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Propulsive factors in waves: A comparative experimental study for an open and a ducted propeller

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ABSTRACT

The estimation of propulsive factors in waves is essential to understand the propulsion characteristics for a ship in actual sea conditions. While the propulsion factors of open propellers in waves have been established by significant experimental work, similar study for the ducted propulsion case couldn't be found. The propeller–duct interaction has a considerable influence on the propulsive factors for a ducted propeller, and hence demands a separate study for understanding the effect of waves. This paper presents the results of model propulsion tests with a 120 m cargo vessel at two Froude numbers under different propeller loadings for a series of head sea conditions, carried out with both a ducted and an open propeller. Comparison of propulsive factors in waves shows that, there are differences in both magnitude and in some cases—also trend between an open and a ducted propeller, most notably in the effective wake fraction, where the ducted propeller shows a stronger influence of the waves. The thrust deduction fraction is found to be independent of propeller loading in a broad range of loadings. The propeller efficiency doesn't seem to be much influenced by the waves, except for the effect of change of propulsion point.

1. Introduction

Ducted propellers have largely been adopted into a range of marine vessels after *Luigi Stipa* and later *Ludwig* Kort (1934) demonstrated that a foil-shaped shroud or an accelerating duct could be used to increase the propulsive efficiency for heavily loaded propellers.

When a ship is operating in waves, there is an augment in the total resistance of the ship causing a shift in the propulsion point. The change in flow conditions and pressure in waves also impacts the propulsion factors. Moor and Murdey (1970) plotted the self-propulsion factors for conventional propellers on different ship models in both loaded and ballast conditions for a series of regular wave conditions. It is concluded that—the divergence of the propulsion factors from still water values is highest at a wavelength equal to the ship length, and returns to still water value at around the wavelength equal to thrice the length of the ship.

The variation of self-propulsion factors with wave-length for a container ship at four different Froude numbers (*Fn* 0.15 to 0.30) presented by Nakamura and Naito (1975) show that the wake velocities increased under wave conditions which is most pronounced at wavelengths corresponding to the natural periods in pitch, as also pointed out by Faltinsen et al. (1980). The thrust deduction fraction decreased with increasing wave height; however, the trend has been reverse in certain small ranges of amplitude and Froude numbers. While the effect of waves on the relative-rotative efficiency has been negligible, there are pronounced reductions in the open water efficiency, especially at the critical wavelength range. Bhattacharyya (1978) mentions the reductions in open water efficiency values as the effect of changes in propeller loading due to the added resistance in waves. In almost all the cases, the quasi-propulsive efficiency values in waves are lower than the calm water value, more so at higher wave amplitudes and at wavelengths close to the length of the ship.

For the ducted propellers, in-depth studies have been carried out regarding the propulsion factors in calm water. English and Rowe (1973) had discussed the effects of ducted propeller/hull interaction on propulsive efficiency for tankers, where, an increment in hull efficiency due to higher wake fraction for the ducted propeller had resulted in a higher propulsive efficiency compared to an open propeller. Based on systematic tests with different duct profiles carried out at Netherlands Ship Model Basin, Oosterveld (1973) concluded that the increase in propulsive efficiency by using an accelerating ducted propeller is obtained by the increase

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Nomenclature

n	[Hz] propeller rotational speed
L_{pp}	[m] length between perpendiculars
B	[m] breadth (moulded)
$T_{AP/FP}$	[m] drafts at aft and fore perpendiculars
Δ	[m^3] volume displacement
C_B	[dimensionless] block coefficient
V	[m/s] speed
D	[m] propeller diameter
λ	[m] wavelength (model scale)
ζ_a	[m] wave amplitude
J^*	[dimensionless] advance coefficient based on model speed (V/nD)
F	[N] tow force
F_D	[N] friction correction force (tow force at propulsion point)
T	[N] total thrust (propeller thrust for the open propeller)
T_D	[N] duct thrust
Q	[N m] propeller torque
K_T	[dimensionless] thrust coefficient ($T/\rho n^2 D^4$) for open propeller
K_{TP}	[dimensionless] propeller thrust coefficient ($T_P/\rho n^2 D^4$) for ducted propeller
K_{TD}	[dimensionless] duct thrust coefficient ($T_D/\rho n^2 D^4$)
$K_{T,Tot}$	[dimensionless] total thrust coefficient ($T/\rho n^2 D^4$) for ducted propeller
K_Q	[dimensionless] torque coefficient ($Q/\rho n^2 D^5$)
t	[dimensionless] thrust deduction fraction
w	[dimensionless] mean Taylor wake fraction
η_R	[dimensionless] relative rotative efficiency
η_O	[dimensionless] open water efficiency
η_H	[dimensionless] hull efficiency
η_D	[dimensionless] quasi-propulsive efficiency
f_E	[Hz] wave encounter frequency

of open water efficiency of the propulsion system. He had mentioned the probability of the nozzle operating less effectively behind a hull compared to open water due to non-uniform inflow, which may cause some parts of the nozzle to have no circulation. Minsaas et al. (1973) tested ducted propellers on large tanker models and obtained higher thrust deduction and lower relative-rotative efficiency compared to conventional open propellers, the latter being attributed to the decrease of duct thrust in the behind condition.

For simplicity, it has been assumed in our work, that the time averaged values of the propeller open water characteristics in waves are similar to the still water values (McCarthy et al., 1961; Nakamura and Naito, 1977). This has allowed the use of calm water open water characteristics for the estimations of propulsive factors for all test conditions. The purpose of this work is to estimate and document the change in propulsive factors in waves for a ducted propeller and view it as a comparison with an open propeller, which may help the estimation of propulsive characteristics in waves for ships fitted with ducted propellers that operate frequently in heavy seas.

2. Model tests

The model tests were carried out with a 1:22.629 scale model of the single-screw 120 m cargo vessel in the large towing tank (length: 260 m, breadth: 10 m, depth: 5 m) at The Marine Technology Centre, Trondheim, Norway. The vessel, designed by Rolls Royce was tested alternately with a conventional open propeller and a ducted propeller of slightly smaller diameter, using a rudder in both cases. Both the propellers were stock propellers designed by MARINTEK. The principal particulars are shown in Table 1, and the details of the stock propellers are mentioned in Table 2. The model was tested at Froude numbers 0.203 (primary speed) and 0.142. The model of the standard 19A type accelerating duct had a length of 77.3 mm and an inner diameter of 195.5 mm. Details of the regular waves tested are provided in Table 3.

Table 1
Principal particulars of the 120 m cargo vessel.

	Full scale	Model scale
L_{pp}	117.6 m	5.197 m
B	20.8 m	0.919 m
$T_{AP/FP}$	5.5 m/5.5 m	0.243 m/0.243 m
Δ	8832.7 m^3	0.762 m^3
C_B	0.657	0.657
V	13.4/9.4 knot	1.449/1.016 m/s

2.1. Test set-up

A transverse beam was mounted amidships with wires in a crow-foot arrangement (Fig. 1) to connect the model to the towing carriage.

The model was towed in the arrangement shown in Fig. 1, and the propeller speed set to different levels to obtain different tow force values. In this sense, the test method corresponds to the so-called British method for propulsion tests. The tow force, propeller thrust, torque and rpm were measured along with incoming wave elevation, ship model motions and accelerations. The propeller thrust and torque were measured with a Cussons propeller

Table 2
Details of stock propellers used for model tests.

	Open propeller	Ducted propeller
Number of blades	4	4
Propeller diameter	185.6 mm	178.3 mm
Pitch ratio at r/R=0.7	0.975	1.297
Blade area ratio	0.515	0.697

Table 3
Details of regular waves tested (head sea conditions: model scale).

Waves	λ/L_{pp}	ζ_a/L_{pp}	T (s)	ζ_a (m)
1	0.55	0.0077	1.353	0.04
2	0.8	0.0154	1.632	0.08
3	1	0.0077	1.824	0.04
4	1	0.0154	1.824	0.08
5	1	0.0231	1.824	0.12
6	1.2	0.0154	1.999	0.08
7	1.5	0.0154	2.234	0.08
8	1.9	0.0154	2.515	0.08