CHAPTER 346

DESIGNING FOR PROPELLER ACTION IN HARBOURS

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Abstract

The scour produced by the action of a ship's propeller is an increasing problem. There is a need for an accurate method of velocity perdition so that adequate steps can be taken to design suitable bed protection systems. The velocity characteristics of the jet produced by the rotating propeller are presented as an aid to the engineer.

Introduction

One consequence of the increases in ship size, installed engine power, and volume of marine transport is an increase attack by propeller slipstreams on the bed and banks of harbour basins and navigation channels. In restricted waterways the situation has been exacerbated since the introduction of bow thrusters in the 1960's which has increased the navigability of large ships to such an extent that they can now operate without tug assistance

A ship's propeller produces thrust by drawing in water, accelerating it and discharging it in the form of a wash. This wash is a highly turbulent submerged jet, the velocities within which depend upon the operating characteristics of the propeller and the speed of advance of the ship. The wash entrains the surrounding water and so the velocities within it decay with distance from the propeller. In this way the jet expands and dissipates its energy by diffusion. If the ship is moving in a confined area, for example in the shallow waters of a harbour basin, the diffusion process within the wash will be restricted and the energy remaining within the jet may cause damage to the bed and nearby quay structures.

Related Research

A survey of harbours in Sweden (Bergh 1981) has shown that 16 out of the 18 ports surveyed have suffered propeller induced damage in recent years. Similar problems have been encountered in several United Kingdom ports and the British Ports Association commissioned a review (Prosser 1986) of existing knowledge. In a survey of all British ports in 1994, Qurrain (1994) found that 42% of these encountered scouring as a result of propeller action, of which 29% regarded this scouring to be a serious problem causing damage to quays, with expensive remedial repairs and costly facility downtime. The diffusion characteristics of a propeller jet have been examined by numerous authors. Investigation which include the influence of the rudder on the diffusion process however, are not extensive and the majority of all predictive equations do not allow for it's inclusion.

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Robakiewicz (1966), Verhey (1983) and Fuehrer (1985) have studied the velocities within the propeller jet in the presence of a rudder, and presented equations for estimating bottom velocities. These equations are limited in that a full velocity distribution cannot be calculated and they are related to an efflux velocity equation, i.e. the maximum velocity on the propeller face, which has been found to be up to 20% in error.

Experimental Set-up

Detailed velocity measurements were taken within the diffusing jets, produced by two propellers with differing characteristics, up to a distance of 10 diameters from the propeller plane. Four jets, corresponding to four speeds of rotation, were investigated for the first propeller which was 0.076m in diameter, while three jets were investigated for a second propeller 0.131m in diameter. Axial and radial measurements of velocity were taken using a twin component Laser Doppler Anemometry system.

Rudder Effect

The magnitudes of the axial and radial velocity components within the wash were measured within the formation stages of the propeller jet, i.e. up to 2.0 D_p. To provide a better understanding of the jet diffusion, velocity vector diagrams were plotted for all experimental results with and without the rudder present. These provided a 2D schematic representation of the flow within the propeller jet. Figures 1(a) to 1(c) are typical of those obtained during the current investigation.

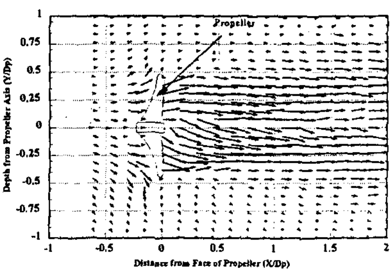

FIGURE 1(a) Resultant velocity vectors (without rudder)

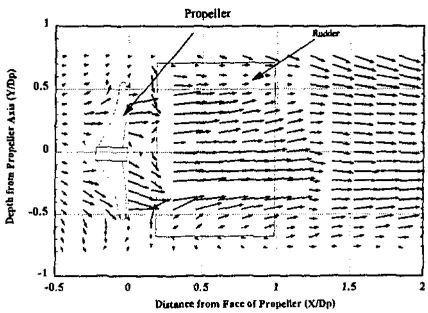

FIGURE 1(b) Resultant Velocity Vectors (Rudder at Zero Degrees)

Figure 1(a) shows the velocity distributions obtained without the rudder. The magnitude of the velocities at the hub is lower than across the blades, and the jet is diffusing away from the propeller centreline due to the radial velocity component. It can be seen that the vectors revert to the horizontal with distance from the propeller, indicating the reduction in the magnitude of the radial velocity component. The velocity distribution at each vertical section from the propeller is approximately symmetrical through the propeller axis which confirms the results of previous work. The results obtained with the rudder situated at zero rudder angle or midships position is shown in figure 1(b).

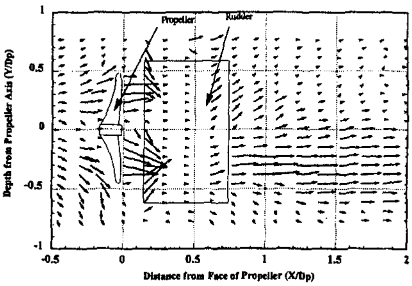

FIGURE 1 (c) Resultant Velocity Vectors (Rudder at +35 Degrees)

It can be seen that the resultant velocity distribution at the face of the propeller is similar to the distribution obtained without the rudder present. There is a significant change in the flow with distance from the propeller, as the jet is circulated around the rudder. There is a rapid reduction in the magnitudes of the velocities at the first section behind the propeller. In subsequent sections the velocities are greater as the flow moves along the sides of the rudder. It can also be seen that the vectors in subsequent section along the rudder are almost to the horizontal. This indicates that the magnitudes of the radial velocities are insignificant, and that the rudder has a straightening effect on the jet. The velocity distribution appears to vary at each section and it can be seen in some sections that there are higher velocities below the propeller centreline than at the corresponding position above the centreline.

Figure 1(c) shows the results obtained when the rudder is placed at an angle of 35 degrees to the propeller axis. The velocities at the face of the propeller are approximately symmetrical through the propeller axis and therefore appear to be unaffected by the rudder. It is the distributions in the subsequent sections that are interesting as the magnitude of the velocity below the centreline can be seen to be greater than above the centreline. This is due to the effects of splitting of the flow by the rudder. The vectors shown represent the velocities in a stream directed towards the bottom. The distribution shows that there is only one position of maximum velocity, unlike the axi-symmetrical profiles found in the absence of the rudder.

In order to provide a better understanding of the propeller diffusion characteristics with the rudder present, velocities were measured throughout the jet using a system of pitot tubes. These results were then plotted in the form of an isovel plot for each speed of rotation, which provided contours of the velocity distribution within the propeller jet. Figures 2(a) to 2(d) show the sequence of isovel plots with the rudder positioned at zero degrees, and is typical of the velocity distributions obtained for all the jets tested at this angle. Figure 2(a) shows the velocities obtained at a distance of 0.46 D_p behind the propeller, at the location of the rudder. The velocities obtained at this section are unlike those obtained for the jet without a rudder as the velocities are not symmetrical through the propeller axis (Stewart 1992). The rudder splits the main wash into two separate streams of jets. one jet is directed towards the water surface, while the other is deflected towards the sea bed. The jets are just forming at this position and the bottom jet below the centreline is clearly defined, with the

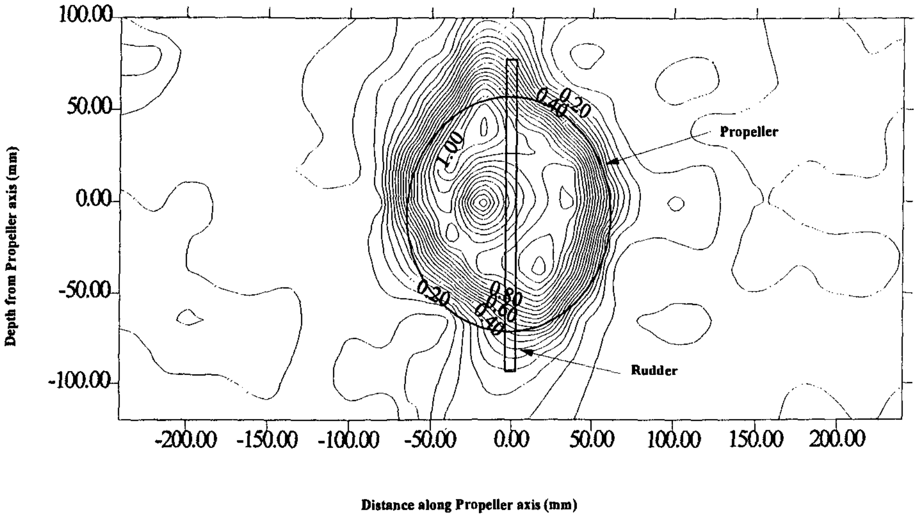

FIGURE 2(a) Isovels at 0.46 Dp for zero rudder angle

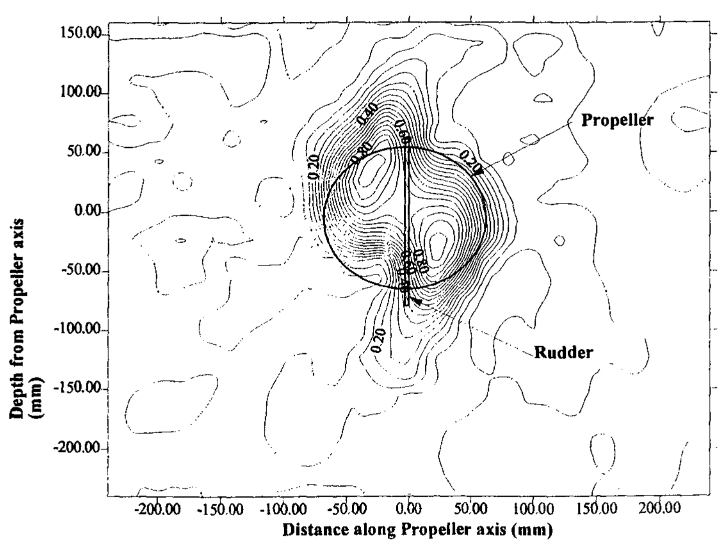

FIGURE 2 (b) Isovels at 0.92 Dp for zero rudder angle

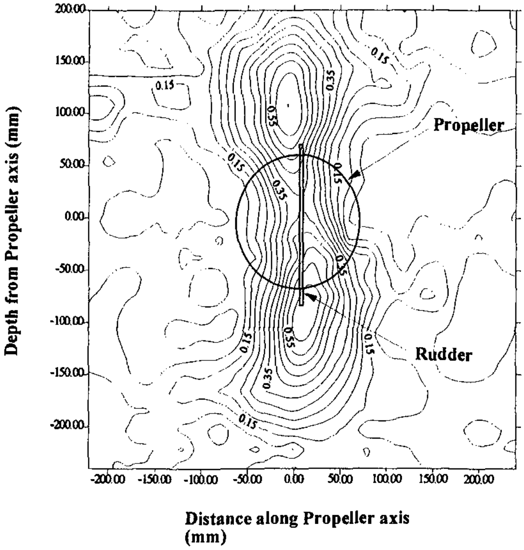

FIGURE 2(c) Isovels at 3.05 Dp for zero rudder angle

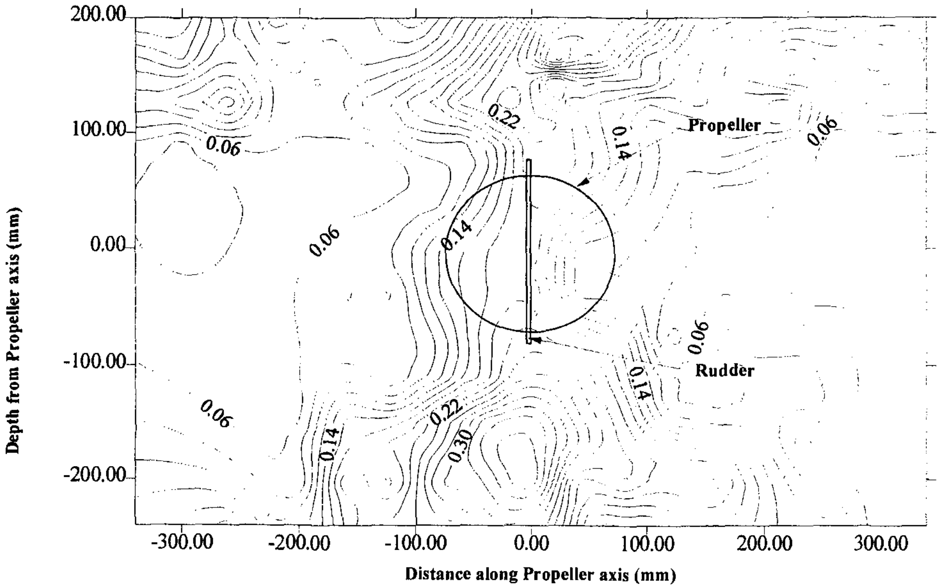

FIGURE 2(d) Isovels at 6.95 Dp for zero rudder angle

surface stream just becoming visible. Figure 2(b) which is located at a section subsequent to the location of the end of the rudder, shows the formation of the two streams, represented by the two high velocity peaks shown on each side of the rudder. This trend continues with distance from the propeller and the two streams are visible at 3.05 D_p as shown in figure 2(c). This position has previously been termed the end of the zone of flow establishment for the jet without a rudder, at which location the maximum velocity would be located on the propeller centreline. It can be seen that with distance from the propeller there is a gradual increase in the distance between the streams, and therefore the maximum velocity is not likely to revert to the propeller centreline. The divergence of the streams continues and this is confirmed in figure 2(d), at 7 D_p, where the two jets are still separating.

It has been shown that the rudder splits the jet into two streams and their deviation continues throughout the remainder of the diffusing jet. The rudder has the effect of altering the diffusion characteristics of a propeller jet and this has resulted in the formation of a different type of jet. There is no further alteration of the streams, other than by natural diffusion with the surrounding fluid, once they have been established. The zone of established flow could therefore be considered to commence at the position of the formation of the two streams. Figure 2(a) showed the formation of the two streams, although not clearly defined. However, it can be seen in figure 2(b) that the two streams are clearly defined and diverging away from each other. This position represents approximately the end of the rudder. It can therefore be concluded that the jet is fully established from the location of the trailing edge of the rudder.

It is evident from the findings of this investigation that the processes of formation and diffusion of a propeller wash, under the influence of a rudder, can in no way be described by the predictive equations that are currently available as the two streams formed by the rudder have been shown to behave as independent jets.

Characteristics of a propeller jet

Efflux Velocity Distribution

The magnitudes of all velocities within the wash produced by the rotating propeller are dependent on the magnitude of the initial velocity within the wash. This velocity, termed the efflux velocity, is found on the cutting edge of the propeller. As can be seen from figure 1 the velocity distribution along the cutting edge, or the efflux distribution, remains unchanged in the presence of the rudder, with an axi-symmetric distribution being developed. It is this initial distribution, along with the subsequent rudder interaction, which forms the wash. The velocity distribution at efflux will be proportional to the thrust developed by the propeller blade. The thrust produced by a ships propeller depends on the geometry of the propeller blades and the speed of rotation. The main characteristics which influence the developed thrust include the pitch and chord length. These characteristics vary with radial distance from the hub, and hence the thrust and therefore the velocity must also vary with distance along the blade.

The position along a propeller blade at which the greatest thrust is produced generally corresponds to the position of maximum velocity, termed the efflux velocity, V_0. Several authors have proposed equations which determine the magnitude of the efflux velocity. The original efflux velocity equation, as reported by Blaauw et al (1978) and adopted by most authors, was based on the Froude momentum theory,

$$V_o = 1.59 n D_p \sqrt{C_t}$$

The assumptions made in the momentum theory have been shown to be invalid. These short-falls in the theory have led to modifications of the theoretical efflux equation by Stewart (1992). These modifications take account of the propeller characteristics as follows,

$$V_o = E_o n D_p \sqrt{C_t} \qquad 1$$

where

$$E_o = \left[\frac{D_p}{D_h}\right]^{-0.323} [C_t]^{-0.1459} [P]^{0.44} [\beta]^{0.513}$$

The magnitude of the axial velocities at the face of the propeller have to date been estimated by solving equations developed by Albertson (1950). He proposed that the velocity distribution within the jet, close to the propeller, follows the Gaussian normal probability function.

Stewart modified the Gaussian equation and presented the following equation, to describe the axial velocity distributions within the propeller jet, based on his own investigations:

$$\frac{V_{xr}}{V_{\max}} = EXP\left(-\frac{1}{2}\frac{(r-R_{mo})^2}{\sigma^2}\right) \qquad 2$$

where the standard deviation of velocity, σ, was equal to 0.5 R_{mo} and the maximum velocity, V_{max} at the face of the propeller is equal to the efflux velocity, V_o. Berger et al. (1981) proposed that the distance to the position of the maximum velocity at the face of the propeller, R_{mo}, could be determined as follows,

$$R_{mo} = 0.67R_p - R_h \qquad 3$$

where R_h is the radius of the hub and R_p is the propeller radius.

The velocity distribution along the face of the propeller can be determined by solving equations 1,2 and 3. Velocity profiles were plotted comparing the results obtained from existing equations and the measured data. The profiles, as shown in figures 3 and 4, indicate that the measured velocity increases from the hub to a distance of approximately 0.7 R_p along the blade, and then decreases rapidly to the blade tips. This is in contrast to the profile predicted by existing equations, where the velocity increases to approximately 0.5 R_p and then gradually decreases to the blade tips. The position of the maximum velocity can also be seen to vary greatly from that determined from existing equations, when compared to the measured velocities. The distance to the maximum velocity, in all of the profiles that were plotted using existing equations, was underestimated when compared to the measured results. The existing equations, which are based on the momentum theory, have been revised and updated on several occasions by replacing the experimental constant. The magnitude of the constant varied in several investigations using different propellers, more recently Stewart updated the equation to relate the constant to the propeller characteristics. This was a calibration of a theory, which is inherently flawed, to suit experimental results. It was decided to investigate a more realistic method by which the magnitude of the axial velocities along the face of the propeller could be obtained.

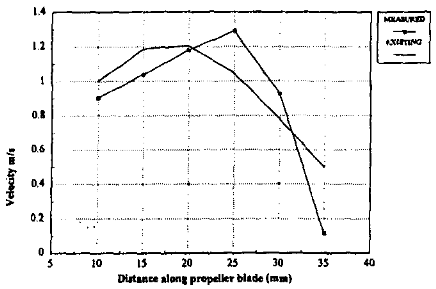

FIGURE 3 Velocity Distribution Comparison for 76mm propeller

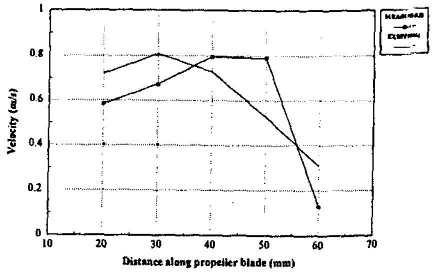

FIGURE 4 Velocity Distribution Comparison for 131mm propeller

A literature survey revealed that Koumbis (1981) investigated the thrust produced by a ship's propeller and developed a computer program which relates the thrust to the characteristics of the propeller blades. The program is based on the Vortice Lattice theory.. In designing a propeller the naval architect determines the most suitable characteristics to provide the optimum thrust for each blade. It therefore seemed reasonable to relate the distribution of velocity on the propeller face to the characteristics which produce this thrust.

The blade cross sections, as shown in figure 5, were obtained for positions along the propeller blade where the velocity measurements had been recorded. It was decided to attempt the derivation of a relationship in which the magnitude of the axial velocity could be expressed in terms of the characteristics of the propeller blades.

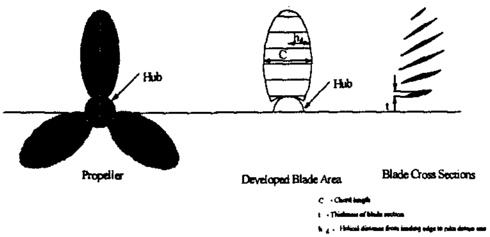

Figure 5 Propeller Blade Characteristics

A literature survey provided detailed information on the design of a propeller, and revealed the properties considered by the naval architect in designing the geometry of the propeller blade. Considering the axial velocity V_{ax}, it can be written as:

$$V_{ax} = f(n, N, r, \mu, \rho, p, t, c, h_D, h_T)$$

where	n	= number of rev/sec	N	= number of blades
	r	= radius of propeller	μ	= kinematic viscosity
	ρ	= density of fluid	p	= pitch of blade
	t	= thickness of blade	c	= chord length

h_D = helical distance from blade section leading edge to rake datum line

h_T = helical distance from blade section leading edge to position of maximum thickness

Using the Pi theorem the equation can be written as:

$$\frac{V_{ax}}{Nnr}=f\left(\frac{\rho nr^2}{\mu},\frac{p}{r},\frac{c}{r},\frac{t}{r},\frac{h_D}{r},\frac{h_T}{c}\right)$$

It was found from the literature survey that the effect of viscosity could be neglected if the Reynolds number of the jet was greater than 10^4. In the present investigation the Reynolds numbers were greater than 10^4, and could therefore be neglected from further analysis This analysis resulted in an equation with a correlation coefficient R^2 of 0.985:

$$\frac{V_{ax}}{Nnr}=1.261-0.974\left(\frac{p}{r}\right)+0.733\left(\frac{c}{r}\right)+18.527\left(\frac{t}{r}\right)+5.028\left(\frac{h_d}{r}\right)$$

$$+0.106\left(\frac{p}{r}\right)^2-7.277\left(\frac{h_d}{r}\right)^2-4.093\left(\frac{h_t}{c}\right)^2 \qquad 4$$

The high correlation obtained for the experimental data shows the assumption that the velocity distribution along the blade was a function of the varying blade characteristics was valid. The velocity distribution obtained from equation 4 and the results obtained from existing equations, were plotted with the experimental results. Figure 6 is typical of that found for the present investigation. It can be seen that there is a significant improvement in the correlation with the measured data, when compared to the results of existing equations. This was found to be the trend of the results obtained for all experiments.

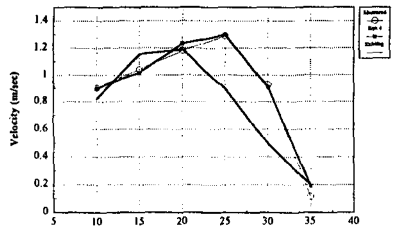

FIGURE 6 COMPARISON OF EXPERIMENTAL DATA WITH THE RESULTS FROM EXISTING AND PROPOSED EQUATION

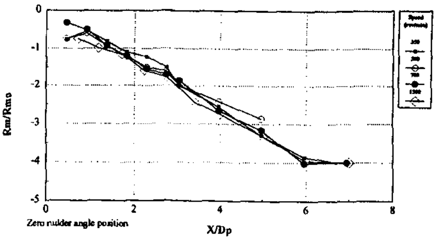

FIGURE 7 LOCATION OF THE MAXIMUM AXIAL VELOCITY WITHIN THE BOTTOM STREAM OF THE DIFFUSING JET

The magnitude of the axial velocity distribution at the face of the propeller can now be determined by solving a single equation, equation 4, instead of the three equations as proposed by existing work. The derivation of this equation is based on the physical properties of the propeller blades rather than the momentum theory which is inherently flawed. Equation 4 will accurately determine the magnitude of the maximum velocity, V_0, and the position at which it occurs along the blade. Its use beyond the scope of the current experimental programme will require further verification. However, when compared to the equations which are currently used, which themselves are based on a limited test programme, it shows great potential.

Location of the maximum velocity

The location of the maximum velocity within the bottom stream was plotted with distance from the propeller. Figure 7 shows the location of the maximum velocity in the bottom stream for each speed of rotation for a zero rudder angle. It can be seen that there is no significant variation in the location of the maximum velocity, with an inclination of approximately 12 degrees observed towards the bottom for each speed of rotation. This is in sharp contrast to that obtained when there was no rudder fitted where the maximum velocity was located along the horizontal propeller axis. It would therefore appear that for a zero rudder angle the location of the maximum velocity is independent of propeller speed of rotation.

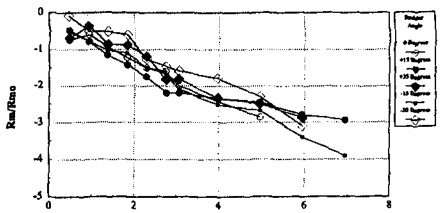

FIGURE 8. LOCATION OF THE MAXIMUM AXIAL VELOCITY WITHIN THE BOTTOM STREAM OF THE DIFFUSING PROPELLER JET FOR CHANGES IN RUDDER CONFIGURATION

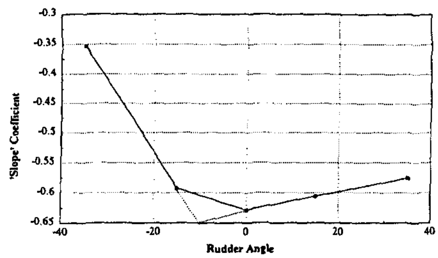

FIGURE 9 EXPERIMANTAL CONSTANT V's RUDDER ANGLE

The vertical location of the maximum velocity in the bottom stream of the jet was then plotted for all experiments and the results obtained for a typical rotational speed, with a varying rudder angle, are as shown in figure 8. The location of the maximum velocity appears to diverge at approximately the same rate for each rudder angle. The greatest depth to the maximum velocity was observed when the rudder is placed at 15 degrees up to a distance of 3 D_p and generally thereafter is greater when the rudder is positioned at zero degrees. The divergence angle was found to be approximately 12 degrees and this was found to be the general trend for this propeller at different rudder angles. The general trend showed that the greatest depths to the maximum velocity were observed when the rudder was placed at positive rudder angles. It can therefore be concluded that the depth to the maximum velocity is dependent of the rudder angle.

Equation for location of maximum velocity

Analysis of the change in position of the maximum velocity showed that it location could best be described by a linear decay equation of the type

$$\frac{R_{mx}}{R_{mo}} = Const.\left(\frac{X}{D_p}\right)$$

where R_{mx} is the maximum velocity location at any distance X from the propeller.

It was obvious that the constant term was a function of the rudder angle, as the location was seen to shift as the rudder angle changed. Figure 9 shows a plot of these constant values against the rudder angle, and it is clear that a significant variation can be observed between the positive and negative rudder angles. This is to be expected as the negative angles cause the rudder to be turned into the bottom stream therefore hindering the flow, while with positive angles the stream is free to expand. Based on this physical interference two separate equations have been developed by which the position of the maximum velocity can be obtained, and these depend on the rudder angle range as follows;

Rudder angle range $-10<\theta<+35$ degrees

$$\frac{R_{mx}}{R_{mo}} = (-0.659 + 0.002\theta)\left(\frac{X}{D_p}\right)$$

Rudder angle range $-35<\theta<-10$ degrees

$$\frac{R_{mx}}{R_{mo}} = (-0.772 - 0.012\theta)\left(\frac{X}{D_p}\right)$$

These equations are a first approximation based on the current experimental investigation and further work would be recommended to provide a clearer understanding of the influence of the rudder on the location of the maximum velocity between the zero and -15 degree rudder position.

Decay of Maximum Axial Velocity

It has been shown that for a jet without a rudder, the decay of the maximum axial velocity is not constant throughout the jet, Qurrain. The present investigation has shown that the jet is fully established from the location of the end of the rudder and therefore a single relationship must be considered to describe the decay of the maximum velocity within the propeller jet with a rudder present.

The rate of decay of the maximum velocity was found to be independent of propeller rotational speed. The rate of decay of the maximum velocity however, varies significantly when compared to previous work due to the presence of the rudder. In order to establish a relationship for the rate of decay, the values of the maximum velocity, V_{max}, within the jet were non-dimensionalised with the maximum velocity at the face of the propeller, V_o, and the distance from the propeller, X, was divided by the propeller diameter, D_p. Analysis of the results was carried out on all the data and it was found that the following type of equation provided the best correlation for the results, as can be seen in figure 10.

$$\frac{V_{\max}}{V_o} = A + B\left(LN\frac{X}{D_p}\right)$$

It was found for all tests that the B coefficient was constant and equal to 0.293. This shows that the actual rate of decay is independent of the rudder angle. There was however a significant variation observed in the values found for the A coefficients. This indicated that although the rudder had no influence on the rate of decay of velocity it clearly was influential in the initial magnitude of the maximum velocity. As was the case in the location of the maximum velocity the A coefficients were compared to the respective rudder angles and again positive and negative angles were seen to influence the magnitude of velocity. Again this is not unreasonable as has already been discussed. As before two equations by which this coefficient should be determined have been produced, again depending on the rudder angle considered.

Rudder angle range $-10<\theta<+35$ degrees

$$A = 0.915 - 0.004(\theta)$$

Rudder angle range -10<θ<-35 degrees

$$A = 1.0 - 0.007(\theta)$$

Concluding Comments

The present investigation has studied the influence of the rudder within a ship's propeller jet, and has confirmed the formation of two high velocity streams, one directed upwards to the surface and the other directed downwards towards the bottom.

The axial velocity distribution at the face of the propeller could only be determined by solving a number of equations based on the results of previous work. The present investigation found that the velocity along the face of the propeller was related to the characteristics of the propeller blade. An equation was developed which related the magnitude of the axial velocity at any point along the blade to the properties of the blade at that point.

It was found that there was an increase in magnitude of the axial velocities by as much as 30% with the rudder present when compared to the jet without a rudder.

The location of the maximum velocity within the propeller jet was on the axis of each stream which were established from the position of the rudder. This led to a redefinition of the zone of established flow. Equations are presented which locate the maximum velocity in the vertical direction allowing for changes in rudder position. The maximum deflection of the bottom stream was observed for the zero ruder angle position and was found to be approximately 14 degrees.

Results have shown that the decay of the maximum velocity within each of the streams was the same at each of the angles tested and was independent of the propeller rotational speed. It was found that there was a logarithmic decay of the maximum velocity at each of the rudder angles tested and the magnitude of the velocity encountered was found to be dependent on rudder position.

By using the equations presented it is now possible for the engineer to establish the maximum velocity at any depth below a rotating propeller. Given the bed clearance conditions it is therefore possible to predict the magnitude of the velocity which will impact on the sea bed. Knowing this velocity, and an understanding of sediment movement prediction techniques, it is possible to design either suitable bed armour units or to predict eroded depths.

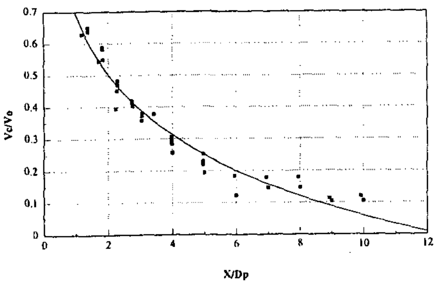

FIGURE 10 DECAY OF THE MAXIMUM AXIAL VELOCITY ALONG THE PROPELLER AXIS FOR ALL EXPERIMENTS AT ZERO RUDDER ANGLE

APPENDIX

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