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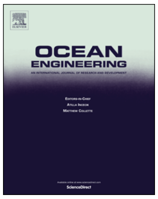

Predicting axial velocity profiles within a diffusing marine propeller jet

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ABSTRACT

A full understanding of the hydrodynamic processes within the jet produced by a manoeuvring ship's propeller is essential in the development and maintenance of ports, docks and harbours. In this investigation the predominant axial velocity component within a freely expanding wash was studied. The flow fields formed by four propellers, each operating at four power levels (speeds of rotation), were investigated under bollard pull conditions and in the absence of a rudder, within a large free surface tank using Laser Doppler Anemometry. The characteristics of these propellers extended the range over which high accuracy measurements have been previously attempted. Comparison were made to existing methodologies by which a prediction of the magnitudes of the axial velocity can be made, and where deficient modifications to the methodologies have been developed and presented. The jets were found to produce a maximum axial velocity along the initial efflux plane at a location near the blade mid-span. The position and magnitude of the axial velocity was seen to decrease as the jet entrained more flow and transitioned from the zone of flow establishment into the zone of established flow.

1. Introduction

The problems within harbours and navigation channels associated with the close proximity of manoeuvring vessels, have been well discussed in a range of both case studies and research investigations, Fuehrer and Römisch (1977), Blaauw and van de Kaa (1978), Bergh and Cederwall (1981), Berger et al. (1981), Fuehrer et al. (1981), Verhey et al. (1987), Hamill (1987), Chait (1987), Stewart (1992), Hashmi (1993), Qurrain (1994), Froehlich and Shea (2000), Sumer and Fredsoe (2002), Hong et al. (2013), Geisenhainer and Aberle (2013) and Hamill et al. (2014). Guidelines for engineers have been developed (PIANC, 2015; BAW, 2010; CIRIA, 2007) incorporating the influence of engineering surfaces, beds and slopes. In all cases these methodologies rely on an understanding of the fundamental process that control the formation and diffusion of the jets formed.

Studies that have concentrated on the formation and diffusion of the jets created by the manoeuvring vessels have been limited by the numbers of test propellers used in the studies, Lam et al. (2012), and while providing a useful insight have not been in a position to provide predictive methods that covered a meaningful range of operation as only one test propeller was used. The formation process, and subsequent diffusion, of a ship's propeller jet must be fully understood if an engineer is to be able to quantify any scouring damage that may occur, and, more importantly, size protection systems to be deployed to prevent further damage.

The flow field produced by the action of rotating propeller blades is complex in nature. Near to the propeller, the passing blades and rotating hub influence the characteristics of the flow. As the jet diffuses downstream, the velocity characteristics become similar to a submerged three-dimensional jet, Albertson et al. (1950).

Under normal operation the propeller flow is influenced by external characteristics such as the hull of the ship or the presence of a rudder for directional purposes. While manoeuvring or near to bollard pull conditions it has been found that such hull effects are negligible, Prosser (1986). The jet produced by a rotating propeller under such conditions is a complex three-dimensional flow with axial, radial and rotational velocity components, Hamill et al. (2003). The axial velocity is the most significant component and is found along the propeller axis of rotation. This component is used to impart a forward thrust to propel the ship in the direction of movement. From the early work of Blaauw and van de Kaa (1978) to the recent PIANC (2015) report, it has been cited that as the axial component is in the order of 10 times the magnitude other components of velocity within the jet, those components "do not need to be considered in the flow analysis of propeller or thruster jets" (PIANC, 2015).

Experimental investigations by naval architects into the velocity fields produced by rotating propeller blades have been focussed on the vicinity of the propeller: Min (1978), Cenedese et al. (1988) and Felli et al. (2006). In contrast, most civil engineering

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Nomenclature

A (–)	coefficient defined in Eq. (23)
B (–)	coefficient defined in Eq. (23)
C (–)	experimentally determined constant (σ/X_o)
C_t (–)	thrust coefficient of propeller ($T/\rho n^2 D_p{}^4$)
c (m)	chord length
D_h (m)	diameter of hub
D_o (m)	initial diameter of slipstream
D_p (m)	diameter of propeller
h_d (m)	helical distance from the blade section leading edge to rake datum line
h_t (m)	helical distance from the blade section leading edge to position of maximum thickness
L_m (m)	characteristic length
N (–)	number of propeller blades
n (rpm)	propeller rotational speed
P' (–)	propeller pitch to diameter ratio
p (m)	propeller blade pitch
Re_{flow} (–)	reynolds number of jet flow ($V_o D_p/\nu$)
Re_{prop} (–)	reynolds number of propeller (nD_pL_m/ν)
R_h (m)	radius of propeller hub ($D_p/2$)
R_m (m)	radial position of maximum axial velocity relative to the jet centreline at any section within the zone of flow establishment
R_{m0} (m)	radial distance from propeller axis to location of maximum axial velocity along efflux plane
R_p (m)	radius of propeller
R^2 (–)	coefficient of determination
r (m)	radial distance across blade from propeller centreline
V_{max} (m/s)	maximum axial velocity
V_o (m/s)	maximum axial velocity along efflux plane
$V_{x,r}$ (m/s)	axial velocity at position x, r
X (m)	cartesian co-ordinate measured laterally from face of propeller
X_o (m)	distance from propeller to end of zone of flow establishment
β	blade area ratio
ν (m^2/s)	kinematic viscosity of fluid
π (–)	constant number pronounced pi (π=3.142)
σ (m)	standard deviation of velocity

designs of structures and scour prevention systems require the downstream evolution characteristics of turbulent propeller jets in order to determine the magnitude and position of propeller-induced scour.

This paper presents the findings from an extensive experimental investigation which tested four propellers which were allowed to freely expand and whose characteristics covered a wide range typical propeller types, with each propeller being tested at four speeds of rotation (power settings) with velocity measurements of the time averaged components of velocity being taken using Laser Doppler Anemometry (LDA).

2. Experimental setup

The propellers used in this investigation varied in size (D_p), numbers of blades (N), pitch to diameter ratios (P'), thrust coefficients (C_t), rake and blade area ratios (β), as shown in Table 1. The number of propeller blades varied from three to six. The pitch to diameter ratio ranged from a minimum of 0.735 up to a maximum of 1.0. The thrust coefficient, at zero advance speeds, ranged from 0.2908 up to 0.558. The blade area ratios varied from of 0.4525 to 0.922. The blades of propeller 1, 3 and 4 had no forward inclination i.e. all blades are at 90° angles to the hub while the blades of propeller 2 were inclined by a further 10°. In selecting these differing propellers it was intended to test over a large practical variation of characteristics typical of sea going vessels.

Table 1
Propeller geometric characteristics.

	Prop 1	Prop 2	Prop 3	Prop 4
Propeller diameter-D_p (mm)	76	92	103	131
Hub diameter-D_h (mm)	14.92	20.32	20.5	27.2
Thrust coefficient-C_t	0.402	0.2908	0.388	0.558
Pitch to diameter ratio-P'	1.0	0.735	0.8283	1.136
Blade area ratio-β	0.47	0.4525	0.6417	0.922
Rake angle (deg)	0	10	0	0
Number of blades-N	3	4	4	6

Froudian scaling was used to determine the speeds of rotation tested. It has been established by Blaauw and van de Kaa (1978) that scale effects due to viscosity can be ignored if the Reynolds number for the propeller exceeded 7×10^4 and the Reynolds number for the propeller flow was greater than 3×10^3. The Reynolds number for the jet flow is given by:

$$R_{e_{flow}} = \frac{V_0 D_p}{\upsilon} \tag{1}$$

The Reynolds number for the propeller is given by:

$$R_{e_{prop}} = \frac{n D_p L_m}{\upsilon} \tag{2}$$

The characteristic length, L_m depends on the blade area ratio, propeller and hub diameters as well as the number of blades. Blaauw and van de Kaa (1978) defined this length term as follows:

$$L_m = (\beta) D_p \pi \left(2N \left(1 - \frac{D_h}{D_p} \right) \right)^{-1} \tag{3}$$

The rotational speeds used in the programme of work were based on standard Froudian scale of the efflux velocity within the jet and were based on calculations for a generic propeller determined by Qurrain (1994) in a survey of typical ro–ro vessel operating from British ports. This propeller had a diameter of 2.5 m, power levels while manoeuvring gave rotations of 200 rpm and a typical thrust coefficient of 0.35 at bollard pull. The efflux velocity, calculated using the equation given by Fuehrer and Römisch (1997), gave a value of V_0=7.3 m/s. The corresponding efflux velocity for each propeller was then scaled from this value and used to back calculate the corresponding speed of rotation required to match this providing target speeds for the experimental propellers (1–4) of 990, 1056, 865 and 640 rpm respectively. The propellers were operated across a range of speeds that bounded these target values, and these are listed in full in Table 2.

The Reynolds numbers for the propellers operating at these rotational speeds ranged from 1.4×10^4 to 7.7×10^4, while the Reynolds numbers for the propeller jet ranged from 5.3×10^4 to 30×10^4, Table 2. The Reynolds numbers for the propellers were, in some cases, slightly less than 7×10^4 however, Blaauw and van de Kaa (1978) and Verhey et al. (1987) proposed these scale effects would be insignificant. The Reynolds numbers for the jets were all greater than 3×10^3 for the speeds of rotation investigated satisfying the criteria for Froudian scaling. All experiments were

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