design optimization task multi-objective and iterative as shown by the flowchart in Fig. 1 and described in the following with more details.

In the basic design stage, the main design strategy was to make use of well-established propeller design practices and experiences, which are well presented in the systematic propeller chart series, to achieve a more reliable basic design and to avoid any interaction (and hence iteration) with the other two design stages. In the basic design stage, the main particulars of both propellers (mainly pitch,

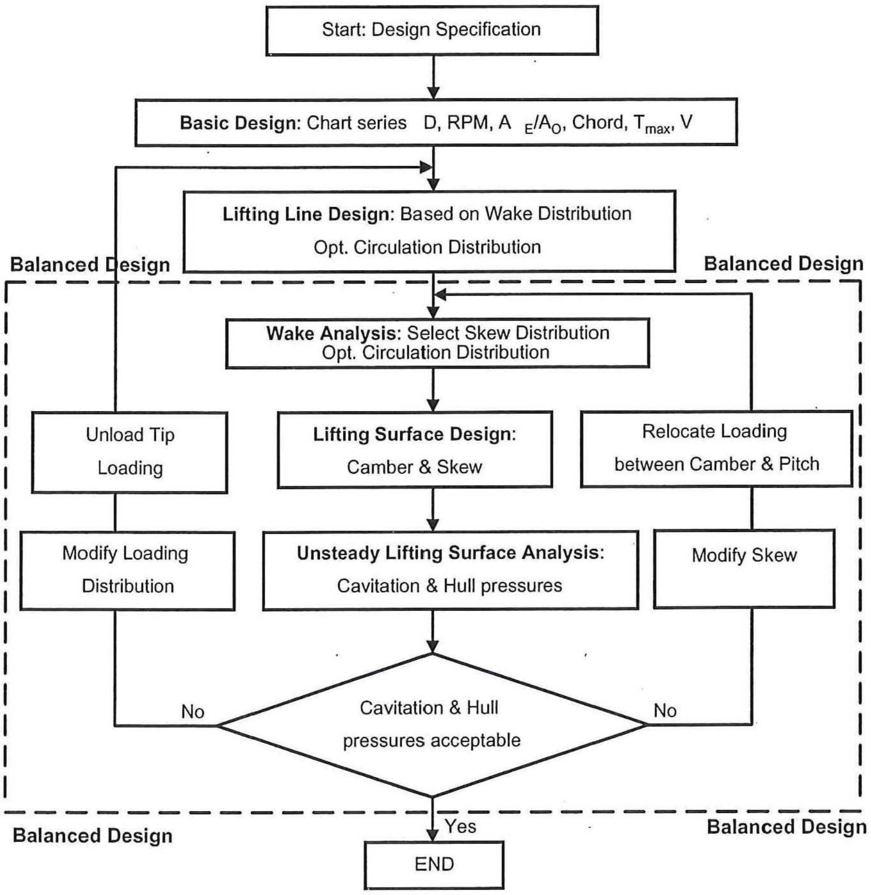

Fig. 1. Propeller design block diagram.

shaft speed and blade area) were selected in iterative manner for the optimum propulsive efficiencies and minimum risk of cavitation for the maximum propeller diameter for each ship with the same ship speed (i.e. 24 knots) by using B-Series propeller chart (van Lammeren et al., 1969) and Burrill's cavitation diagram (Burrill and Emerson, 1963). The wake fraction and thrust deduction fraction used were based on the self-propulsion tests with stock propellers.

As shown in Table 2, after the basic design, the open water efficiency for the IKH propeller was 3.8% higher than that of the BH due to the increased propeller diameter and resulting lower propeller shaft speed. Consequently the IKH was expected to achieve a saving in shaft power of 2.7%, due to the improvement in the open water efficiency despite the 1% increase of hull resistance.

Table 2
Comparison of basic propulsive performance.

	Speed (kn)	P/D	J	K_T	$10K_Q$
BH	24	1.1	0.784	0.201	0.3776
IKH	24	1.2	0.891	0.203	0.4150
K_T/J^2	η_o	N (rpm)	Q (kN m)	P_D (kW)	B.A.R
0.326	0.667	93.4	2904	28,314	0.72
0.256	0.693	73.0	3617	27,311	0.62

In the lifting line design stage, the design objective was to adapt the propellers, which were designed from the chart series, to the wakes of the target ships based on Lerbs' lifting line method (Lerbs, 1952). Hence the circulation distributions of both propellers were optimized to its individual axial wake distribution, which was obtained from the model tests, by using an in-house lifting line code for achieving the maximum propeller efficiency with the criteria of absorbing their required engine powers.

The balanced design stage consisted of three sub-stages such as "wake analysis", "lifting surface design" and "unsteady lifting surface analysis". In the wake analysis sub-stage the wake distributions of both ship models were carefully analyzed for selecting the propeller skew distributions in case that the cavitation was inevitable. The objective of the lifting surface design sub-stage was to further improve the lifting line design results in terms of the blade camber, propeller pitch and propeller skew. For this purpose, Greeley and Kerwin's lifting surface design code (Greeley and Kerwin, 1982) was used. The objective of the unsteady lifting surface analysis sub-stage was to predict the propeller cavitation

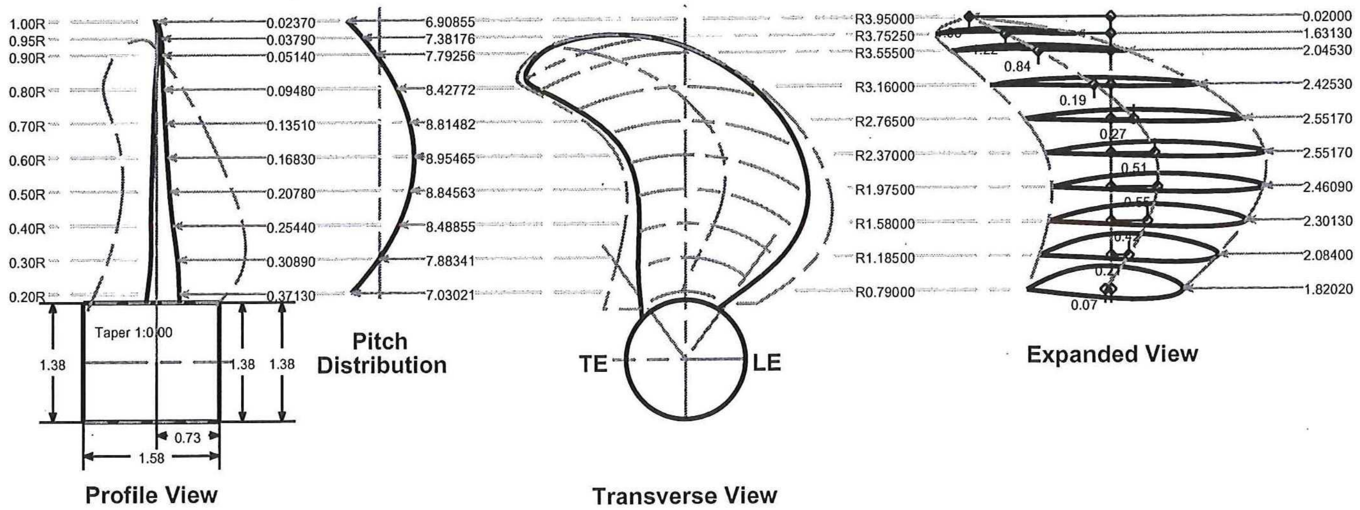

Fig. 2. Designed propeller for Basis Hull.

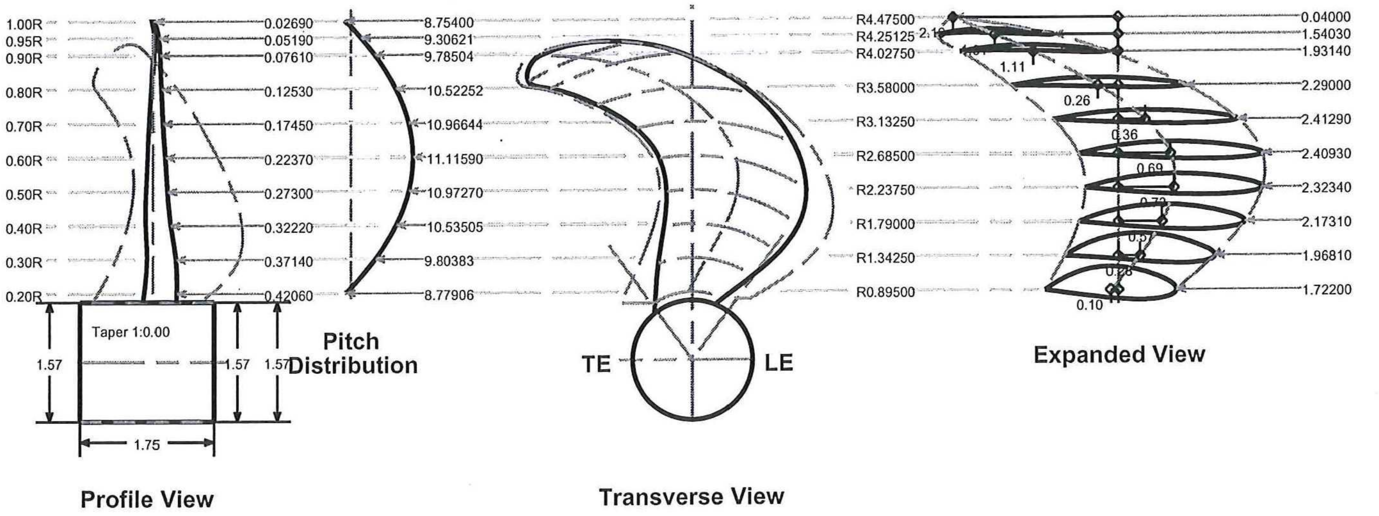

Fig. 3. Designed propeller for Inclined Keel Hull.

performance and vibration. For this purpose in-house unsteady lifting surface code UPCA91 (Szantyr and Glover, 1990) was used. As shown in Fig. 1 if the cavitation extent and ship hull pressures were acceptable, the circulation distribution optimized from the lifting line design stage would be kept unchanged, and the design iteration would not go back to the lifting line design stage. In this case, the loading at certain radii may be relocated locally between the maximum camber and pitch at those radii to improve their cavitation extent. In case that the cavitation and hull pressures were excessive, hence not acceptable, firstly the skew of propeller would be increased to improve the situation. If the resulting cavitation and hull pressures were still not acceptable, the radial distribution of the propeller loading had to be modified, usually by unloading the blade towards the tip. In this case the design iteration had to be taken back to the lifting line design stage as shown in Fig. 1.

The main features and sectional details of each propeller are shown in Figs. 2 and 3 as the final design obtained from the above described design process whilst the basic dimensions of the propellers are given in Table 3 together with the numerical results of their performances based on the unsteady lifting surface analysis as described above.

As can be seen in Table 3 the BH showed the power delivered to the propeller at this optimum operating condition was $P_D = 27{,}962$ kW. The similar analysis for the IKH propeller indicated that the delivered power, $P_D = 26{,}888$ kW for the optimum operating condition. This revealed that the delivered power for IKH propeller would result in a 3.84% saving compared to the BH at a 22.6% lower shaft speed rate.

The hull pressure computations were carried out at a point on the hull where the pressures were expected to have the peak values. These positions for the BH and IKH were at 6.2 m and 6.83 m above the propeller shaft axis in the propeller plane, respectively. IKH hull was designed to have a similar level of propeller clearance to BH hull and to run at a deeper draught which has the effect of reducing the potential for sheet cavity developed over the suction side of the propeller, together with improving the radiated hull surface pressure. To give a more comprehensive comparison between the BH and the IKH, harmonic analysis of the fluctuating pressure induced by the propeller up to fourth blade rate are shown in Fig. 4. These comparison results show that the IKH will offer benefits by reducing the hull pressure fluctuations at the first and second harmonic by almost 35%.

3. Experimental analysis of propulsion

The model propellers were manufactured by SSPA according to the design data provided by the authors to SSPA. However during this process an unfortunate error took place resulting in that the manufactured BH model propeller had a smaller BAR than the designed one as shown in Table 4. The difference was 5.5% decrease in the BAR due to the human error during the exchange of information on the chord lengths of the blade sections in the excel tables although the drawings were correct. However the remaining data of the BH propeller were the same as the designed one produced by the authors. This unfortunate situation, in fact, put the BH model propeller in more efficient and hence more competitive than the intended numerical design that must be born in mind in the comparisons. In other word, the BH model propeller would be over-performing due to its lower frictional loss. However, the propeller manufactured will be exposed to higher risk of cavitation and hull pressure than the propeller

Table 3
Comparison of basic dimensions and numerical propulsive performance of designed propellers at the design speed (24 knots).

	Speed (kn)	Blade no.	Dia. (m)	B.A.R
BH	24	5	7.91	0.72
IKH	24	5	8.95	0.62
P/*D*	Thrust (kN)	*N* (rpm)	*Q* (N m)	P_D (kW)
1.06	1948	93.4	2856	27,962
1.17	1975	73.0	3498	26,888

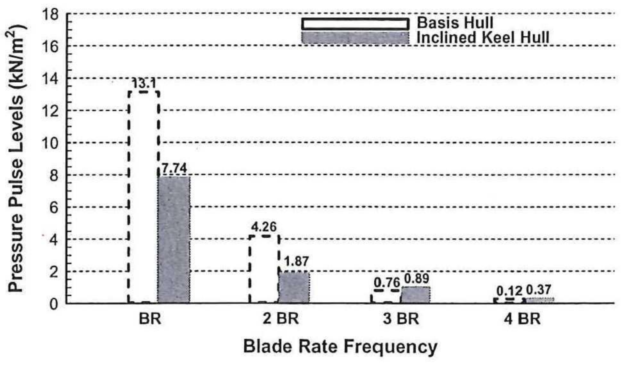

Fig. 4. Comparison of numerical hull pressures induced by the propeller.

Table 4
Comparison of BH propeller—designed and manufactured.

BH propeller	Blade no.	B.A.R
BH-designed	5	0.72
BH-manufactured	5	0.68

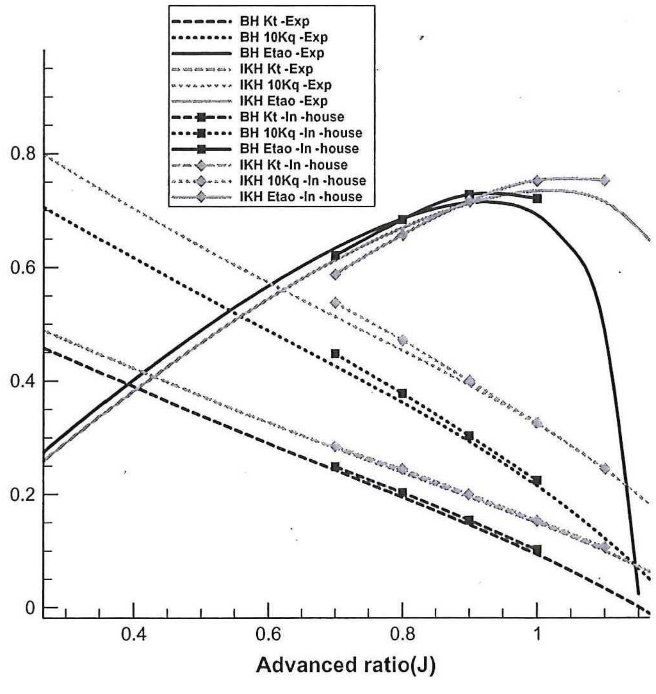

Fig. 5. Comparison of open water efficiency from model test and in-house lifting surface code for Basis Hull and Inclined Keel Hull (model scale).

Table 5
Comparison of propulsive performance at 24 knot.

	P_E (kW)	N (rpm)	η_o	η_H	η_R	η_D	P_D (kW)
BH	20,323	92.9	0.698	1.094	0.996	0.760	26,751
IKH	20,531	72.8	0.726	1.095	1.005	0.799	25,689

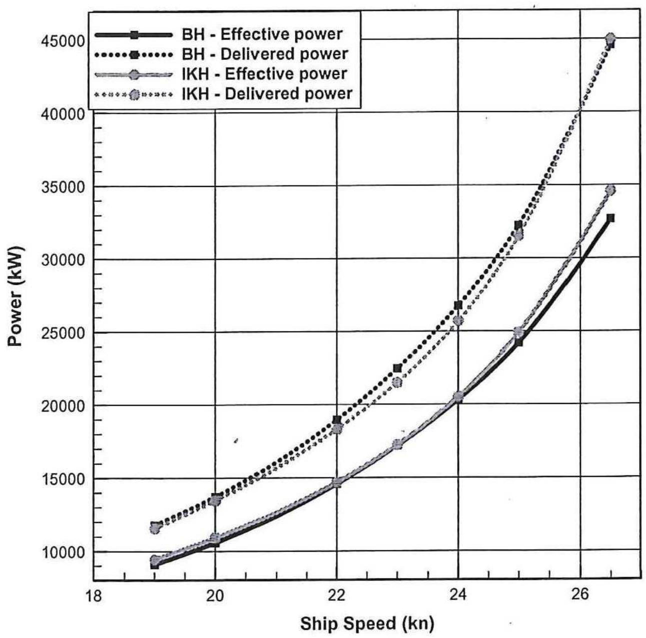

Fig.6. Comparison of delivered power at full scale.

designed although the earlier presented hull pressure predictions were all based on the designed, i.e., correct propeller.

The entire propulsion tests were conducted in SSPA and reported by Allenstrom and Riisberg-Jensen (2011a). The comparison of the propeller open water performances from the model tests and in-house unsteady lifting surface code for the models of the two propellers is shown in Fig. 5. Numerical predictions of thrust and torque coefficients correspond to the model test results within 5%. The self-propulsion model tests were carried out at several cruising speeds around the design ship speed of 24 knots and full scale power prediction was conducted using the ITTC 78 performance prediction method.

Table 5 shows the comparative propulsive efficiency and its components as well as the full scale delivered power at the design speed (24 knots) for the BH and IKH. The results of the final model test for the BH showed that the optimum propeller efficiency was 0.698 whilst the power delivered to the propeller was P_D=26,571 kW. The similar analysis for the IKH propeller indicated that the optimum propeller efficiency was 0.726 and the delivered power was P_D=25,689 kW. This revealed that the open water and relative-rotative efficiencies of the IKH propeller were 4% and 1% higher than that of the BH at a 21.5% lower shaft speed, respectively. This would result in a 4% saving in the delivered power for the IKH despite the fact that the IKH produced a 1% higher effective power than that of the BH. Another factor that must be born in mind in this comparison is that the manufactured BH model propeller would be over-performing than the designed one which would result in the reduced relative performance gain for the IKH.

Fig. 6 shows the comparison of the delivered power at full scale for both the hulls which clearly presents an average of 4% power saving around the design speed. The power saving is apparent between 18 and 26 knots with a maximum of 4.3% at 23 knots.

4. Conclusions

This paper presents the final outcome of the IKH development, which explored the propulsive benefits of 13% larger propeller diameter than the BH, in terms of hydrodynamic performance with the help of advanced CFD tools and large scale model tests conducted in the Streamline project Streamline, (2010). The optimum designs for the BH and IKH propellers are presented using the in-house software codes and an assessment of the numerical predictions of propulsive efficiency made against model test results was made.

Based on the knowledge gained so far it was found that the success of the 'Inclined Keel Hull' application into a large commercial vessel requires a fine balance between the minimal increase in the bare hull resistance and a maximum gain in the propulsive efficiency. More specifically the following conclusions are reached based on the investigation presented in this paper:

1) Numerical study indicated that the IKH can offer 4% of power saving and benefits of reducing the hull pressure fluctuations approximately by 35% over the BH pressure levels at first two harmonics for the design speed of 24 knots.
2) Model tests revealed that the open water and relative-rotative efficiency of the IKH propeller was 4% and 1% higher than that of the BH, respectively, at a 21.5% lower shaft speed. This resulted in a 4.3% maximum saving in the delivered power at 23 knots whilst the saving was 4% at the design speed
3) The above findings favorably confirm the numerical predictions for power saving and hence supporting the worthiness of the IKH concept for the design applications of large commercial vessels.

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