Abstract — The aim of this study was to clarify postural control in the pitch direction using a combination of the flexion angles of the root and fin tip of the pectoral fin in *Mobula japanica* using Three-D-Computational fluid dynamics analysis. We made Mobula models that allow flexion of the tip of the fin and the root of the fin independently. It was revealed that independent pectoral fin flexion promotes a change in the velocity distribution around the body and, as a result, the pitch moment is generated.

Index Terms — Flexion angle, Pectoral fin, Mobuliform, Velocity distribution, Pitch moment

I. INTRODUCTION

In order to adapt to their habitat, most marine organisms have gained specific functions and shapes through the process of evolution. In *Mobula japanica*, the bone structure of the pectoral fin consists of osteocartilaginous tissue, and the swimming style is a combination of two motions: mobuliform locomotion, or pectoral fin flapping, and rajiform locomotion, in which the fin edges propagate waves [1, 2]. Although the flapping motion in *Mobula japanica* is similar to the wing flapping motion in birds and insects, it is a spontaneous muscle activation rather than a passive deformation of their pectoral fins, since birds and insects do not have skeletal muscles in their wings. Thus, the flapping motion of *Mobula japanica* is different from the flapping motion of other organisms due to the deformation of their fin shape. We assume that the pectoral fin muscle is likely to improve fluid dynamic effects and/or control postural maneuvering. In the case of fluid dynamic characteristics, previous studies have demonstrated the vortex system of swimming in fish [3] and the *Manta birostris* [4]. To our knowledge, however, the effects of changes in the deformation of pectoral fins on fluid dynamic characteristics, such as velocity distribution and surface pressure distribution, remain unclear. To clarify these phenomena, we focused on the mobuliform locomotion in *Mobula japanica*, using a rigid-phase model of a one-cycle flapping motion investigated through three-dimensional computational fluid dynamic (3D-CFD) analysis, and found flapping phase–dependent fin deformations that affected the velocity and surface pressure distribution [5]. In the case of postural maneuvering, previous studies have demonstrated the relationship between the body tilt angle and the pectoral fin motion in steelhead trout, *Oncorhynchus mykiss*, and bluegill, *Lepomis macrochirus* [6], or relationships between rolling torque and the centers of mass and buoyancy [7–9]. In addition, Wilga and Lauder demonstrated that pectoral fins appear to be critical for initiating maneuvering behaviors, but not for lift production, and for steady horizontal locomotion in the leopard shark, *Triakis semifasciata*. However, these fish move by the oscillation of the body and caudal fin, which is completely different from mobuliform

![Fig. 1 Sinking locomotion in Mobula japanica](image-url)

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locomotion, the locomotion style of *Mobula japanica*. For example, Fig. 1 shows the typical body pitching locomotion of *Mobula japanica*. Although it is apparent that the pectoral fins are flexed during sinking, the relationship between postural maneuverability and the flexion angle of the pectoral fin is unknown. Hence, the purpose of this study was to investigate through 3D-CFD the postural maneuverability of the combination of the flexion angle of the fin tip and the root joints of the pectoral fins relative to the velocity and surface pressure distributions.

II. METHODS

An analytical model of *Mobula japanica* was created using free and open source software (Blender 2.78a, Blender Institute B.V.) and was made of two basic shapes, as shown in Fig. 2: the body shape was a prolate spheroid, and the pectoral fin was a rectangle. The body shape was 0.6 [m] wide, 1.0 [m] long, and 0.3 [m] high; the aspect ratio of the pectoral fin shape was 3.2, and the sizes were set at 1.6 [m] wide, 0.5 [m] long, and 0.05 [m] high.

Since the flexion of the pectoral fin was remarkable at the root and central part, the pectoral fin flexor is 0.25 [m] from the tip of the fin, and each flexion angle of the fin set at $\theta_F = \{0, 30, 60, 90\}$ [deg]. The pectoral fin root joint flexor is 0.55 m from the tip of the fin, and each flexion angle of the root joint is set at $\phi_R = \{-45, -30, -15, 0, 15, 30, 45\}$[deg], as shown in Fig. 3. Figure 4 shows the typical one-cycle mobuliform locomotion in *Mobula japanica*; Mobula1 to Mobula5 denote the down-stroke phase, and Mobula5 to Mobula9 indicate the up-stroke phase. As compared to the phase of Mobula6, which is the base position, it is obvious that the pectoral fin was flexed at the root joint in Mobula5, Mobula7, and Mobula8; also at the tip joints in...
III. RESULTS

A. Effect of changes in the pectoral fin angle ($\theta_F$) on velocity distributions

Figure 5 shows the velocity distribution around cross sections of $\theta_F(30)$ (Fig. 5(a)) and $\theta_F(90)$ (Fig. 5(b)) at $y = 0.7$. As seen from the front, the velocity distribution under the front edge of the pectoral fin and body in $\theta_F(90)$ is higher than that in $\theta_F(30)$. In the back part of body at $y=1.3$, the velocity of $\theta_F(90)$ (Fig. 5(c)) increased at the upper and lower parts of the body, as compared to the velocity of $\theta_F(30)$ (Fig. 5(d)). The regions of the increased velocity distributions are substantially equal both upper and lower parts of the body. It also shows the velocity distribution around cross sections of $\theta_F(30)$ (Fig. 5(e)) and $\theta_F(90)$ (Fig. 5(f)) at $y = 1.38$. In the case of $\theta_F(90)$, the high-velocity distribution at the upper part of body is larger than that of $\theta_F(30)$.

B. Effect of changes in the pectoral fin root joint ($\varphi_R$) on velocity and surface pressure distributions

Figure 6 shows the velocity distribution in $\varphi_R(-45)$ (Fig. 6(a and b)) and $\varphi_R(+45)$ (Fig. 6(c and d)). As compared to the bottom side of the velocity distribution, the upper side is higher when the root joint of the pectoral fin flexed in a negative direction, whereas the distribution is lower when the root joint of the pectoral fin flexed in a positive direction.

Figure 7 shows surface pressure distributions in $\varphi_R(0)$ (Fig. 7(a)), $\varphi_R(+45)$ (Fig. 7(b)). When the fin was in the positive flexed position (Fig. 7(b)), the negative pressure distribution become large at the root joint and leading edge as compared to $\varphi_R(0)$ (Fig. 7(a)).
C. Effect of combined changes in the pectoral fin angle (θ_F) and the pectoral fin root joint (φ_R) on velocity distributions

Figure 8 shows the velocity distribution in (θ_F, φ_R) = (0, 30) (Fig. 8(a)) and (θ_F, φ_R) = (30, 30) (Fig. 8(b)) at z=1.2, and at z=1.3 (Fig. 8(c and d)). As compared to the independent change in φ_R (Fig. 8(a)), the low-velocity distribution had spread at the upper rear part of the body under the condition of the combined changes in θ_F and φ_R (Fig. 8(b)). It should be noted that this tendency was opposite to that of the changes of only θ_F, as shown in Fig. 5. Further, as the distance from the body in the height direction (z=1.3; Fig. 8 (c and d)), the spread of this area tends to disappear comparing to those of z=1.2 (Fig. 8(a and b)).

IV. DISCUSSION

A. Effect of independent changes in θ_F and φ_R on velocity and surface pressure distributions

Generally, the flow velocity around a cylinder in a laminar flow increases. Therefore, it is obvious that a fast flow distribution is formed around the model body. The results (Fig. 5) show that a large θ_F would cause high velocity distribution at the upper part of the body. In the small θ_F, however, the velocity distribution of the upper part of the body is comparable to that of the lower part of the body. High velocity distribution is formed by narrowing the interval of the streamlines passing between the pectoral fins due to the change of the pectoral fin angle θ_F(+), and suggested that these phenomena would remain up to the upper rear part of the body. Similar tendencies were demonstrated in a previous study [5]; when θ_F is large (downstroke phase), the velocity increases steeply under the front edge of the pectoral fin in Mobula japonica, since this phenomenon means that Mobula japonica’s shape makes descending easy.

φ_R would also affect the velocity (Fig. 6) and surface pressure distributions (Fig. 7). As the pectoral fin flexed upwards (φ_R (+)), a high velocity distribution appears in the lower part of the body, and at the same time a negative pressure is generated at the front edge of the pectoral fin. Therefore, as shown in Fig. 9 ((i) - (xiii)), an attractive force is generated in the lower part of the body, and this attraction can be regarded as a rotational force in pitch direction with the center of gravity of the body. These results suggest that independent changes in θ_F and φ_R would control postural maneuverability, especially in the pitch direction.

B. Effect of combined changes in θ_F and φ_R on velocity distributions

As compared to the independent changes in θ_F and φ_R, the low velocity distribution appeared at the upper
Fig. 9 Sinking locomotion in Mobula japonica: (left column) Schematic figure for relationship between the changes in $\theta_F$ and $\phi_R$ and postural maneuverability, (a) initial phase, (b) head down by pitching motion, (c) effect of a combined change in $\theta_F$ and $\phi_R$ for maintain the moving direction, (right column) Actual sinking locomotion in Kaiyukan. Orange and blue ellipse denotes the changed velocity distributions, orange straight arrows are the attractive force, and red circle arrows and circled plus/minus are the concept of pitch motion.
rear part of the body under the condition of combined changes in $\theta_f$ and $\varphi_R$. These results could be considered as a stronger effect of canceling by $\varphi_R$ than the high velocity distribution formed by $\theta_f$. Therefore, we assume the influence of $\varphi_R$ as the main factor for the overall changes in the fluid dynamic characteristics in *Mobula japanica*, and $\theta_f$ has a secondary effect.

These phenomena can be illustrated as shown in Fig. 9 (a, b and c). By controlling $\varphi_R$, as shown in Fig. 9(a), an attractive force is generated by the velocity distribution difference around the body, and a pitch moment is then produced. In response to phase, the head is directed downward and shifted to the sinking locomotion, as shown in Fig. 9(b). Figure 9(c) illustrates the velocity distribution and the attractive force under combined changes in $\theta_f$ and $\varphi_R$. The faster velocity distribution changes induced by the root joint flexion of the pectoral fin ($\varphi_R$) would be offset by the lower velocity distribution changes generated upon the upper rear part of the body by the flexion of the pectoral fin ($\theta_f$). Therefore, these results suggest that the tip of the pectoral fin during the last phase of the upstroke phase would be a decelerated action by the voluntary flexion of the pectoral fin tip to control the pitch direction. With respect to our results, for *Mobula japanica* to move downward, it is a necessary and sufficient condition that $\varphi_R$ is positive, meaning that it is in the upstroke phase, and the body rotates in the pitch direction. Indeed, right column of Fig. 9 shows actual sinking locomotion of *Mobula japanica*: in the initial stage of sinking locomotion (Fig. 9(i) - (vi)), only the flexion of the root joint of the pectoral fin ($\varphi_R$) is involved, and it is in the upstroke phase. By the latter half of the sinking locomotion (Fig. 9(vii) - (xiii)), however, the combined flexion of the pectoral fin ($\theta_f$) had appeared. Generally, profile drag could be reduced by adding winglets at the tip of an airplane’s wing [10]. Previous studies have demonstrated that an increased anhedral angle could reduce the coefficient of drag ($C_D$) in a pigeon model [11], and the increased anhedral angle could also reduce the $C_D$ [12], causing these angles to stabilize in the lateral direction while flying [11, 13]. Based upon these previous studies and our observations, we could speculate that synergistic pectoral fin flexion ($\theta_f$ and $\varphi_R$) in *Mobula japanica* would be relevant in different roles: the flexion angle of the root joint of the pectoral fin ($\varphi_R$) mainly controls posture in the pitch direction, and the flexion angle of the pectoral fin ($\theta_f$) may have fine-tuned postural maneuverability.

C. Limitations and future works

We examined the effects of $\theta_f$ and $\varphi_R$ on velocity and surface pressure distributions using static mobuliform models, whereas the dynamic deformations of pectoral fins while flapping in *Mobula japanica* are simultaneous mobuliform and rajiform motions. In addition, our models might be too simple because they utilize a prolate spheroid and rectangles. Moreover, we did not consider the shape of the leading edge or trailing edge and/or the differences in curvature of deformed pectoral fin as compared with those of *Mobula japonica*. Also, previous study had demonstrated the effect of the differences in the shape of the caudal fin to the swimming performance using four different rigid shapes [14]. However, morphology and actual performance have high complicated interrelationships. Further studies are needed to clarify these phenomena, dynamic deformation patterns, and the shape of the body and pectoral fins.

V. CONCLUSIONS

In this study, the relationship between pectoral fin flexion and postural maneuverability during sinking locomotion in *Mobula japonica* was clarified by the velocity distribution through 3D-CFD. Pectoral fin flexion was expressed by a model that considers the tip of the fin ($\theta_f$) and the root of the fin ($\varphi_R$) independently. It was revealed that independent pectoral fin flexion promotes a change in the velocity distribution around the body and, as a result, pitch moment is generated. These results suggest that the independent changes in $\theta_f$ and $\varphi_R$ would control postural maneuverability, especially in the pitch direction. In addition, it is speculated that in the upstroke phase, the action is decelerated by the voluntary flexion of the pectoral fin tip and may fine-tune postural maneuverability.

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