Flow Field Measurement around a Marine Propeller by Laser Doppler Velocimeter *

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Measurement of flow velocity distribution around a marine propeller was carried out by Laser Doppler Velocimeter (LDV) in a cavitation tunnel. An LDV measurement system which can supply both velocity data and measuring position data relative to the blade was developed, and the information about instantaneous velocity distribution around propeller blades was obtained. Authors succeeded in revealing the vortex system around propeller blades. The effect of a strong vortex extending from blade tip was recognized in the measured velocity data. Accelerated and contracted flow behind blades was also observed. Thrust and torque estimated from velocity distribution in slip stream were compared with direct measurement results. Comparison between experimental results and lifting surface theory shows that the existence of strong tip vortices shown by the experiment can not be followed by the theory. It is necessary to investigate a separated flow in the region near the blade tip, in order to improve the theoretical method.

Key Words : Flow Measurement, Unsteady Flow, Marine Propeller,
Laser Doppler Velocimeter, Vortex

1. Introduction

The hydrodynamic characteristics of marine propellers can now be estimated theoretically, because the lifting surface theory was made available using a high speed computer more than ten years ago⁽¹⁾. Lifting surface theory supplies not only thrust and torque but also microscopic information such as pressure distribution on propeller blade. In order to obtain the microscopic information, experimental studies such as measurements of pressure distribution on propeller blade⁽²⁾ and measurements of velocity

distribution, around propeller blades^{(3),(4)} have been performed. As a result, it is almost clear that the theory can express approximately the actual phenomena, although there are some differences between the theoretical and the experimental results. One of the differences is in the phenomenon appearing in the region near the blade tip⁽⁵⁾. Although it is important to survey the hydrodynamic behavior in the region near the blade tip in order to estimate the characteristics of propellers, there are few studies on the tip region on account of the difficulties in treating by either theory or experiment. Authors are studying the flow field around the propeller with three blades of low aspect ratio, the geometry of which magnifies the tip characteristics.

Recent progress in measurement technique with LDV (Laser Doppler Velocimeter) is remarkable, and the technique has provided the ability to measure time-varying velocities. Consequently, the technique is being applied to many fields such as flow phenomena in hydraulic machinery⁽⁶⁾, flow around the rotor blade of helicopter⁽⁷⁾

* Received 31st October, 1984.

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and so on. There are also some studies on marine propellers made by using LDV. Almost all studies on marine propellers, however, treat the mean velocity during propeller rotation. The mean velocity is not sufficient as the information on the velocity field varying around propeller blades especially near the tip region.

Authors developed an LDV measurement system, in which triggering pulses, synchronized with the propeller rotation, initiate collection of the LDV data, in order to measure the periodically varying velocity field, and succeeded in showing the instantaneous velocity field around operating propeller blades. The following are the results of the measurements which provide insight into flow structure around a propeller. The experiment was performed in a cavitation tunnel with a test section of 0.75 m diameter at the Ship Research Institute.

2. LDV Measurement System

The arrangement of the LDV measurement system is shown in Fig.1. The LDV system is composed of DISA 55X, one component backscatter optics, and DISA 55L90a, counter processor, and others (8). This system enables simultaneous measurement of only one velocity component, thus requiring three sets of measurements to acquire all three components. In the system, after checking whether validated velocity data are acquired or not, the velocity data and the signal for rotating blade angle from the propeller dynamometer are fed to a microcomputer. The continuation of the data accumulation gives the velocity distribution along a circumference drawn by propeller rotation. It is necessary to control the number of tracing particles in the flow in order to secure the reliability of the LDV measurement. A commercial water paint was used as particles to be poured into the tunnel. As a result the measurement was performed under the condition that the number of the validated data points per second was 300-500 and that the number was 10-30 percent of the number of the particles passing through the measuring position.

3. Model Propeller and Experiment Condition

We used a model propeller with three blades of low aspect ratio.

Fig. 1 LDV Measurement System

Table 1 Particulars of Model Propeller
MPNo.221

Diameter (m)	0.300
Boss ratio	0.313
Pitch ratio	0.850 (const.)
Exp. area ratio	0.515
Blade thickness ratio	0.048 (at root)
Angle of rake	0°
Number of blade	3
Blade section	NACA 4 digit

Fig. 2 Geometry of Model Propeller
MPNo.221

Particulars and configuration of the propeller are shown in Table 1 and Fig. 2, respectively. The blade of the propeller has no camber unlike the ordinary marine propeller. The experiment was performed with the model propeller operating in a uniform flow. Number of propeller rotations was set at $n = 12 \text{ s}^{-1}$ and tunnel water speed V_v was varied to produce the required advance coefficient $J = V / nD$. (D : propeller diameter, V : propeller advance speed in infinite field) The effect of the tunnel wall was taken into consideration by using the theoretical relation between velocity upstream of the propeller in tunnel V_v and velocity upstream of the propeller in infinite region V , (5)

$$\frac{V_v - V}{V} = \frac{2}{\pi} \left(\frac{R}{R_T} \right)^2 \frac{K_T}{J^2}$$

where R and R_T are radius of the model propeller and that of tunnel, respectively, and K_T is thrust coefficient. Coordinate system is shown in Fig.3. The coordinate X is measured in the backward direction of propeller shaft, the coordinate θ is measured positive in the contra-rotating direction of propeller, and the coordinate r is measured in the radial direction. The velocities V_X , V_T and V_R are velocity components of the coordinate direction.

Fig. 3 Helicoidal Coordinates

4. Results of the Measurement of Velocity Distribution

The experimental results of the velocity distribution V_X and V_R along the circumference at a given

Fig. 4 Circumferential Distribution of Axial Velocity Components V_X ($J = 0.584$, $X / D = 0.11$)

Fig. 5 Circumferential Distribution of Radial Velocity Components V_R ($J = 0.584$, $X / D = 0.11$)

radius just behind the propeller blade are presented in Figs. 4 and 5 for the case of $J = 0.584$. Measured values are plotted for every degree of blade angular position θ taken as the abscissa. The velocity V_v is used for the normalization of velocity. Three bladed propeller causes three periods of the velocity distribution in one rotation. Data in the figures show the velocity field of the strong tip vortices and weak free vortex sheets. In Fig. 4 (V_x), the direction of the velocity peak for $r = 0.95 R$ is opposite to that for $r = 0.925 R$. This is because the two measurement positions are at outside and inside of the tip vortex, and the tip vortex takes place between the two measurement positions. Small disturbance shown on the left side of the velocity peak for $0.925 R$ and $0.9 R$ in Fig. 4 is considered to be the effect of a free vortex sheet emanating at trailing edge. In Fig. 5 (V_R), it is clear that flow direction changes rapidly at the position of the tip vortex. Fig. 6 is the plots of vectors composed of V_T and V_R seen from behind. Velocity field behind propeller blade, especially flow around tip vortex can be well understood by this figure.

5. Mean Velocity Distribution

Measured circumferential distributions of velocity components V_x , V_T and V_R yield the circumferential mean values $\bar{V}_x$, $\bar{V}_T$ and $\bar{V}_R$. Fig. 7 shows the mean velocity component $\bar{V}_x$ for the case of $J = 0.364$. The increase of the velocity component $\bar{V}_x$ with increasing axial distance is shown. The accelerated region becomes narrow as the position shifts downstream, which indicates a slipstream contraction. Outside the slipstream, velocity behind the propeller is lower than that before it.

6. Pitch Distribution

Pitch $2\pi h$ of the helicoidal flow was calculated using the velocity components $\bar{V}_x$ and $\bar{V}_T$. Radial distribution of the pitch is presented in Fig. 8 for the case of $J = 0.364$. The pitch of observed tip vortex cavitation and the pitch calculated by lifting surface theory (LST) are also plotted. The fact that the pitch of the tip vortex is smaller than the pitch of

Fig. 6 Velocity Vector Diagram $V_T + V_R$
($J = 0.584$, $X / D = 0.11$)

Fig. 7 Radial Distribution of Mean Axial Velocities $\bar{V}_x$ ($J = 0.364$)

the inside helicoidal flow, indicates a rolling-up of the edge of the vortex sheet, and makes one imagine easily the shape of the vortex system of the flow separated at the blade tip.

7. Circulation around Blade Section

Circulation Γ around the blade section at radius r is given by formula (9)

$$\Gamma = 2\pi r \bar{V}_T / l$$

(l : number of blades)

which is valid on the simple assumption. Radial distribution of the circulation is shown in Fig.9. The values of $x/D = 0.1, 0.2$ and 0.5 in the figure mean the axial positions where the values $\bar{V}_T$ were measured. The three results should be equal in principle. It is due to the limitation of the formula that the equality of the three results is not sufficient. Also shown is a result calculated by lifting surface theory (LST). Estimated value by the measurement and theoretical value are in good agreement in general. However, high peak and steep gradient of the experimental data near the tip are not followed by the lifting surface theory. The strong circulation near the tip is considered to cause a separated tip vortex which becomes main part of slip stream vortex system.

8. Comparison of Thrust and Torque between Flow Field Analysis and Direct Measurement

Flow field data V_x and V_T from LDV measurement can be used for the estimation of thrust coefficient $K_T = T / \rho n^2 D^4$ (T : thrust, ρ : density of water) and torque coefficient $K_Q = Q / \rho n^2 D^5$ (Q : torque) of the propeller through the flow field analysis. The estimated values are compared with values directly measured by propeller open test (POT) and with theoretical values by lifting surface theory (LST), in Table 2. The values estimated by the flow field analysis and the direct measurement are in satisfactory agreement, which proves the reliability of the values measured by the LDV measurement system.

Fig. 8 Radial Distribution of Pitch of Helicoidal Flow ($J = 0.364$)

Fig. 9 Radial Distribution of Circulation around Blade Section

Table 2 Thrust and Torque

	J=0.584		J=0.362	
	K_T	K_Q	K_T	K_Q
Direct Measurement (POT)	0.088	0.0140	0.183	0.0240
Lifting Surface Theory (LTS)	0.088	0.0140	0.157	0.0202
Cal. from Velocity Data (LDV)	0.084	0.0138	0.187	0.0235

9. Concluding Remarks

An LDV measurement system was developed to measure the periodically varying flow field around a rotating marine propeller. A three-dimensional complex flow field around a propeller operating in a uniform flow was measured and an inspection of the measured velocities reveals the complexity of the flow field around a propeller. The comparison between the measured results and the results calculated by lifting surface theory shows that it is necessary to take into account the separated flow in the region near the blade tip, in order to improve the theoretical analysis method. If the measurement as discussed in this report becomes easier and faster in future, the measurement system will be applicable to analysis of propeller blade performance, and further to improvement of propeller geometry.

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