Thrust analysis of propulsion mechanisms with pectoral fins in a Manta robot

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Abstract. The development of autonomous underwater robots is required for the ecological survey of aquatic life. Conventional underwater robots have a common mechanism for propulsion with screw propellers. Noises generated by screw propellers have a possibility of giving a bad effect on the biological behavior. Robots mimicking fish propulsion mechanisms are less likely to seriously affect living things. In our laboratory, a Manta robot that has a propulsion mechanism with pectoral fins has been developed. The operation range of the conventional Manta robot was limited by a cable for remote control. It needs an autonomous navigation system based on localization not so as to be restricted by cables. Constructing the model that takes into consideration the thrust of propulsion mechanisms with pectoral fins is expected to be used for localization. In this paper, we analyze the thrust of propulsion mechanisms with pectoral fins, using a Wei's model. In addition, we compare the analysis results with ones obtained by an actual Manta robot, and verify whether the analysis is correct.

1. Introduction
The development of fisheries resources and the ecological survey of aquatic life are carried out in the sea [1]. However, it is dangerous for humans to directly investigate underwater, and the activity time is restricted. Thus, it needs to develop autonomous underwater robots [2]. For general underwater exploration robots, screw propellers are used as propulsion mechanisms [3]. However, the propulsion mechanism using the screw propeller has a problem that underwater noises caused by cavitation adversely affect to organisms underwater [4], a problem that catches aquatic animals and plants, and so on.

Mikuriya et al. [5] developed a Manta robot that has a propulsion mechanism with pectoral fins, which are constructed by mimicking the pectoral fin of the manta ray. The Manta robot generates a propulsive force by moving the fins attached to the propulsion mechanism with pectoral fins, so that it can make forward and backward motion, turning motion, diving motion, and surfacing motion. Since the propulsion mechanism with pectoral fins is not using a screw propeller, it has little influence on aquatic life, and it is suitable for ecological survey of aquatic life. There is a problem that the operation range in the conventional Manta robot is limited, because such a robot communicates by a cable. Radio waves are attenuated in the water, so that it is difficult to use GPS and remote control by wireless communication. It needs an autonomous navigation system with localization for Manta robots to conduct an ecological survey of aquatic life not so as to be restricted by cables.
In this research, we aim to construct a model for localization so that it takes into consideration the thrust generated by the propulsion in Manta robots mechanism with pectoral fins. Since the localization method using a model does not use many sensors, it is easy to be applied to a Manta robot which is one of small sized underwater robots. In addition, by integrating such a model with information provided by other localization methods, an improvement of accuracy of localization can be expected. In this paper, we analyze the thrust of the propulsion mechanisms with pectoral fins in Manta robots, by using a thrust model developed by Wei et al. [6]. In addition, comparing the analysis results with ones obtained by an actual Manta robot, it is verified whether the analysis is correct.

2. Outline of Our Manta Robot

Figure 1 shows a top view of our Manta robot.

![Manta robot](image)

**Figure 1.** Manta robot.

The Manta robot has a pair of the propulsion mechanism with pectoral fins on the left and right sides of the fuselage and has a control unit in the center. Each propulsion mechanism with a pectoral fin is composed of six fin-rays which is a skeleton of the fin. There are fins between fin-rays to push out water, and a stretchable silicon wrap is used for the material of the fin. For a total of 12 fin-rays, a servomotor is attached to each one independently. The Manta robot gains a thrust by moving up and down fin-rays and generating a traveling wave in the fin. The center part of the robot includes the control unit for controlling the propulsion mechanism with pectoral fins and some weights for setting the specific gravity of the Manta robot to about 1. The size of the Manta robot is 405 mm in length, 620 mm in width, 90 mm in height and 5.3 kg in weight when all the fin-rays are in a horizontal state.

3. Thrust model

The thrust generated by the propulsion mechanism with pectoral fins is expressed using a model. In this research, we used the thrust model developed by Wei et al. [6].

3.1. Force received from fluid

The force $F$ [N] that an object in a flow receives from a fluid is expressed by the following equation:

$$F = \frac{1}{2} \rho CU^2 S$$

(1)

Here, $\rho$ [kg/m$^3$] is the density of a fluid, $C$ is the drag coefficient, $U$ [m/s$^2$] is the flow velocity, and $S$ [m$^2$] is the reference area. The $C$ is determined by the shape of the object and by Reynolds number, and it is a dimensionless number obtained by experiments.

$F$ [N] can be decomposed into forces parallel to the surface of the object and forces perpendicular to it, and in the case of smooth, thin, flat objects, the force parallel to the surface can be neglected. Therefore, the force that the Manta robot's fin receives from the fluid is a component perpendicular to the fin's surface in $F$ [N].
3.2. Setting the coordinate system

In the motion analysis of the propulsion mechanism with pectoral fins, the coordinate system shown in figure 2 is defined in the propulsion mechanism with pectoral fins for the Manta robot.

![Figure 2. Coordinate system for the fin.](image)

3.3. Waveforms formed by fin-rays

The propulsion mechanism with pectoral fins forms a traveling wave by moving fin-rays up and down, thus generates a propulsive force. When the traveling wave is a cosine wave, the angle \( \theta(s, t) \) [rad] of the fin-ray at the point \( s \) [mm] on the \( X_q \) axis is expressed by the following equation:

\[
\theta(s, t) = \theta_{\text{max}} \cos \left(2\pi f t - \frac{2\pi}{\lambda} s + \phi_0 \right)
\]  

Here, \( \theta_{\text{max}} \) [rad] is the maximum angle of the fin-ray, \( f \) [Hz] is the frequency of the fin-ray, \( t \) [s] is the time, \( \lambda \) [mm] is the wavelength, and \( \phi_0 \) [rad] is the initial angle of the fin-ray.

3.4. Thrust by the propulsion mechanism with pectoral fins

An arbitrary point \( P \) on the fin can be expressed as follows:

\[
P = \begin{bmatrix} x_q(s, h, t) \\ y_q(s, h, t) \\ z_q(s, h, t) \end{bmatrix}
\]  

with

\[
x_q(s, h, t) = s, \quad y_q(s, h, t) = h \cos[\theta(s, t)], \quad z_q(s, h, t) = h \sin[\theta(s, t)]
\]

if the \( X_q \) coordinate is \( s \) [mm] and the distance from the origin \( O_q \) is \( h \) [mm]. The point \( P \) is shown in figure 3.

![Figure 3. Point P on the fin.](image)

The velocity vector \( v_p \) of the point \( P \) is expressed as follows:

\[
v_p = \begin{bmatrix} 0 \\ -h \theta'_t \sin[\theta(s, t)] \\ h \theta'_t \cos[\theta(s, t)] \end{bmatrix}
\]
where $\theta'_t$ denotes the time derivative of $\theta(s,t)$. The normal vector $n$ of the point P is expressed by the following equation:

$$
\mathbf{n} = \frac{\partial \mathbf{P}(s,h,t)}{\partial s} \times \frac{\partial \mathbf{P}(s,h,t)}{\partial h} = \begin{bmatrix}
-h\theta'_s \\
-s\sin[\theta(s,t)] \\
\cos[\theta(s,t)]
\end{bmatrix}
$$

(5)

where $\theta'_s$ is the derivative of $\theta(s,t)$ with respect to $s$. Note here that $\times$ represents the cross product. Therefore, the normal unit vector $\mathbf{n}_0$ of the point P is as follows:

$$
\mathbf{n}_0 = \frac{n}{||n||} = \frac{1}{((h\theta'_s)^2 + 1)^{1/2}} \begin{bmatrix}
-h\theta'_s \\
-s\sin[\theta(s,t)] \\
\cos[\theta(s,t)]
\end{bmatrix}
$$

(6)

From equations (1), (4) and (6), the propulsive force $F_n$ [N] by the propulsion mechanism with pectoral fins is expressed by the following equation:

$$
F_n = -\frac{1}{2} \rho C \iint_D \left( v_p \cdot \mathbf{n}_0 \right)^2 \mathbf{n}_0 dS \\
= -\frac{1}{2} \rho C (\lambda f)^2 \iint_D \frac{\left( h\theta'_s \right)^2 \text{sgn}(h\theta'_s)}{(h\theta'_s)^2 + 1} \begin{bmatrix}
-h\theta'_s \\
-s\sin[\theta(s,t)] \\
\cos[\theta(s,t)]
\end{bmatrix} ds dh
$$

(7)

where $\cdot$ denotes the inner product.

4. Verification of the analysis and actual measured values in thrust

We analyze the thrust generated by the propulsion mechanism with pectoral fins of the Manta robot using MATLAB. In addition, we compare the measured thrust values by the previous research in Mikuriya et al. [5] with the present analysis result.

4.1. Rectangle method

To calculate the thrust generated by the propulsion mechanism with pectoral fins, a rectangle method was used as a numerical integration method. The rectangle method is a method of dividing the region of the model to be analyzed into square elements, and thus obtaining an approximate solution by summing the analysis results of each node.

4.2. Analysis conditions

Equation (7) is calculated using a difference method and the thrust by the propulsion mechanism with pectoral fins is analyzed. Three kinds of operational conditions were used the thrust measurement experiment of a Manta robot conducted by Mikuriya et al. [5]. Referring to these, we calculate the parameters so that the fins generate the same motion as that in [5], and name them the cases a, b and c, respectively. The measured swimming speed of the Manta robot in the cases a, b and c are 0.0873 m/s, 0.135 m/s, and 0.184 m/s, respectively. The fin shape is a rectangle as shown in figure 4. The fin in the propulsion mechanism with pectoral fins was divided into many squares whose one side is 1 mm and analyzed using a rectangle method.

Several parameters used for the analysis are shown in table 1. $\rho$ [kg/m$^3$] was set to 998.2 kg/m$^3$ as the density of water at 20˚C. $C$ was given 1.12 which is the drag coefficient of a square thin plate [7]. The average thrusts per cycle are calculated on the Xq axis.
Table 1. Parameters used for the analysis.

| Parameters | Cases |
|------------|-------|
| $\lambda$ [mm] | a | b | c |
| $\theta_{\text{max}}$ [rad] | 0.317 | 0.380 | 0.443 |
| $f$ [Hz] | 0.8 | 0.9 | 1.0 |
| $\phi_0$ [rad] | 0 | 0 | 0 |
| $\rho$ [kg/m$^3$] | 998.2 | 998.2 | 998.2 |

4.3. Analysis results
From the previous study in Mikuriya et al. [5], the measured thrusts for the case a, b and c are 0.189 N, 0.689 N, and 1.15 N, respectively. The analysis results, when $C = 1.12$, show that the average thrusts per cycle in the cases of a, b and c are 0.265 N, 0.659 N, and 1.36 N, respectively. Figure 5 shows the measured thrusts and the analysis results for the cases of a, b and c when $C = 1.12$.

4.4. Setting of drag coefficient
The $C$ is in general a dimensionless number obtained by experiments. Here, a more appropriate drag coefficient is determined using the analysis result. The drag coefficient at which the sum of errors between the three measured thrusts and three analysis results becomes a minimum is 0.95. The drag coefficient of fins of the Manta robot was set to 0.95 and analyzed again. It was found, from the analysis results, that the average thrusts per cycle for the cases of a, b and c were 0.225 N, 0.559 N, and 1.14 N, respectively, when $C = 0.95$. Figure 6 shows the measured thrusts and the analysis results for the cases of a, b and c when $C = 0.95$. 

Figure 4. Fin shape.
Figure 5. The analysis results when $C = 1.12$.

Figure 6. The analysis results when $C = 0.95$.

4.5. Considerations
The total error of between the measured thrusts and the analysis results is 0.316 N when $C = 1.12$, whereas, it is 0.176 N when $C = 0.95$. When $C = 0.95$, the total difference of between the measured thrusts and the analysis result is 44.3 % lower than that of when $C = 1.12$. Therefore, it is thought that 0.95 is appropriate for the drag coefficient of the Manta robot’s fin. Figure 5 and figure 6 show that the measured thrusts increase as the swimming speed increases. The analysis results are also shown to be the same trend as the measured values. From this result, it is considered that a localization system can be constructed for the Manta robot based on the thrust model.

5. Conclusion
In this paper, we have conducted the thrust analysis of the Manta robot by using a thrust model by the propulsion mechanism with pectoral fins. In addition, we compared the analysis results with ones obtained by an actual manta robot, and verified whether the analysis is correct. As a result, it was found that the analysis result and the measured thrusts showed the same trend. In future, we will model the movement of Manta robot based on the analyzed thrust and will aim to construct a localization system using such a model.

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