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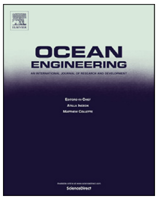

Analysis of the thrust deduction in waterjet propulsion – The Froude number dependence

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ABSTRACT

The definition of thrust deduction in waterjet propulsion is different from that of a propeller driven hull and cannot be interpreted in the same way. A particularly interesting feature of the waterjet thrust deduction is the large variation with Froude number. This is well known from experience, but has never been fully explained. The objective of this paper is to use CFD to address the reasons for these large variations. To this end, the thrust deduction fraction is split into resistance increment fraction and jet thrust deduction fraction. The former is due to the self-propelled hull resistance change in comparison with the bare hull resistance and the latter is due to the difference between gross and net thrust. This split reveals that the main reason for the thrust deduction variation is the hull resistance change. Analysis of the resistance increment in different speed ranges is performed by studying the hydrostatic and hydrodynamic pressure changes on the hull as well as the friction change due to the waterjet system. Despite the negative thrust deduction fraction in the intermediate speed range there is no indication of a resistance reduction compared to that of the bare hull at these speeds.

1. Introduction

The waterjet propulsion concept is based on increasing the flow head through a pump inside a ducting channel and then discharging the ingested flow with a higher momentum flux behind. The most common waterjet intake design is flush to the hull bottom, however, depending on the craft type the intake geometry can be ram or scoop shaped (Kruppa et al., 1968). Depending on the specific speed of the waterjet pump, a mixed flow or an axial flow pump can be employed in the unit (White, 2008). Within the speed range of 30–60 knots, the major waterjet manufacturers suggest this propulsion method over conventional propellers.

Since the waterjet unit is embedded in the hull, the interaction effects between the waterjet system and the hull are quite different from those of conventional propellers. In contrast with the propeller/hull interaction effects, which are rather well defined, there are still unanswered questions regarding the waterjet/hull interaction. Three major research studies in this field are the doctoral thesis by Coop (1995), van Terwisga (1996) and Bulten (2006). Coop investigated the interaction between waterjet and hull using model scale and full scale measurements, as well as empirical and analytical methods. He discusses the possible mechanisms contributing to the overall interaction effect and lists the waterjet momentum forces causing lift and moment about the centre of gravity, the wake momentum losses and the loss of the planing surface at the intake opening as the most significant ones. Coop reports the largest measured negative thrust deduction fractions (up to −8%) around the hump speed. He states that the ITTC suggested method for towing the hull along the shaft line is the most conservative approach, which yields the highest bare hull resistance.

In his doctoral thesis, van Terwisga (1996) showed that the thrust deduction fraction of a waterjet propelled hull varies considerably with speed and may even obtain negative values in an intermediate speed range. Through a set of analytical, numerical and experimental studies, he found a difference between gross thrust and net thrust[1] especially around ship speeds where the transom is not fully cleared. He states that the difference is practically zero for higher speeds and therefore, the difference between gross thrust and bare hull resistance is a good measure of the resistance increment of the hull due to the waterjet-induced flow. Through an uncertainty analysis of propulsion tests, he shows that the error made in the flow rate measurement in power estimation increases with decreasing jet velocity to ship velocity ratio. He divides the effects causing the resistance change of a self-propelled hull, into a global sinkage/trim effect and a local effect on the flow around the intake due to the ingested flow. Then he states that if the assumption of independence between the changes due to the local and the global flow is

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[1] Definition of gross thrust and net thrust are given in Section 2.

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Nomenclatures

A	control surface
B	hull beam [m]
BH	bare hull
BH_{SP}	BH with the same sinkage and trim as SP
c_p	local pressure coefficient [–]
C_T	hull resistance coefficient [$-$]
D_e	exit drag [N]
D_i	intake drag [N]
Fn	Froude number [–]
F_px	pump force per unit mass in x-directon [N]
i, j, k	tensor indices denoting the ordinates
Lpp	length between perpendiculars [m]
N	normal unit vector
Q	volume flow rate [$m^3/3$]
R_a	rope force [N]
R_bh	bare hull resistance [N]
SP	self-propelled hull
t	thrust deduction fraction (waterjet) [$-$]
T_g	gross thrust vector component in x-directon [N]
t_j	jet system thrust deduction fraction [$-$]
T_net	net thrust vector component in x-directon [N]
t_p	thrust deduction fraction (propeller) [$-$]
t_r	resistance increment fraction [–]
u	velocity vector [m/s]
u_0	undisturbed velocity [m/s]
x, y, z	Cartesian earth fixed coordinates
ΔR	resistance increment [N]
ρ	density of fluid [kg/m^3]
σ	hull sinkage [m]
σ_x	x-component of pressure and shear stresses [Pa]
τ	hull trim angle [$degrees$]
η	transverse distance from hull symmetry plane [m]
ξ	vertical distance from transom edge [m]

true, the change in resistance may be estimated from a Taylor series in the global and local flow parameters, keeping only linear terms. Based on the measurements of a powerboat propelled by a single waterjet unit, he concludes that the trim angle is the most important parameter for analyzing the resistance increment of the hull.

Bulten (2006) studied the flow inside waterjet propulsion systems employing Computational Fluid Dynamics (CFD) tools. The integration of axial force component on the waterjet unit, as well as a simplified version of the integral momentum balance equation, were applied to calculate the waterjet thrust. Bulten reports a clear deviation between the results of these methods for higher ship speeds. He also computed a large vertical force in the same speed range. According to these findings, Bulten concludes that the method based on the momentum balance for the waterjet control volume is incorrect. possibly because of the influence of the hull in the vicinity of the waterjet inlet and partly because of neglecting the contributions of the pressure distribution acting on the streamtube.[2]

The ITTC High-Speed Marine Vehicle Committee (ITTC 17, 1987) and the ITTC Specialist Committee on Waterjets (ITTC 21, 1996; ITTC 22 1998; ITTC 23 2002; ITTC 24 2005) have proposed a test procedure for investigation of waterjet/hull interaction which was modified during the years. A measurement campaign was also conducted by the ITTC Specialist Committee on Waterjets on a semi-displacement hull with two sets of axial flow waterjets. The results of this study, which was performed by many different institutes, show a large scatter for the thrust deduction fraction. This highlights the importance of the waterjet flow rate measurement.

The Office of Naval Research (Rispin, 2007) carried out a comprehensive set of measurements on a demi-hull with a pair of waterjet units. The difference of boundary layer thickness due to scale change was taken into account in the data scaling procedure. Consequently, although the thrust deduction fraction in the intermediate speed range was positive at model scale, taking this correction into account resulted in a negative thrust deduction fraction. This conclusion raises the question of whether or not the thrust deduction is dependent on scaling.

Kamal et al. (2015) carried out an experimental comparative study of the powering of waterjet and screw propeller for a medium speed wave-piercing catamaran. They predict the thrust deduction fraction to be very low for the waterjet propelled hull (-0.1 to -0.35) but no certain reason for the small values is provided.

Several studies employing Reynolds Averaged Navier-Stokes (RANS) methods have been carried out modeling waterjet-propelled hulls and including power estimation, e.g. (Kandasamy et al., 2010, 2011; Takai et al., 2011). However, the detailed waterjet/hull interaction effects have not been the focus of these studies.

Eslamdoost et al. (2013) presented a method based on potential flow theory for studying the waterjet driven hull flow. They also identified the parameters which contribute to the waterjet/hull interaction in (Eslamdoost et al., 2014). In their third consequent paper (Eslamdoost et al., 2016), these authors investigated the difference between the net thrust and gross thrust of a waterjet unit through a RANS study. They show that the net thrust and the gross thrusts are not the same and deviate from each other, especially in the speed range where the nozzle is submerged in the transom wave.

Thus, many researchers have contributed to the understanding of the waterjet/hull interaction effects but yet there is a knowledge gap in explanation of the reasons for the large variation of the thrust deduction fraction with speed, as well as of the negative thrust deduction values sometimes reported in the intermediate speed range. The goal of the present paper is to study the thrust deduction fraction of a waterjet propelled hull in a wide speed range and to clarify the reasons for the large variation of this fraction.

In the following, first, the definitions required for the analysis of the waterjet system are introduced in section 2. Then, the hull geometry and the towing tank measured sinkage and trim are presented in section 3 and section 4, respectively. A brief review of the computational technique for the waterjet flow simulation is given in section 5 and in section 6 the components which contribute to the thrust deduction fraction in different speed ranges are discussed in detail. Finally, several conclusions are drawn.

2. Theory

The thrust deduction fraction is the relation between the bare hull resistance and the thrust required to propel a vessel. For a conventional propeller, the net thrust is employed to define the thrust deduction fraction as follows,

$$t_p = 1 - \frac{R_{bh} - R_a}{T_{net}}, \tag{1}$$

where R_{bh} and T_{net} are the bare hull resistance and the net thrust of the propeller/s. Since the frictional resistance of the hull at model scale, due to lower Reynolds number, is larger than the full scale frictional resistance a towing force is applied to the hull during the self-propulsion test. This force is called the rope force and is shown with R_a.

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[2] See Fig. 1 and read the corresponding text for the definition of the streamtube.