

Predicting axial velocity profiles within a diffusing marine propeller jet

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1	PREDICTING AXIAL VELOCITY PROFILES WITHIN A DIFFUSING MARINE
2	PROPELLER JET
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4	
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11	ABSTRACT
12	
13	A full understanding of the hydrodynamic processes within the jet produced by a manoeuvring
14	ship's propeller is essential in the development and maintenance of ports, docks and
15	harbours. In this investigation the predominant axial velocity component within a freely
16	expanding wash was studied. The flow fields formed by four propellers, each operating at four
17	power levels (speeds of rotation), were investigated under bollard pull conditions and in the
18	absence of a rudder, within a large free surface tank using Laser Doppler Anemometry. The
19	characteristics of these propellers extended the range over which high accuracy
20	measurements have been previously attempted. Comparison were made to existing
21	methodologies by which a prediction of the magnitudes of the axial velocity can be made, and
22	where deficient modifications to the methodologies have been developed and presented. The
23	jets were found to produce a maximum axial velocity along the initial efflux plane at a location
24	near the blade mid-span. The position and magnitude of the axial velocity was seen to
25	decrease as the jet entrained more flow and transitioned from the zone of flow establishment
26	into the zone of established flow.
27	
28	KEYWORDS
29	Propeller Jets, Scour, Ports, Dock and Harbours, Hydraulics & Hydrodynamics

31 NOTATION

A	(-)	Coefficient defined in Equation 23		
В	(-)	Coefficient defined in Equation 23		
С	(-)	Experimentally determined constant (σ/X_o)		
Ct	(-)	Thrust coefficient of propeller $(T/\rho n^2 D_{\rho}^4)$		
С	(m)	Chord length		
D _h	(m)	Diameter of hub		
Do	(m)	Initial diameter of slipstream		
Dp	(m)	Diameter of propeller		
h _d	(m)	Helical distance from the blade section leading edge to rake		
		datum line		
ht	(m)	Helical distance from the blade section leading edge to		
		position of maximum thickness		
Lm	(m)	Characteristic length		
Ν	(-)	Number of propeller blades		
n	(rpm)	Propeller rotational speed		
P'	(-)	Propeller pitch to diameter ratio		
р	(m)	Propeller blade pitch		
Re flow	(-)	Reynolds number of jet flow $(V_o D_p/v)$		
Re prop	(-)	Reynolds number of propeller (nD_pL_m/v)		
Rh	(m)	Radius of propeller hub (Dp/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		
Rp	(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		

	Vo	(m/s)	Maximum axial velocity along efflux plane
	V _{x,r}	(m/s)	Axial velocity at position x, r
	Х	(m)	Cartesian co-ordinate measured laterally from face of
			propeller
	Xo	(m)	Distance from propeller to end of zone of flow establishment
	β		Blade Area Ratio
	ν	(m²/s)	Kinematic viscosity of fluid
	Π	(-)	Constant number pronounced pi (π =3.142)
	σ	(m)	Standard deviation of velocity
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53 1.0 INTRODUCTION

54 The problems within harbours and navigation channels associated with the close proximity of 55 manoeuvring vessels, have been well discussed in a range of both case studies and research 56 investigations, Fuehrer & Römisch (1977), Blaauw, H.G., and van de Kaa, E.J. (1978), Bergh 57 & Cederwall (1981), Berger et al. (1981), Fuehrer et (1981), Verhey et al. (1987), Hamill 58 (1987), Chait (1987), Stewart (1992), Hashmi (1993), Qurrain (1994), Froehlich & Shea 59 (2000), Sumer & Fredsoe (2002), Hong et al. (2013), Geisenhainer & Aberle (2013) and 60 Hamill et al. (2014). Guidelines for engineers have been developed (PIANC (2015), BAW 61 (2010) and CIRIA (2007)) incorporating the influence of engineering surfaces, beds and 62 slopes. In all cases these methodologies rely on an understanding of the fundamental 63 process that control the formation and diffusion of the jets formed.

64

55 Studies that have concentrated on the formation and diffusion of the jets created by the 56 manoeuvring vessels have been limited by the numbers of test propellers used in the studies, 57 Lam *et al.* (2012), and while providing a useful insight have not been in a position to provide 58 predictive methods that covered a meaningful range of operation as only one test propeller 59 was used. The formation process, and subsequent diffusion, of a ship's propeller jet must be 50 fully understood if an engineer is to be able to quantify any scouring damage that may occur, 51 and, more importantly, size protection systems to be deployed to prevent further damage.

72

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).

77

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 threedimensional 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 Blauuw 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).

89

90 Experimental investigations by naval architects into the velocity fields produced by rotating 91 propeller blades have been focussed on the vicinity of the propeller: Min (1978), Cenedese *et* 92 *al.* (1988) and Felli *et al.*(2006). In contrast, most civil engineering designs of structures and 93 scour prevention systems require the downstream evolution characteristics of turbulent 94 propeller jets in order to determine the magnitude and position of propeller-induced scour.

95

96 This paper presents the findings from an extensive experimental investigation which tested 97 four propellers which were allowed to freely expand and whose characteristics covered a wide 98 range typical propeller types, with each propeller being tested at four speeds of rotation 99 (power settings) with velocity measurements of the time averaged components of velocity 100 being taken using Laser Doppler Anemometry (LDA).

101

102 2.0 EXPERIMENTAL SETUP

103 The propellers used in this investigation varied in size (D_p) , numbers of blades (N), pitch to 104 diameter ratios (P'), thrust coefficients (C_t), rake and blade area ratios (β), as shown in **Table** 105 1. The number of propeller blades varied from three to six. The pitch to diameter ratio ranged 106 from a minimum of 0.735 up to a maximum of 1.0. The thrust coefficient, at zero advance 107 speeds, ranged from 0.2908 up to 0.558. The blade area ratios varied from of 0.4525 to 0.922. 108 The blades of propeller 1, 3 and 4 had no forward inclination i.e. all blades are at 90° angles 109 to the hub while the blades of propeller 2 were inclined by a further 10°. In selecting these 110 differing propellers it was intended to test over a large practical variation of characteristics 111 typical of sea going vessels.

112

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

117
$$R_{e_{flow}} = \frac{v_0 D_p}{v}$$
 Equation 1

118

119 The Reynolds number for the propeller is given by:

120
$$R_{e_{prop}} = \frac{n D_p L_m}{v}$$
 Equation 2

121

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

124
$$L_m = (\beta)D_p \pi \left(2N \left(1 - \frac{D_h}{D_p}\right)\right)^{-1}$$
 Equation 3

125

126 The rotational speeds used in the programme of work were based on standard Froudian scale 127 of the efflux velocity within the jet and were based on calculations for a generic propeller 128 determined by Qurrain (1994) in a survey of typical ro-ro vessel operating from British ports. 129 This propeller had a diameter of 2.5m, power levels while manoeuvring gave rotations of 200 130 rpm and a typical thrust coefficient of 0.35 at bollard pull. The efflux velocity, calculated using 131 the equation given by Fuehrer and Römisch (1997), gave a value of V₀=7.3m/s. The 132 corresponding efflux velocity for each propeller was then scaled from this value and used to 133 back calculate the corresponding speed of rotation required to match this providing target 134 speeds for the experimental propellers (1 - 4) of 990, 1056, 865 and 640 rpm respectively. 135 The propellers were operated across a range of speeds that bounded these target values, 136 and these are listed in full in Table 2.

137

The Reynolds numbers for the propellers operating at these rotational speeds ranged from 1.4 x 10⁴ to 7.7 x 10⁴, while the Reynolds numbers for the propeller jet ranged from 5.3 x 10⁴ to 30 x 10⁴, **Table 2**. The Reynolds numbers for the propellers were, in some cases, slightly less than 7 x 10⁴ however, Blaauw & 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 carried out in a free-surface tank 7.5 x 4.4 x 1 m in size, partitioned to allow the unhindered expansion of the propeller jets to be investigated (Qurrain 1994).

146

147 Velocity was measured using Laser Doppler Anemometry (LDA), which is a well-established 148 non-intrusive technique developed by Yeh & Cummins (1964). The 3D LDA adopted in this 149 research was a Dantec Dynamics three-component backscatter system with a water-cooled 150 Stabilite 2017 5W Argon-Ion laser manufactured by Spectra Physics as the illuminating light 151 source. Frequency shifting of 40 MHz using a Bragg cell was used to remove directional 152 ambiguity in the velocity measurements.

153

The optical probe was mounted on an automatic Dantec Dynamics 3D-traverse with measurement accuracies within \pm 0.05 mm in three orthogonal directions. The measurement volume was located at a distance of 240 mm from the LDA probe. Three-dimensional LDA configurations required the transformation of measurements made in a non-orthogonal coordinate system into a Cartesian system. The transformation of measurements was carried out each time the laser was set-up.

160

The LDA technique indirectly measured the velocity of the flow by measuring the speed of the (seeding) particles suspended in the flow. The seeding material used in this study was nonspherically shaped polyamide particles having a mean particle size of 20 μ m and density of 1.03 g/cm³. All measurements were made in fully coincident mode i.e. all three processors had to recognise a valid data point before accepting the data. The maximum data rates were determined by the rates obtained with the lowest power channel. Data rates ranged between a minimum of 30 and a maximum of 1000 particles per second.

An experimental measurement grid was established at which velocity readings were taken in sections across the face of the propeller. The centre of the propeller hub, at the cutting edge of the propeller blades, was taken as the zero location and measurements were taken on a Y

171	(horizontal), Z (vertical) grid in 2 – 5mm steps. The sections were repeated at 20mm intervals
172	moving away from the propeller in a horizontal plane, X.

174 3.0 TIME-AVERAGED ANALYSIS OF THE AXIAL VELOCITY COMPONENT

175 **<u>3.1 Zone of Flow Establishment</u>**

The maximum velocity, located on the initial plane of the jet, is termed the efflux velocity: V₀.
Hamill *et al.* (2014) discuss the 3D nature of this velocity and concluded that for the axial
component, the magnitude could be obtained from:

179
$$V_0 = 1.22 n^{1.01} D_p^{0.84} C_t^{0.62}$$
 Equation 4

180

This equation presents an alternative means of calculating V₀, which although still based on the form of equation developed from the traditional actuator disc theory used in current design guideline such as PIANC (2015), it attempts to provide corrections to the limiting assumptions used in that theory which tend to overestimate the V₀ value. This deviation in predicted values of V₀ is clearer for larger propellers.

186

187 All subsequent velocity values, at any location within the diffusing jet, have been shown to be 188 dependent on the magnitude of this initial value V_o. The formation and diffusion process that 189 occur within the jet are also accepted to occur within two regions of transition as shown in 190 Figure 1. The first, where the jet forms and becomes established, is called the Zone of Flow 191 Establishment (ZFE). The second, where the jet subsequently decays to merge with any 192 background flow, is called the Zone of Established Flow (ZEF), Albertson et al. (1950). In 193 propeller jets the flow is said to be fully established when the maximum velocity location 194 moves from across the blade to act along the line of the propeller shaft axis. The differing 195 mechanisms that operate within these zones has resulted in previous researchers trying to 196 establish the location of the changeover so that different analytical techniques can be applied 197 to each zone.

198

Fuehrer & Römisch (1977) and Blaauw & van de Kaa (1978) found the end of the "ZFE" coccurred at a relative distance of $X_0/D_p = 2.6$. Verhey *et al.* (1987) suggested the zone length 201 was $X_0/D_p = 2.77$, while Stewart (1992) proposed the zone extended to approximately X_0/D_p 202 = 3.25 from the initial efflux plane.

203

204 Figure 2 shows the measured velocity distributions obtained for propeller 2, at a test rotational 205 speed of 1000rpm. This profile is typical of all the tests conducted, for all the propellers tested. 206 The axial velocity distribution at 2D_p consisted of a low velocity core with the maximum peak 207 velocities located either side of the jet centreline. By 3D_p, further entrainment of surrounding 208 fluid caused a decrease in the magnitude of the axial velocity distribution. The locations of the 209 peak velocities were still evident at positions along the propeller blades. However by 4D_p, the 210 profiles have taken on the uniform normal distribution shape associated with the zone of 211 established flow. The central core was fully entrained and the maximum velocity reverting to 212 the centreline of the jet.

213

214 Investigations of the axial velocity profiles between 2D_p and 4D_p, at 20 mm intervals, showed 215 that the transition location from the "ZFE" to the "ZEF" occurred at $X_0/D_p = 3.15, 3.26, 3.49$ 216 and 2.9 for propellers 1, 2, 3 and 4. Over the range of propeller characteristics tested in this 217 study it is suggested that the extent of the initial zone can be approximated to be between 3 218 $\leq X_{o}/D_{p} \leq 3.5$, indicating significant difference from some of the earlier published work. 219 Stewart (1992) confirmed the extent of the zone of flow establishment occurred when the 220 maximum axial velocity was located along the propeller centreline at approximately X₀/D_p = 221 3.25. This compares favourably with the results of this investigation.

222

223 **3.1.1** Magnitude of the Maximum Axial Velocity

Albertson *et al.* (1950) assumed there was no decay of the maximum axial velocity in the zone of flow establishment as distance from the jet source increased. Blaauw & van de Kaa (1978), Verhey (1983) and Fuehrer & Römisch (1977), working with propeller jets, also agreed with this statement. Hamill (1987) however, found this hypothesis only held true up to a short distance of approximately $X/D_p = 0.35$ behind the propeller. Beyond this distance, through direct measurements, Hamill (1987) concluded the maximum axial velocities within the propeller jet decreased with distance from the propeller as a result of lateral mixing i.e. the jets expansion and its entrainment of ambient fluid, and was influenced by the blade area ratio
(β) as shown in equation 5:

233
$$\frac{V_{max}}{V_0} = 0.87 \left(\frac{x}{D_p}\right)^{-\frac{\beta}{4}}$$
 Equation 5

234

Stewart (1992) stated the application of equation 5 could not be generalised to any propellerand developed the following linear decay equation:

237
$$\frac{V_{max}}{V_0} = 1.0172 - 0.1835 \left(\frac{X}{D_p}\right)$$
 Equation 6

238

239 The predictive solutions from the methods proposed by Albertson et al. (1950), Hamill (1987) 240 and Stewart (1992) were compared with the measured results from this investigation. Figure 241 3 shows an exemplar of the comparison found between the current predictive methodologies 242 and the measurements taken. Decay in magnitude of the velocity with distance from the 243 propeller was found in all cases demonstrating that the suggestions based on the work by 244 Albertson et al. (1950) are invalid. Equation 7, proposed by Hamill (1987), was found to 245 overestimate the decay of the maximum axial velocity for propellers 2 and 4, with limited fit 246 being found form short regions with propellers 1 and 3. In the remainder of the zone, the 247 equation did not adequately determine the measured data. Equation 6 was developed from 248 tests conducted using propellers 1 and 4, which were also used in this investigation so it was 249 expected that the solutions of equation 6 would adequately predict the axial velocity decay 250 trends for those propellers. However, equation 6 was found to underestimate the axial 251 velocity decay trends, by up to 25%, for propellers 2 and 3 and therefore insufficiently 252 extrapolated outside the test range from which it was derived. Over all none of the current 253 methods provide an adequate method by which the maximum velocity at any axial distance 254 within the ZFE could be determined.

255

It was apparent from examining the measured data that the decay trends of the maximum axial velocity follows a linear profile as was suggested by Stewart (1992). Based on a stepwise variable selection process, of all available data for the four propellers tested at four speeds of rotation, analysis determined that the variables that most influenced maximum axial velocity (V_{max}) were the non-dimensionalised distance from the propeller source (X/D_p) and the propeller pitch to diameter ratio (P'). The following equation having a high coefficient of determination (R² = 0.964) was derived:

263
$$\frac{v_{max}}{v_0} = 1.51 - 0.175 \left(\frac{x}{D_p}\right) - 0.46 P'$$
 Equation 7

264

265 The output solutions of equation 7 were compared with the results of the empirical 266 investigation and in all cases, the output solutions of this equation adequately predicted the 267 decay trends of the maximum axial velocity from $X/D_p = 0.35$ to the end of the initial zone of 268 flow establishment, Figure 4. It is therefore suggested for distances up to $X/D_p = 0.35$ no 269 decay of the efflux velocity occurs as suggested by Hamill (1987) and that the maximum 270 velocity with distance is equal to that found on the efflux plane. After this, the maximum axial 271 velocity decays linearly throughout the remainder of the zone of flow establishment and can 272 be determined using equation 7, given the efflux velocity (V_0), distance from the propeller (X), 273 propeller diameter (D_p) and pitch to diameter ratio (P') as input variables.

274

275 **3.1.2** Axial Velocity Distributions within the Zone of Flow Establishment

Along the initial efflux plane, and throughout the zone of flow establishment, the distribution of the axial velocity component was found to increase from the jet centreline towards a maximum value before then decreasing rapidly towards the tip of the blade, Hamill (1987). McGarvey (1996) derived an equation based on the physical properties of propeller blades to determine the distribution of the axial velocity component along the efflux plane:

$$281 \qquad \frac{V_{x,r}}{Nnr} = 1.261 - 0.974 \left(\frac{p}{r}\right) + 0.733 \left(\frac{c}{r}\right) + 18.53 \left(\frac{t}{r}\right) + 5.028 \left(\frac{h_d}{r}\right) + 0.106 \left(\frac{p}{r}\right)^2 - 7.277 \left(\frac{h_d}{r}\right)^2 - 4.093 \left(\frac{h_t}{c}\right)^2$$

282

Equation 8

Albertson *et al.* (1950) found the velocity distribution at any section within a submerged jet to follow the general trend of the Gaussian normal probability function. Hamill (1987) made changes to the normal probability function and produced the following equation:

286
$$\frac{V_{x,r}}{V_{max}} = EXP\left(-\frac{1}{2}\frac{(r-R_{m0})^2}{\sigma^2}\right)$$
 Equation 9

287 Hamill (1987) measured the standard deviation, σ , as constant and equal to $0.5R_{m0}$ up to a 288 downstream distance of X/D_p = 0.5:

289
$$\sigma = \frac{1}{2}R_{m0}$$
 for X/D_p < 0.5 Equation 10

290

Beyond $X/D_p = 0.5$, to the end of the zone of flow establishment, the standard deviation was defined as:

293
$$\sigma = \frac{1}{2}R_{m0} + 0.075 \left(X - \frac{D_p}{2}\right)$$
 for X/D_p > 0.5 Equation 11

294

The output results of equation 8, proposed by McGarvey (1996), were compared with the experimental results in this study and **Figure 5** is a typical representation of the findings. While the shape of the profile predicted does follow that expected the only propeller that gave good agreement was propeller 1 (upon which the equation was developed). The method is overly cumbersome and can be difficult to apply. This equation has therefore poor generalisation capabilities when applied to any propeller.

301

302 Axial velocity distributions within the zone of flow establishment were measured and 303 compared with the output results of equations 9, 7 and 4 using non-dimensionalised values 304 of $V_{x,t}/V_{max}$ versus X/D_p. Figures 6 shows a typical comparison, with good agreement being 305 predicted both in terms of magnitudes and profile shape. The use of equation 9, in conjunction 306 with equations 11, 10, 7 and 4, adequately determined the axial velocity distributions within 307 the Zone of Flow Establishment in the jets produced by each of the experimental propellers 308 tested, and removes the need to establish refined methods of analysis, and is recommended 309 for use in predicting the velocity distributions of the axial velocity within the zone.

310

311 3.2 Zone of Established Flow

312 3.2.1 Magnitude of the Maximum Axial Velocity Decay within the Zone of Established Flow 313 Differences exist in the decay between the zone of flow establishment and the zone of 314 established flow. This can be explained by the differences in the diffusion processes in these 315 two zones. In the first zone, diffusion is occurring both internally and externally. The jet is 316 entraining its low velocity core as well as the ambient fluid. The decay of maximum velocity is 317 therefore much more rapid than in the zone of established flow were the central core has 318 already been entrained and only the external entrainment of the surrounding fluid is taking 319 place, Stewart (1992).

320

Albertson *et al.* (1950) stated that for all jets, including propeller jets, the decay of velocity was
 proportional to the distance from the source could be found using:

323
$$\frac{V_{max}}{V_0} = \frac{1}{2C} \left(\frac{X}{D_p}\right)^{-1}$$
 Equation 12

324

where the constant C is the variation of the standard deviation of velocity with distance.

Other researchers also adopted the general form of equation 12: Fuehrer & Römisch (1977),
Blaauw & van de Kaa (1978), Berger *et al.* (1981) and Verhey (1983). These equations are
as follows for each author respectively:

330
$$\frac{V_{max}}{V_0} = 2.6 \left(\frac{X}{D_p}\right)^{-1}$$
 Equation 13

331
$$\frac{V_{max}}{V_0} = 2.8 \left(\frac{x}{D_p}\right)^{-1}$$
 Equation 14

332
$$\frac{V_{max}}{V_0} = 1.025 \left(\frac{x}{D_p}\right)^{-0.6}$$
 Equation 15

333
$$\frac{V_{max}}{V_0} = 1.275 \left(\frac{x}{D_p}\right)^{-0.7}$$
 Equation 16

334

Through direct experimental measurements Hamill (1987) suggested the decay of the maximum velocity can be described using the following equation, taking into account the propeller geometry:

338
$$\frac{V_{max}}{V_0} = A \left(\frac{X}{D_p}\right)^B$$
 Equation 17

339 where:

$$340 \qquad A = -11.4 \ C_t + 6.65 \ \beta + 2.16 \ P'$$

341
$$B = -C_t^{0.216}. \beta^{1.024}.P^{-1.87}$$

342

343 Stewart (1992) reported the decay of the maximum axial velocity was independent of the 344 speed of rotation and propeller type used. A straight-line equation was proposed to determine 345 the decay within the zone of established flow:

$$\frac{v_{max}}{v_0} = 0.543 - 0.0281 \left(\frac{x}{D_p}\right)$$
 Equation 18

347

Hashmi (1993) found the maximum velocity in the wash was still measurable up to $X/D_p = 16$ downstream from the propeller. Hashmi (1993) therefore proposed the following equation in exponential form to predict the decrease in V_{max}:

351
$$\frac{V_{max}}{V_0} = 0.638 \ e^{-0.097 \left(\frac{X}{D_p}\right)}$$
 Equation 19

352

Large differences therefore exist in the extensive range of semi-empirical equations available to determine the decay of the maximum axial velocity within the zone of established flow. The decay trends of the maximum axial velocity were therefore measured for each of the experimental propellers tested to allow a comparison to be made between the measured and predicted output solutions of the existing semi-empirical equations.

358

359 Equations 13 and 14 proposed by Fuehrer & Römisch (1977) and Blaauw & van de Kaa 360 (1978) overestimated the measured decay trends, Figure 7. Equations 15 and 16 suggested 361 by Berger et al. (1981) and Verhey (1983) produced similar decay trends throughout the zone 362 of established flow but showed under predictions of propeller 2 (and over predictions of 363 propeller 4) by some 20%, Figure 8. The linear equation 18 proposed by Stewart (1992) 364 adequately predicted the decay of propellers 1 and 4 from which it was derived, Figure 9. 365 However, the output solutions of equation 18 underestimated the decay trends of propellers 366 3 and 4, Figure 9. The generalisation capabilities of equation 18 were reduced when used to 367 predict the decay trends of propellers outside the test range of which it was derived. The 368 exponential form of equation 19 proposed by Hashmi (1993) also underestimated the decay 369 of all propellers at the beginning of this zone, Figure 9. It is obvious from these comparisons 370 that the simplified decay expressed by these equations is not sufficient to account for the 371 variations measured.

373 The power trend equation 17 suggested by Hamill (1987) is based on the main propeller 374 characteristics: propeller pitch to diameter ratio, blade area ratio and thrust coefficient. The 375 output solutions of equation 17 were found to adequately determine the experimental results 376 of propellers 1 and 2, giving low percentage differences of 20%, Figures 10 a and b. Equation 377 17 was also used to determine the maximum axial velocity within the ZEF of propellers 3 and 378 4. However, this equation overestimated the maximum axial velocity, Figures 10 c and d. It 379 does however, show that the variations can be better described by including the aspects of 380 the propeller geometry within the prediction.

381

In a manner similar to that adopted for the Zone of Flow Establishment, a stepwise variable selection process was tested and it was found that the variables which most influenced the determination of the maximum axial velocity (V_{max}) were the same, i.e. the nondimensionalised distance from the propeller source (X/D_p) and propeller pitch to diameter ratio (P'). An equation having a high coefficient of determination (R² = 0.924) was derived.

387
$$\frac{V_{max}}{V_0} = 0.964 - 0.039 \left(\frac{x}{D_p}\right) - 0.344 P'$$
 Equation 20

388

Figure 11 shows an exemplar comparison of the output from equation 20 with the data obtained from the tests using propeller 4. The measured decay trends were adequately predicted using the distance from the initial efflux plane and pitch to diameter ratio as input variables. Overall, equation 20 performs well in predicting the decay of the maximum axial velocity within the zone of established flow, and it is recommended that it should be used in place of the existing methodologies.

395

396 **3.2.2** Axial Velocity Distributions within the Zone of Established Flow

Hamill (1987) investigated the methods available to determine the axial velocity distributions
within the zone of established flow proposed by Blaauw & van de Kaa (1978), Berger *et al.*(1981), Verhey (1983) Fuehrer & Römisch (1977). The equations proposed by Berger *et al.*(1981) and Verhey (1983) were found to be limited when applied to propeller jet flow. The

401 solutions proposed by Blaauw & van de Kaa (1978) and Fuehrer & Römisch (1977) are 402 respectively as follows:

403
$$\frac{V_{x,r}}{V_{max}} = EXP \left[-15.4 \left(\frac{r}{x} \right)^2 \right]$$
 Equation 21

404
$$\frac{V_{x,r}}{V_{max}} = EXP\left[-22.2\left(\frac{r}{x}\right)^2\right]$$
 Equation 22

405

406 The output solutions of equations 21 and 22, when calculated using equations 4 and 20, were 407 compared with measured non-dimensionalised axial velocity profiles for all the tested 408 propellers. Comparisons were made at downstream distances of $X/D_p = 4$, 5 and 6 within the 409 zone of established flow, and an example of the typical output obtained is shown in Figure 410 12. The output solutions of equation 22 proposed by Fuehrer & Römisch (1977) were found 411 to adequately predict the axial velocity distributions within the zone of established flow, 412 consistently, for all four experimental propellers investigated. These results agree with those 413 of Hamill (1987) and Stewart (1992), in that, equation 22 proposed by Fuehrer & Römisch 414 (1977) adequately predicts the axial velocity distributions within the zone of established flow. 415 It is suggested equation 22 needs no further modification and should be used in future 416 analysis.

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418 4.0 SUMMARY AND CONCLUSIONS

A range of experimental propellers was tested at zero advance speeds, simulating the manoeuvring operation when a ship departs from a port. The experiments simulated a freely expanding jet, with no interference from any harbour configuration or the presence of any rudder effect. The time-averaged (mean) velocity of these jets were investigated. This timeaveraged analysis can be used to assist engineers in designing suitable scour protection systems to prevent damage of erodible seabed materials by expanding the envelope of information available upon which engineering decisions can be based.

426

Semi-empirical equations have been derived, based on the main propeller characteristics and
rotational speed, to determine the location, magnitude and distribution of the axial velocity
within the freely expanding propeller jet produced by an un-ducted propeller.

When used in conjunction with Equation 4 for prediction the efflux velocity V₀, (Hamill (2014)) the maximum axial velocity decayed linearly throughout the zone of flow establishment after an initial distance of $X/D_p = 0.35$. The variables which most influenced the decay of the maximum axial velocity were: the efflux velocity (V₀), distance from the propeller (X), propeller diameter (D_p) and propeller pitch to diameter ratio (P'):

436
$$\frac{V_{max}}{V_0} = 1.51 - 0.175 \left(\frac{X}{D_p}\right) - 0.46 P'$$

437 Similarly, within the zone of established flow a semi-empirical equation based on the propeller438 characteristics determined the magnitude of the maximum axial velocity:

439
$$\frac{V_{max}}{V_0} = 0.964 - 0.039 \left(\frac{X}{D_p}\right) - 0.344 P'$$

When used with equations 4, 7 and 20 the distribution of axial velocity within the Zone of Flow Establishment was found to be adequately described by the equations developed by Hamill (1987), while for distributions within the Zone of Established Flow the method reported by Fuehrer (1977) is recommended.

444

The suite of equations presented and discussed within this paper relate to a free expanding propeller jet and bring together the current knowledge available to the engineer. The testing conducted, using state of the art LDA measurement in an expansive experimental, has allowed knowledge gaps to be filled and an integrated axial velocity predictive method published.

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