A method for estimating the bed velocities produced by a ship's propeller wash influenced by a rudder.

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Introduction

When a ship manoeuvres within the confines of a harbour it does so with minimal bed clearance and at near to maximum power. The propeller produces thrust by drawing in water and accelerating it. This accelerated flow is discharged from the propeller in the form of a jet or wash. Under these circumstances the wash can impact on the bed with velocities in excess of 8 m/sec. These high velocities erode the seabed, and where this occurs near to quay structures serious damage may result. Bergh and Magnusson (1987) Chait (1987) and Johnston (1985) are among many who have given specific details of problems which have occurred world-wide.

In order that an engineer may provide adequate protection to the bed form the erosive power contained within the propeller wash a full understanding of the magnitude and distribution of the velocities within it must be known. Stewart (1983), Fuehrer (1977) and Berger (1981), among others, have studied the wash and have provided predictive equations for velocity calculations. However, they have not included the influence of the rudder on the formation and distribution of the wash.

Related Research

Robakiewicz (1966), Verhey (1983) and Fuehrer et al. (1987) carried out investigations which allowed for the presence of the rudder, and they presented methods by which the velocities on the sea bed could be calculated. These equations are limited in that a full velocity distribution cannot be calculated and they are related to an efflux velocity equation which has been found to be up to 20% in error.

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Hamill and McGarvey (1996) presented the initial findings from a study aimed at providing a method for designing for propeller action in harbours and this paper contains information which extends that already presented at ICCE'96.

Experimental set-up

A number of model propellers, operating at up to four speeds of rotation, have been tested in an experimental tank 7.5m x 4m x 1 m deep. Rudders were manufactured in accordance with the Ship Design Manual, and these were tested within the normal range of operation, at angles of up to 35 degrees on either side of the propeller axis. Velocity measurements, in both the axial and radial directions, were taken on a fine 3D grid within the wash using a twin component Laser Doppler Anemometer and an array of Pitot static tubes.

Rudder effect

Hamill and McGarvey (1996) discussed the influence of the rudder, on the propeller wash. The wash was found to split into two different jets, one directed towards the free surface the other directed towards the seabed, as shown in figure 1. It was found that there was an increase in the magnitude of the axial velocity by as much as 30% with the rudder present when compared to the jet without a rudder. A method by which the velocity distribution on the face of the propeller could be calculated was given. This has been shown to provide a more accurate value for the efflux velocity.

As the rudder turns into either the bottom jet, or surface jet, it changes the resulting velocity magnitudes and distributions which prevails within the wash. This can be seen in figure 2 which represents the same situations as figure 1 but with the rudder turned -15 degrees into the bottom jet. The bottom jet has now been moved in both the vertical 'y' and transverse 'z' plane when compared to the zero rudder location

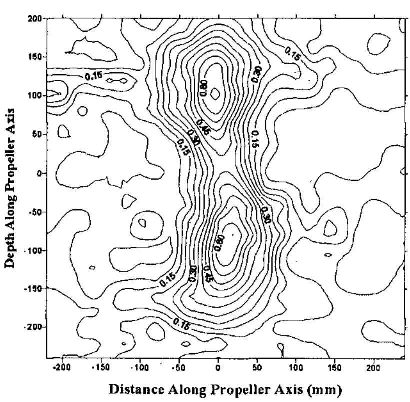

Figure 1 Isovels at zero rudder angle

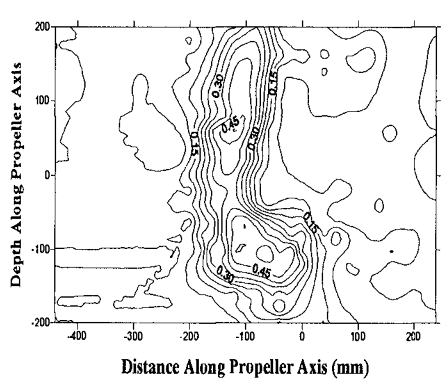

Figure 2 Isovels at –15 degree rudder angle

The equations presented by Hamill & McGarvey (1996) provide a method for calculating the position of the maximum velocity in the 'y' plane only. It is clear form figure 2 that transverse diffusion is also present within the wash.

The ability to locate the position of maximum velocity in the three dimensional space behind the propeller, along with a method for predicting its magnitude, allows the calculation of the velocity distribution around that value to be attempted. Previous distribution equations have been based on an axis-symmetrical approach. However, as the rudder angle changes it becomes clear that within the bottom stream a symmetric assumption would be invalid and as a consequence separate distribution equations have been developed which describe the velocities vertically and transversely within the jet, allowing for changes in rudder position.

Propeller wash characteristics

Having already established a relationship for the velocities on the 'y' (vertical) plane, Hamill and Mc Garvey (1996), the location of the maximum velocity along the 'z' plane was then observed. It was expected that this would be more influenced by altering the rudder angle due to the deflection of the jets by the rudder which provides directional control for a ship.

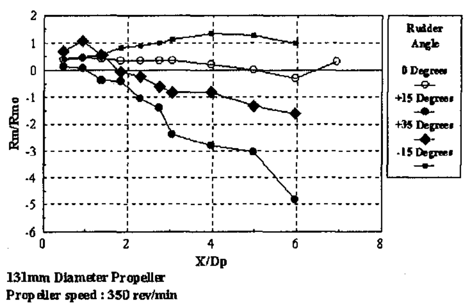

Figure 3 Location of Maximum Velocity on Z plane

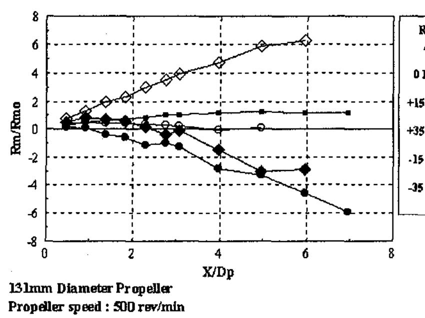

Figure 4 Location of Maximum Velocity on Z plane

The location of the maximum velocity within the bottom stream in the 'z' direction of the jet was tracked and plotted. It was found that the rudder had a significant effect in controlling the direction of the bottom stream. The location of the maximum velocity within the bottom stream of a typical wash is as shown in figure 3. The general trend of the surface stream showed that with a change in rudder position there was a corresponding change in the stream which tended in the general direction of the rudder, for all of the angles tested. Figure 3 shows however that this trend does not continue for the bottom stream. It can be seen that with an increase in the rudder angle from 15 to 35 degrees there is in fact a reduction of the diffusion angle of the bottom stream. Figure 4 shows the location of the maximum velocity in the bottom stream of another wash, for all of the angles tested. It can be seen that for the negative rudder angles the streams diffuse in the direction of the rudder however once again it can be seen that there is a reduction of the horizontal diffusion angle as the rudder angle is increased from 15 to 35 degrees. The explanation for this ambiguous trend lies in the initial formation stages of the jet, and is the result of the direction of rotation of the propeller and increasing positive rudder angles.

Equation for location of maximum velocity on Z-plane

As was the case for the vertical plane, the location of the maximum velocity in the 'z'-direction is best described by a linear decay equation of the type;

$$\frac{R_{mz}}{R_{mo}} = Const.\left(\frac{X}{D_p}\right) \qquad 1$$

where R_{mz} is the location of maximum velocity in the 'z' plane at any axial distance 'X' from the propeller. Figure 4 showed the location of the maximum velocity in the Z-direction for a typical test propeller, for all of the rudder angles tested. It can be seen that for the zero rudder angle position the bottom stream moves towards and crosses the propeller centreline. It has been shown that the bottom stream tends in the direction of the rudder and as the rudder angle varies there is a corresponding variation in the direction of the bottom stream. There was a change in this trend observed for the +35 degree rudder angle in which there is a reduction of the jet deflection as the rudder is turned from +15 to +35 degrees.

With reference to figure 4 it is clear that the magnitude of the constant term in equation 1 is some function of the rudder angle. The magnitudes of these constants for each propeller, propeller speed of rotation and rudder angle combination was obtained by a simple regression analysis, and these are compared to the change in rudder angle in figure 5.

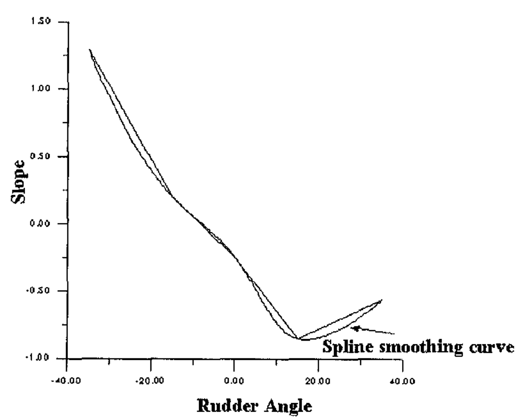

Figure 5 Measure slope for location of maximum velocity on Z plane at various ruder angles.

It can be seen that there is a gradual decrease in the slopes from the -35 degree rudder position to the +15 degree rudder angle and then as expected there is a reduction in the slope from +15 to +35 degrees. A spline curve was then fitted to determine if a mathematical relationship existed between the slopes and the rudder angle, and is plotted as shown in figure 5. It can be seen that the curve peaks at some position between +15 and +20 degrees and thereafter there is a reduction in slope and without further tests this rudder angle remains ambiguous. It was therefore decided to develop a relationship between the slope and rudder angle within the range of -35 and +15 degrees. It was found that the following linear relationship provided the best correlation for the data,

$$m_z = -0.27 - 0.04(\theta) \qquad 2$$

which achieved a correlation of 0.98 where θ is the rudder angle in radians. The location of the maximum velocity along the Z-plane may therefore be determined using the following equation, within the range $-35<\theta<+15$ degrees,

$$\frac{R_{mz}}{R_{mo}} = 1 + m_z \cdot \left(\frac{X}{D_p} \right) \qquad 3$$

It would be recommended that further tests be carried to clear the ambiguity surrounding the location of the maximum velocity on the Z-plane when the rudder is located between +15 and +35 degrees. It appears that at some angle within this range the general trend changes where there is in fact a decrease in the rate of diffusion with increasing rudder angle.

This equation when used with those for the vertical plane position, R_{my}, reported in Hamill & McGarvey (1996), enable the location of the position of the maximum velocity in the 3D space behind the propeller to be determined.

The velocity distributions within the propeller jet.

A method has already been reported by which the magnitude of the maximum axial velocity, at any axial distance X within a propeller jet, can be determined, Hamill & McGarvey (1996). It is also necessary to predict accurately the velocity distributions around this maximum value so that adequate bed protection can be designed to protect quay structures.

The velocity distributions, within the zone of established flow, for a free expanding jet without a rudder present are symmetrical about the axis of the propeller. The velocity distributions at any point within the jet have been shown to follow the normal probability curve as proposed by Albertson (1950), and modified by Fuehrer and Romisch (1977). Their equation has been successfully used by several authors and was found to describe quite accurately the velocity distributions within a propeller jet without a rudder present.

Influence of rudder on velocity profiles

The rudder has been shown to split the flow into two high velocity streams, one directed towards the surface and the other directed towards the bottom. It was decided to investigate the velocity distributions within the bottom stream as this is the jet which induces bed velocities, and as a result, can lead to erosion of the bed. It has previously been shown that a variation in rudder angle significantly alters the diffusion characteristics of the bottom stream, with a confining and an elongation effect within the stream, resulting in a loss in the symmetry common to the free expanding wash.

Velocity distribution on vertical Y-plane.

The velocity profiles along the Y-plane through the jet axis, at increasing distance from the propeller, were plotted for the bottom stream. Figure 6 shows the axial velocity distributions for a typical jet with a zero rudder angle. It can be seen that with distance from the propeller there is a decay in magnitude of the velocity profiles and an increase in the distance to the location of the maximum velocity. It can be seen that they appear quite similar to the normal probability distributions suggested by previous authors. It can be seen that the distributions are approximately symmetrical through the stream axis, although the velocities are slightly greater along the profile above the stream axis that is due to the proximity of the surface stream close to the propeller. As the distance from the propeller increases, the distances between the streams also increase and the influence of the surface stream becomes less significant. This was found to be the general trend of all the results obtained for the zero rudder angle position.

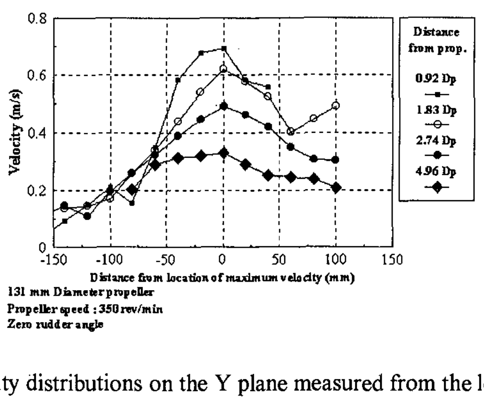

Figure 6 Axial velocity distributions on the Y plane measured from the location of maximum velocity within the bottom stream.

In order to describe the velocity distribution it is necessary to consider the normal probability curve proposed by Albertson to describe the velocity profiles,

$$\frac{V_{xr}}{V_{\max}} = EXP\left[-0.5\left(\frac{y}{\sigma}\right)\right]^2 \qquad 4$$

where V_{xr} is the velocity at the point under consideration and y is the distance from the propeller axis to the point. The term σ is the standard deviation of velocity and is the distance from the axis to the point at which the velocity has a value of 0.605 V_{max} and this term depicts the depth of the profile. It was therefore required to determine the location of the standard deviation of velocity so the velocity distributions within the propeller jet could be established.

The location of the maximum velocity, and the velocity distributions on the Y-plane within the propeller jet, were found to be dependent on rudder angle. Therefore, as the shape of the distribution profile depends on the standard deviation of velocity, it would be reasonable to assume that the standard deviation of velocity is dependent on the magnitude of rudder angle. The location of the maximum velocity on the Y-plane has been established in terms of the distance below the propeller axis. It was therefore decided to establish a point one standard deviation of velocity below the maximum as the distance below the propeller axis, $R_{\sigma y}$. It was observed that there was a gradual increase in the distance to this point with distance from the propeller and this can be observed when plotted as shown in figure 7. The location of the maximum velocity on the Y-plane is also plotted for comparison.

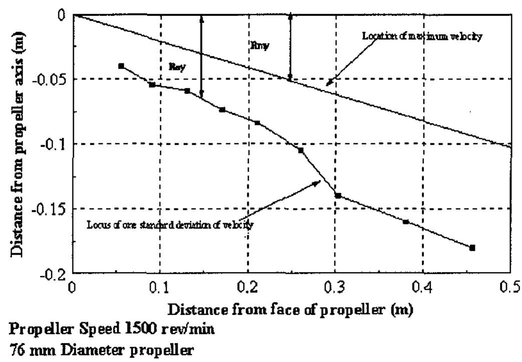

Figure 7 Location of standard deviation of velocity On Y plane for a zero rudder angle

It was found that a linear regression provided the best relationship between the rudder angle and the locus of one standard deviation. Thus a point at one standard deviation of velocity can be located from the following equation,

$$R_{\sigma y}=-0.8R_{mo}-(-0.322+0.0012\theta)X \qquad 5$$

The velocity distribution can be established based on equation 4 proposed by Albertson where y is the distance from the location of the maximum velocity on the profile and is equal to R_{my}-y_m in which y_m is the distance from the propeller axis to the point under consideration. Figure 8 shows a schematic view of the velocity profiles within the propeller jet to avoid confusion. The standard deviation of velocity, σ, as shown in figure 8 is equal

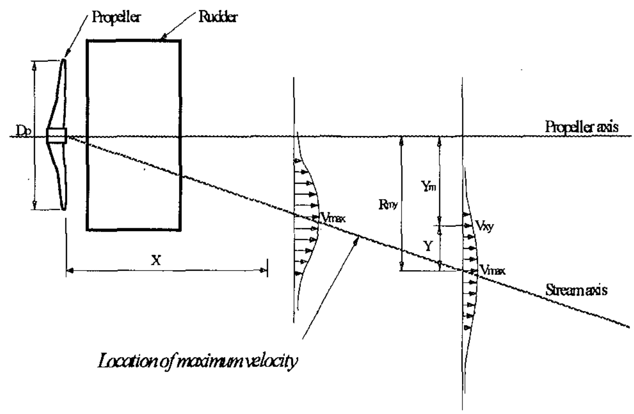

Figure 8 Velocity distribution schematic for Y plane

to $R_{\sigma y}$-R_{my}. The velocity distribution within the propeller jet can therefore be described as follows,

$$\frac{V_{xr}}{V_{\max}} = EXP\left[-0.5\left(\frac{R_{my}-y_m}{R_{\sigma y}-R_{my}}\right)^2\right] \qquad 6$$

where $R_{\sigma y}$ is calculated from equation 5.
This equation will predict quite accurately the velocity distributions within the propeller jet for a given rudder angle at distances up to 10 D_p.

Velocity distribution on the Z-plane

In a similar manner to that employed for the analysis of the locus of one standard deviation on the 'y' plane, a relationship for the 'z' plane was also established. Thus $R_{\sigma z}$ can be calculated from

$$R_{\sigma z}=0.2R_{mo}+(-0.141-0.014\theta)X \qquad 7$$

The velocity distribution along the Z-plane can now be established based on the normal probability equation where the distance along the profile, z, is equal to R_{mz}-z_m, in which z_m is the distance from the propeller axis to the point under consideration, and R_{mz} is the distance to the maximum velocity. For clarity this is shown in figure 9. The standard deviation of velocity, σ, is equal to $R_{\sigma z}$-R_{mz}, therefore the axial velocity distribution on the z axis may be expressed as follows,

$$\frac{V_{xz}}{V_{\max}} = EXP\left[-0.5\left(\frac{R_{mz}-z_m}{R_{\sigma z}-R_{mz}}\right)^2\right] \qquad 8$$

where $R\sigma z$ is calculated from equation 7.

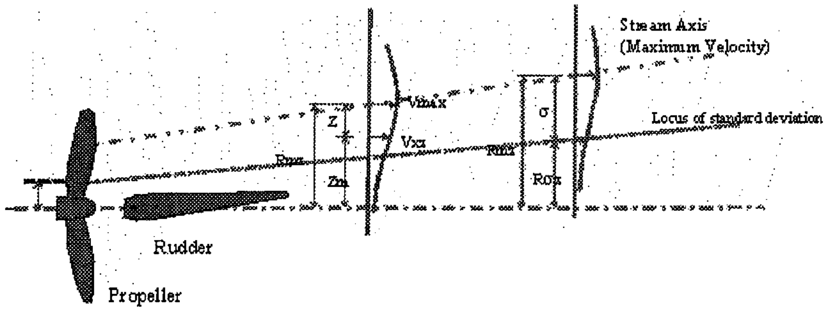

Figure 9 Velocity distribution schematic for Y plane

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 influence of the rudder on the maximum velocity at the face of the propeller i.e. the efflux velocity, was found to be insignificant, although at high propeller speeds and large rudder angles some confinement was observed with a variation of approximately 8% noticed.

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. The location of the maximum velocity within the jet was found to be independent of propeller speed however, there were significant changes in the location of the maximum velocity due to variations in rudder position. Equations are presented which locate the maximum velocity in the vertical and transverse directions allowing for changes in rudder position.

The velocity distributions were found to change dramatically when compared to the jet without a rudder. Investigations showed that the equations used to predict the velocity distributions within the jet without a rudder present cannot successfully be applied to the jet with a rudder. The rudder position significantly changed the diffusion characteristics of the propeller jet and as a consequence distribution equations were developed to describe the velocities vertically and transversely within the jet, allowing for changes in rudder position, based on the normal probability curve suggested by Albertson (1950).

The velocities at any point within the jet can be determined using the equations presented. They are first approximation equations and further work should consider a greater number of rudder positions. Having established knowledge of the velocities within the propeller jet, it is now possible to design adequate scour protection.

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